THURSDAY, AUGUST 26, 2004

*** Author presenting Paper**

Session: U1-E

BLOOD FLOW I
Chair: T. Thomas
Siemens Medical

U1-E-1 510AC 10:30 a.m.
(Invited)
DECOMPOSITION OF FLOW SIGNALS INTO BASIS FUNCTIONS: PERFORMANCE ADVANTAGES, DISADVANTAGES, AND COMPUTATIONAL COMPLEXITY

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The filter used to separate blood signals from the unwanted tissue clutter signal is an important part of a color flow imaging system. Due to limited number of signal samples available from each packet of Doppler data, traditional methods using time-invariant high pass filters gives poor frequency separation. Decomposition of the signal packet into basis functions is an alternative way of separating blood signals from clutter. By appropriate choice of basis functions, the unwanted clutter components in the Doppler signal are concentrated in a limited part of the corresponding energy spectrum, and can be removed by a linear projection. The Legendre polynomials form an orthonormal set of basis functions, and have been used in several commercial ultrasound scanners for clutter rejection in color flow imaging. The clutter component is in this case found by a polynomial fit to the signal, and the polynomial order determines the filter characteristics. Polynomial regression filters give excellent stop band damping, and short transition band, and outperforms FIR filters. A number of different performance measures for clutter filters will be discussed. If the covariance matrix of the clutter signal is known, the eigenvector basis gives decomposition with the clutter energy concentrated in a minimum number of eigenvalues, and a regression filter of minimum order can be constructed. The clutter covariance matrix can be estimated by spatial averaging over a region in the ultrasound image. This adaptive filter approach has been proven successful in suppressing high bandwidth clutter signals in situations with irregular tissue movements. Images examples will be shown. Optimal detection of blood signal by Neuman-Pearson test can also be solved by eigenvector decomposition. A major disadvantage of the regression filter is that they induce a bias in the blood velocity estimate, both for the autocorrelation and the crosscorrelation method. The bias can be predicted from the filter coefficients, and will also be demonstrated by image examples.

U1-E-2 510AC 11:00 a.m.

COMPARISION BETWEEN DOPPLER OPTICAL COHERENCE TOMOGRAPHY AND HIGH FREQUENCY ULTRASOUND SPECKLE VARIANCE FLOW IMAGING

V. X. D. YANG*[1,2], A. NEEDLES[3], D. VRAY[4], S. LO[2], M. L. GORDON[2], S. FOSTER[3], B. C. WILSON[2], and I. A. VITKIN[2], [1]MD-PhD program, University of Toronto, [2]Ontario Cancer Institute, University Health Network, [3]Sunnybrook and Women's College Health Sciences Center, [4]CREATIS.
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Objective: Visualization of the microcirculation can provide important diagnostic and therapeutic monitoring information in vascular and neoplastic diseases. We have previously described a Doppler Optical Coherence Tomography (DOCT) system capable of detecting microcirculation at velocities as low as 100 μm/sec to a depth of 2 mm. High frequency ultrasound (>20MHz) can image deeper; however, real-time visualization of slow blood flow is difficult to achieve. Our aim is to develop a non-invasive ultrasound technique for microvascular imaging of slow flowing blood.

Methods: We describe a speckle-variance flow processing (SFP) algorithm based on detecting the changes in B-mode pixel intensity on a high frequency ultrasound system operating at 40-60 MHz. The velocity sensitivity of the algorithm was determined by a flow phantom using blood mimicking fluid. In vivo experiments involving tadpoles, rodents (mice and rats), and human volunteers were performed to compare the ultrasound SPF performance to DOCT.

Results: The velocity sensitivity was determined to be 100-200 μm/sec at 30 frames/sec with 512 lines per image, and the SFP results exhibit a non-linear relationship with the flow velocity. Microcirculation in the tadpole cardiovascular system and tumour blood flow in rodents were observed using ultrasound SFP and DOCT. Initial demonstration of using this method in detecting subcutaneous blood flow in human volunteers was also performed and compared to DOCT.

Conclusions: To the best of our knowledge, this is the first demonstration of real-time microcirculation imaging using non-Doppler high frequency ultrasound. The velocity sensitivity and spatial resolution of such a system approaches that of DOCT, with improved depth penetration, and can be utilized to visualize slow blood flow in the microcirculation of small animals and humans.

Natural Science and Engineering Research Council Ontario Cancer Institute University Health Network Canadian Institutes for Health Research Canadian Cancer Society Sunnybrook and Women's Health Science Center

U1-E-3 510AC 11:15 a.m.

LIMITATIONS OF DUAL FREQUENCY MEASUREMENTS FOR EMBOLUS CLASSIFICATION

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Transcranial Doppler ultrasound (TCD) is a sensitive technique for detection of micro-emboli in the cerebral circulation. Such emboli may be solid, liquid or gaseous, and their backscatter properties, and likely clinical significance depend both on their size and especially their composition. In many situations the composition is unknown and therefore it is difficult, for example, to distinguish signals from small and innocuous gaseous emboli and those from large and potentially malign solid emboli. One technique that has been used to help in this respect is a dual frequency method, in which measurements of the ratios of the Doppler signal from the embolus and from the surrounding blood ('Measured embolus to blood ratios' or MEBRs) are made at two different frequencies. A potential problem of this technique is that it is not possible to exactly match the ultrasonic beam shapes at the two frequencies, and that therefore differences in MEBRs are not purely a result of the acoustical properties of the embolus. In this work we studied a commercial ultrasound transducer (DWL) designed for dual frequency measurements at 2 MHz and 2.5 MHz. Free field theoretical and experimental beam shapes were obtained at each frequency and found to be in good agreement; in each case there were significant differences between the fields obtained at the two frequencies. Experimental measurements were also made of beam shapes at the two frequencies after they had passed through samples of human temporal bone; once again there were significant differences between fields measured at the two frequencies. A simple mathematical model was developed to determine the uncertainties in measurement of relative MEBRs in the Middle Cerebral Artery at the two frequencies assuming a realistic range of vessel-beam configurations. The vessel was modelled as an ideal 3mm diameter unbranched straight cylindrical vessel; emboli were modelled as point scatterers which travel parallel to the vessel axis, and it was assumed all such trajectories are equally likely. Errors were calculated for different bone samples, different insonation angles, and different degrees of misalignment between the ultrasound beam and the vessel, each of which influenced the results to a certain degree. Combining results from different angles and bone samples, the calculated errors in measuring ΔMEBR (MEBR(2 MHz) - MEBR(2.5 MHz)) were distributed approximately normally with a mean value of -0.2 dB, and a standard deviation of 1.1dB. Although these errors are relatively small in absolute terms, the algorithms employed in commercial machines only classify emboli as particulate if ΔMEBR falls between –0.8 dB and 2 dB (rising to 2.5 or 3 dB for very large values of MEBR(2 MHz)). Even if all other aspects of the measurement process were perfect, and that the 'true value' of ΔMEBR fell exactly in the middle of the range for solid emboli, the results of this study predict that errors due to slight differences in beam shapes at 2.0 MHz and 2.5 MHz would cause 20% of solid emboli to be classed as gaseous.

U1-E-4 510AC 11:30 a.m.

IMPLANTABLE DOPPLER SYSTEM FOR SELF-MONITORING VASCULAR GRAFTS

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Peripheral vascular disease necessitates replacing diseased leg arteries with substitute vessels, known as vascular grafts. Ideally fashioned from the patient's own veins, artificial vessels are used if no suitable vein is available. Artificial grafts are placed in >60,000 patients/year in the USA. Unfortunately, most artificial grafts fail (flow goes to zero) relatively quickly: 40% of these patients lose their legs within three years.

Vein grafts, when routinely scanned by duplex ultrasound at 6-month intervals and treated for any reduced flow, provide >80% leg survival over 5 years. Regular duplex examination does not extend artificial graft life, presumably because when flow starts to fall, it proceeds to zero too quickly to be detected by such surveillance. We have developed a system to extend the life of artificial grafts by providing daily flow monitoring.

We report on a CW Doppler system to be embedded in the walls of an artificial graft. A diffraction-grating transducer, within and parallel to the graft wall, produces a beam angled across the lumen; a slab transducer, positioned adjacent to the diffraction-grating transducer, receives Doppler-shifted backscattered ultrasound from blood that moves through the transmitted beam. Our diffraction-grating transducer, fabricated by the NIH Resource for Medical Ultrasound Transducer Technology at USC, is a PZT array 1.4 mm long, 1 mm high, and 75 microns thick; driven by a single coax at 20 MHz, it produces two beams at 51 to the transducer plane. The Doppler system of diffraction-grating transducer and adjacent slab receiver is 1 mm wide, 3.5 mm long, and, mounted on a ceramic backing for strength, 275 microns thick. It fits easily into the graft wall with minimal effect on the graft. With the Doppler system in the graft wall and blood-mimicking fluid pumped through the graft, $<$ 1 mW drive signals produce received Doppler signals of >30 dB signal-noise ratio. Measurements of flows over a range from 100 - 900 ml/min by this system show errors of <10%.

Monitoring the flow is of no value unless falling flow values, the sign of a failing graft, can be communicated to a physician so that he can intervene. In the last few years implantable electronic transceivers have been developed that allow pacemakers to wirelessly communicate with bedside units. We have adapted this technology so that our implantable unit can measure graft flow nightly and communicate the results to a bedside monitor; that monitor can in turn notify a physician if falling flow in the graft indicates impending failure. Using a conventional pacemaker battery, our implantable unit, 1 x 2 x .5 will be capable of performing nightly monitoring and transmission for greater than 5 years before needing a battery change.

We will present the details of this system, and discuss future broader applications for monitoring flow and other hemodynamic variables of interest in blood vessels within the body.

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HIGH FREQUENCY B-MODE ULTRASOUND BLOOD FLOW ESTIMATION IN THE MICROVASCULATURE

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Recent developments of new animal models of human disease have shown the need to quantify vascular hemodynamics and morphology in the microcirculation. It has been shown that high-resolution B-mode ultrasound imaging at 40 MHz is a suitable imaging modality for the assessment of mouse tumours and other cardiovascular targets. Colour Doppler imaging can be used for blood flow detection, however frame rates are limited to a few frames per second if the detection of slow flow is a priority as it is in tumour microvascular studies. Also the spatial resolution of the B- mode image is compromised when narrowband transmit pulses are used. This study extends speckle tracking approaches to estimate blood flow by analysing ultrasound speckle motion along a 30 fps sequence of high frequency B-mode images. Two complementary techniques are compared. First, a newly developed speckle-variance flow processing (SFP) algorithm estimates the evolution of the image intensity measured at a fixed point along the sequence of images. This frame-to-frame differential approach gives an estimate of the velocity index. Secondly, the classical Speckle Tracking (ST) method estimates the displacement of a speckle pattern from frame to frame. The size of the speckle pattern is calculated from the 3D PSF. The size of the tracking region is determined from the velocity magnitude and direction. The displacement is estimated by minimization of a similarity function (sum-absolute difference distance in a pattern matching algorithm). The velocity vector field is then deduced from this displacement estimate. A UBM (Ultrasound Biomicroscopy) system (VisualSonics, Toronto, Canada) operating at 40 MHz was used to acquire image sequences at 30 fps, with a resolution of 40 micron (axial) and 70 micron (lateral). Phantom measurements were made on a 1 mm diameter wall-less vessel flow phantom. A blood mimicking fluid was introduced into the cylindrical vessel with a calibrated pump in the range of 0.1 mm/s to 30 mm/s. It was found that for flow rates between 0.1 mm/s to 1 mm/s, SFP gives a linear increase as a function of calibrated flow. From 1.0 mm/s to 30 mm/s, however, SFP acts as a motion detector. It was also found that ST gives accurate estimations of velocities from 0.1mm/s to 10mm/s. Thus, at 30 fps both methods perform best under conditions of low flow rate, given that there is a high stability of the surrounding tissue. At these low flow rates parabolic flow profiles are obtained showing the behaviour of the flow inside the section of the cylindrical vessel. In vivo image sequences at 30 fps of Xenopus laevis embryos (tadpoles) have also been processed using both methods. These sequences show blood flow in 100 micron aortic branches, clearly demonstrating the feasibility of mapping flow in the microcirculation with high frequency B-mode images.

Session: U2-E

HEART CHARACTERIZATION
Chair: J. Miller
Washington University

U2-E-1 510BD 10:30 a.m.

ULTRASONIC STRAIN AND STRAIN RATE IMAGING FOR THE ASSESSMENT OF REGIONAL MYOCARDIAL FUNCTION IN MICE

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Introduction: With high frequency imaging becoming more widely available, functional imaging of the murine heart has attracted increasing interest. Previously, standard gray scale imaging has been used to characterize ventricular morphology (wall thickness, cavity size) and function (ejection fraction, fractional shortening). However, prior studies in large animals and humans based on relatively low frequency insonation (2.5-5MHz) have shown that ultrasonic strain (S) and strain rate (SR) imaging is a more sensitive measure of myocardial function which can be used to assess regional myocardial deformation for individual cardiac segments.

Aims: The aims of this study were: i) to test the feasibility of measuring S and SR in small animals, ii) to determine normal S and SR values in mice and iii) to test whether these new ultrasonic indices could differentiate normal from abnormal myocardial function in mice.

Methods: In ten normal mice (age 105$\pm$4 d) and ten genetically manipulated mice with heart failure (MLP-/- mice; age 105$\pm$10 d), gray-scale M-mode data and B-mode Myocardial Velocity Imaging (MVI) data sets were acquired using a GE Vivid 7 equipped with a 13MHz linear array transducer (i13L) using parasternal short axis views (frame rate 294+/-35 Hz). Pulse repetition frequency was minimized while avoiding aliasing. For standard gray-scale measurements, anterior (Ant) and inferior (Inf) wall thickness (WT) and left ventricular diameter (LVD) were measured at end-diastole (ED) and end-systole (ES). From these measurements, fractional shortening (FS) was derived. SR data were obtained from the MVI data sets by calculating the myocardial velocity gradient over a region of 0.7 mm after manual tracking of the region of interest, while S was extracted as the temporal integral of this SR curve. Maximal systolic velocity (Vmax), SR (SRmax) and S (Smax) were measured in the anterior, inferior and lateral wall. For the first two segments, radial motion and deformation characteristics were thus measured while for the latter segment these measurements represented circumferential motion/deformation. All measurements were made using dedicated software (SPEQLE 4.6.4). Differences between normal and LP-/- mice were tested using a student's t-test.

Results: See table

Conclusions: The measurement of both systolic radial and circumferential S and SR in mice were shown to be feasible. Both radial SRmax and Smax identified abnormal systolic function in a transgenic mice model of dilated cardiomyopathy. Moreover, both parameters were shown to be more sensitive than standard gray scale measurements. Thus, ultrasonic S and SR imaging can offer a new and potentially more sensitive approach for the non-invasive assessment of murine regional myocardial function.

		WT	MLP-/-	p-value
WT ED	Ant	1.00±0.18	0.94±0.13	NS
(mm)	Inf	0.92±0.14	0.93±0.20	NS
LVD ED	(mm)	2.48±0.36	3.48±0.68	<0.05
FS	(%)	58±7	39±18	<0.01
Vmax	Ant	-0.36±0.24	-0.18±0.14	0.065
(cm/s)	Inf	3.1±0.6	1.9±0.4	<0.001
	Lat	1.4±0.3	1.0±0.5	<0.05
SRmax	Ant	13.0±5.0	3.9±3.0	<0.001
(1/s)	Inf	22.6±3.7	12.0±4.6	<0.001
	Lat	-10.7±3.8	-10.6±8.8	NS
Smax	Ant	50±10	10±9	<0.001
(%)	Inf	46±17	33±9	<0.05
	Lat	-36±16	-22±9	<0.05

This work was supported by the Fund for Scientific Research – Flanders (FWO-Vlaanderen)

U2-E-2 510BD 10:45 a.m.

AUTOMATIC DETECTION AND TRACKING OF LEFT VENTRICULAR LANDMARKS

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Background: The mitral ring (MR) and the apex are important landmarks in apical echocardiograms. The MR motion relative to the apex can be used to assess ventricular function, and the landmarks can be used to assist automatic detection of the endocardium.

Aim: The aim of the study is to make a real-time method for automatic detection and tracking of the apex and two points defining the MR.

Method: The method is based on using tissue Doppler to track a set of candidate points in a cardiac cycle. In the first frame the points are positioned with adequate resolution covering the region of interest. In each consecutive frame we track each candidate point by integrating the tissue Doppler estimates. For each candidate point in each frame we temporarily store the estimated velocity, the distance from the probe, and the tissue intensity.

Each candidate point is given a score based on certain characteristics: 1) The MR has a fibrous structure and favorable 90 degree direction relative to the ultrasound beams, making the landmarks bright. 2) Points within tissue return to the same position after a heart cycle, while points within blood typically do not. 3) In the base of the ventricle, ie. close to the MR the tissue has higher maximum displacement than other parts of the septum and myocardium. In addition, we know that the two points defining the MR are placed approximately at the same depth, they have a lateral distance to each other within a given range, and they have a similar motion. We locate the two points, which maximize the combined score of these characteristics.

To locate the apex we use the following observations: 1) There is little movement close to the probe until we reach myocardium. 2) Pericardium in the apex often has a high intensity gradient. 3) There is a twisting and untwisting motion of the left ventricle which cause the scatterers at the apex to rotate in and out of the image plane resulting in time-varying gray-scale intensities. Each candidate point is scored according to these characteristics and the point with the maximum score is selected as the apex point.

Results: For validation we used apical 2-ch and 4-ch views from 22 patients (age 52-81) using a Vivid 7 scanner. The detected landmarks were compared to that of manually selected landmarks by four cardiologists. The detector failed in 4 cineloops (computer-to-observer distance (COD)$>$1.5cm) and these were excluded. COD and inter-observer distances (IOD) for the landmarks were 5.9$\pm$2.5mm and 4.9$\pm$1.8mm, respectively. COD and IOD for maximum MR displacement were 0.46$\pm$0.41mm and 0.32$\pm$0.23mm; and for systolic velocity the COD and IOD were 0.28$\pm$0.21cm/s and 0.24$\pm$0.16cm/s.

Conclusions: The results indicate that the automatic algorithm locates different landmark positions than the observers. However, errors in clinical measures such as MR displacement and velocity are within acceptable limits. This is probably because points within tissue close to the MR have similar motion.

U2-E-3 510BD 11:00 a.m.

A MODEL BASED APPROACH TO ESTIMATE CONTRACTILE FORCE DEVELOPMENT USING MYOCARDIAL VELOCITY IMAGING: A VALIDATION STUDY DURING ALTERATIONS IN CONTRACTILITY AND HEART RATE

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Ultrasound (US) deformation imaging is used to quantify regional myocardial function, i.e. force development. Forces within the myocardial wall may be described by a stress tensor that is the sum of passive/elastic (σ_p) and active(σ_a) stresses. Regional deformation represents the net effect of these forces acting on the segment under investigation. We developed a mechanical model based approach to calculate these stress components separately using myocardial velocity imaging(MVI). The timing and shape of the extracted σ_a profiles match those in isolated muscle experiments. **Study Aim**: To further validate this model based approach and see whether it could detect changes in active force development. Therefore, we compared peak active stress(σ_{amax}) with peak positive rate of pressure rise($dPdt_{max}$), a common clinical contractility index, during changes in heart rate(HR) and contractility. **Model**: MVI data were used to make a kinematic model of the left ventricle(LV) with an ellipsoid geometry. A short axis slice was reduced to a spring mass model of 400 nodes with 3 forces acting on each node: σ_a and σ_p, in the circumferential direction, and pressure force(PF) in the radial direction. The material parameters of the exponential stress/strain relation were estimated during diastole when it was assumed that σ_a=0. These parameters were used to calculate σ_p during systole and PF was calculated from LV cavity pressure. With PF and σ_p, the balance of forces was solved for σ_a. **Experimental Data**: In 9 closed chest pigs US data were recorded using a Toshiba PowerVision 6000 equipped with an RF interface for research purposes and a 5MHz phased array transducer. Mmode images(PRF=5kHz) were recorded in a short-axis view. Myocardial velocities were estimated offline using cross correlation techniques. Mean velocities were extracted by segmenting the posterior wall and septum on the Mmode image. End diastolic LV diameter and wall thickness were measured to establish the geometry. A micro-manometer tipped catheter was placed in the LV to measure pressure. Contractility was increased by incremental dobutamine infusion (DI = 5-20 μg/kg/min, n = 9). HR was varied by atrial pacing (AP = 120-180 bpm, n =9). Finally contractility was decreased by esmolol infusion (0.5$\pm$0.15 mg/kg/min) and data acquired during subsequent pacing (120-180 bpm) (EI group, n= 6). **Statistics**: Multiple comparisons were performed using ANOVA with a post hoc Fishers LSD test. All groups were pooled and a linear Pearson correlation was used to compare $dPdt_{max}$ and σ_{amax}. Statistical significance was inferred for $P<0.05$. **Results**: Table 1 shows that σ_{amax} increased significantly with each stage of DI. During AP σ_{amax} remained relatively constant while it decreased significantly with EI. σ_{amax} correlates with $dPdt_{max}$(r=0.79 $P<0.001$). **Conclusion**: σ_{amax} reflects changes in contractility while being relatively independent of heart rate.

Peak active stress compared with peak dPdt

Dobutamine			Atrial Pacing
Stage	σ_{amax} (kPa)	$dPdt_{max}$ (mmHg/s)	Stage
Baseline	20.5±1.3	1460±283	Baseline
5 μg/kg/min	21.8±1.8	1957±283	120 bpm
10μg/kg/min	26.7±2.3 42	2698±286 42	140 bpm
15μg/kg/min	32.1±1.9†	3440±339†	160 bpm
20μg/kg/min	38.6±2.5 135	4336±389 135	180 bpm

		Esmolol		
σ_{amax} (kPa)	$dPdt_{max}$ (mmHg/s)	Stage	σ_{amax} (kPa)	$dPdt_{max}$ (mmHg/s)
21 ±1.1	1338±201	Baseline	22.6±1.7	1351±174
		Infusion	17.6±2.1 42	753±125 42
22.3±2.1	1527±2207	120 bpm	18.6±3.6 42	926±105 42
23.8±2.5	1554±220	140 bpm	19.4±2 42	938±78 42
22.9±1.1	1579±197	160 bpm	19.2±1.8 42	1012±152 42
21.2±1.25	1578±151	180 bpm	18±2.9 42	949±118 42

Results are reported as mean ± standard deviation. 42 P<0.001 vs baseline.
† P<0.001 vs 10μg/kg/min, 135 P<0.001 vs15μg/kg/min

This work was supported by the Fund for Scientific Research - Flanders (FWO - Vlaanderen)

U2-E-4 510BD 11:15 a.m.

VISCOELASTICITY MEASUREMENT OF HEART WALL IN IN VIVO

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Background: Though the viscoelasticity of the heart wall is important in the diagnosis of the myocardium, it has not yet noninvasively measured in *in vivo*. Based on new finding that a steep pulsive wave propagates along the interventricular septum (IVS) at isovolumetric relaxation timing just after the timing (T_0) of the aortic valve (Ao) closure (Kanai et al. Ultrasound Med Biol 27, 2001), we propose a new method to measure the viscoelasticity of the heart wall in this paper. **Method:** To simultaneously measure the rapid velocity signals at multiple points along the IVS (Kanai et al. IEEE Trans UFFC 43, 1996), a conventional ultrasonic diagnosis equipment was modified to allow 15 scan lines from a sector scanner to be arbitrarily selected in real time and the myocardial velocity signals are measured almost simultaneously at about 150 points set from the base to the apex along the IVS. The delay time of the pulsive wave from the root of the Ao to the apex is very small of several milliseconds, which cannot be measured by conventional equipments. By applying the short-time Fourier transform to each signal around T_0, therefore, the phase

value of the measured pulsive wave is detected for each frequency until 100 Hz. By showing the instantaneous phase values on the B-mode image, the situation of the propagation of the pulsive wave is displayed like a movie. The propagation direction is identified and then the propagation speed of the pulsive wave along the IVS is determined for each frequency component. By comparing the dispersion characteristics of the resultant speed with the theoretical equation of the propagation speed of the Lamb wave with the complex elasticity coefficients, the viscoelasticity of the IVS is noninvasively determined, where the Voigt model is employed. **In vivo experimental results:** For each of 3 healthy subjects, the propagation situation of the wavefront of the pulsive waves was clearly obtained. It propagates from the root of the Ao to the apex along the IVS. For 40 Hz component, the propagation speed rapidly decreased from 5.6 m/s just after the Ao closure timing ($t=T_0$) to 2.7 m/s at $t=T_0+16$ ms. For 90 Hz component, the propagation speed decreased from 7.0 m/s at $t=T_0$ to 4.7 m/s at $t=T_0+16$ ms. The viscosity values decreased rapidly from about 2.1 kPa·s just after the Ao closure timing ($t=T_0$) to 0.1 kPs·s at $t=T_0+16$ ms. These phenomena will correspond to the rapidly decrease in the inner pressure at the beginning of the isovolumetric relaxation period. Similar values were obtained for other two healthy subjects. **Conclusions:** We found that at the beginning of the isovolumetric relaxation period, the pulsive wave is generated due to the closure of the Ao valve and it propagates along the IVS as the Lamb wave. By definitely detecting its propagation speed, we noninvasively determined the viscoelasticity characteristics of the IVS. This method offers potential for *in vivo* imaging of the tissue characterization, which cannot be recognized by conventional echocardiography, tissue Doppler imaging (TDI), CT, or MRI.

U2-E-5 510BD 11:30 a.m.

A NEW METHOD FOR TWO-DIMENSIONAL MYOCARDIAL STRAIN ESTIMATION BY ULTRASOUND: AN IN-VIVO COMPARISON WITH SONOMICROMETRY

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Introduction: One-dimensional ultrasonic (US) strain (S) and strain rate imaging have been shown to be angle dependent. In order to overcome this problem, fully resolved two-dimensional (2D) strain estimates are required. Hereto, a new methodology for the estimation of 2D strain has been developed in our lab. It was developed based on earlier in-silico and in-vitro experiments.

The aim of this study was to develop and validate this new methodology in the in-vivo setting.

Methods: 2D velocities were estimated using 2D RF tracking with a 1D kernel. At the first frame of the heart cycle, 35 equidistant lines were defined across the cardiac wall perpendicular to the epicardium in a region of interest. Subsequently, 35 equidistant points were positioned along each of these lines. For each frame the position of each point was then updated based on the estimated velocity vector. The average radial S through the wall was then calculated as the change of length of a line with respect to its initial length. Similarly, the perpendicular S component could be calculated from the change in distance between lines. Velocities were regularised assuming a linear velocity gradient through the wall. Therefore, for each frame, a linear fit through both velocity components along a track line was performed. Each point on a line was then displaced according to its regularised velocity estimates. In this way the points along a line were kept equidistant throughout the cycle, while allowing the lines to follow the wall and lengthen/shorten as the wall thickens/thins. At the end of the cycle all points were forced to return to their initial position by assuming a linear drift over the heart cycle. The method was validated in 5 open chest sheep where US RF data were acquired in a parasternal long axis view using a Toshiba PowerVision 6000 with an RF interface. Myocardial radial (R) and longitudinal (L) S were simultaneously estimated in the inferolateral wall using the new methodology. Four segment-length sonomicrometry crystals (SM) were placed in a tetrahedral configuration just lateral to the imaging plane giving a continuous reference for the L and R S. After baseline acquisitions, the deformation was modulated by 1) esmolol infusion, 2) dobutamine infusion and 3) inducing ischemia by occlusion of a distal branch of the circumflex coronary artery. Peak systolic S values (S_{max}) were compared by means of linear regression and the correlation coefficient.

Results: For both S_{max} components strong correlations were found between the US and the SM measurements. For the R estimates the correlation coefficient was found to be $r = 0.98$ with $S_{us} = 1.13S_{sm} + 0.0038$. For the L component the correlation coefficient was $r = 0.95$ with $S_{us} = 1.07S_{sm} + 0.0028$.

Conclusion: Simultaneous estimation of 2D myocardial S using US RF tracking showed to be a robust method in an in-vivo setting. Myocardial S could thus be assessed in-plane, independent of insonation angle.

U2-E-6 510BD 11:45 a.m.

A NEW MULTIFREQUENCY TRANSDUCER FOR MICROEMBOLI DETECTION AND CLASSIFICATION

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Introduction: The classification of circulating microemboli as gaseous or particulate matter is essential to establish the relevance of the detected embolic signals and the appropriate treatment. The Transcranial Doppler technology has not fully succeeded yet to characterize unambiguously the composition of microemboli. Recently, the authors have proposed a new approach to detect and classify gaseous emboli. The method is based on their nonlinear acoustic properties. It has been established that for specific ultrasonic exposure conditions, a gaseous embolus vibrates nonlinearly, leading to the generation of harmonic and/or subharmonic components in the frequency spectrum of the backscattered embolic signal. The implementation of this approach requires the use of a dedicated transducer with the ability of transmitting the adequate frequencies and receiving simultaneously the high frequency scattered nonlinear components. Method: The microemboli transducer is a multifrequency transducer. It is composed of two independent transmitting elements and a separate receiving part. The transmitting elements, made of piezocomposite material, consist of a central piston element with a 20 mm diameter operating at a center frequency of 360 kHz and an outer ring element, of 3.7 mm width, transmitting at 130 kHz. The transducer has a total aperture of 30 mm. The receiving element consists of a PVDF layer 110 μm thick located on the top of the transmit elements. Acoustic beam widths at -6 dB at the region of interest as measured with a hydrophone were 14 mm and 35 mm for the inner and outer elements respectively. The generated maximal acoustic pressure ranged from 145 kPa up to 370 kPa, sufficient to induce nonlinear behavior of gas emboli. The capabilities of this new transducer to detect and classify emboli have been tested in vitro. Gas emboli with diameter between 10 μm up to 120 μm were used and ultrasound bursts of 10 cycles at 360 kHz and 7 cycles at 130 kHz were transmitted. Results: Hydrophone measurements showed that the transmit elements cover a frequency band from 100 kHz to 600 kHz at 6dB. The reception of the scattered microemboli signals as accomplished with the PVDF layer, showed to be sensitive over a frequency band ranging from 50 kHz up to 2 MHz. The transducer was tested in an in vitro setup using gaseous emboli. It was found that a specific range of gaseous embolus size was detected depending on the transmitting element. Using the 130 kHz outer element in transmission, microemboli between 35 μm and 105 μm could be classified as gas emboli through their 2nd harmonic or subharmonic while gaseous microemboli between 10 μm and 40 μm were accurately descriminated using the 360 kHz inner element using their scattered 2nd harmonic component. Conclusions: The in vitro results demonstrate that the multifrequency transducer is capable to detect and classify a wide range of gas microemboli (from 10μm to 105μm). In conclusion, nonlinear properties of microemboli combined to a new transducer generation offer a real opportunity to detect and classify microemboli.

Session: U3-E

ULTRASOUND MEMS TECHNOLOGY
Chair: F. Levent Degertekin
Georgia Institute of Technology

U3-E-1 511AB 10:30 a.m.

MICROFABRICATED ULTRASONIC TRANSDUCERS MONOLITHICALLY INTEGRATED WITH HIGH VOLTAGE ELECTRONICS

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Capacitive microfabricated ultrasonic transducers (cMUTs) recently have been demonstrated to be capable of producing clinical quality images. Much has been written about the potential of integrating cMUTs with control electronics, and some early work has been published. To date, there has not been published work demonstrating the monolithic integration of cMUTs with control electronics with the necessary characteristics to allow for clinical quality medical imaging.

In this paper, we present the first results of fabricating cMUTs monolithically integrated with high voltage switching electronics. The switching electronics process used has the same voltage limitations as that of commercially used multi-plexing chips (i.e. 200 Vp-p). Water-tank results demonstrate that a cMUT monolithically integrated with controlling high voltage switch operates as anticipated when the capacitance and resistance of the switch is properly inserted into the cMUT model. cMUT elements of conventional probe geometries for linear probes show a 3-dB insertion loss due to the inclusion of the switch. Water-tank results further demonstrate no measurable effect of the switch on the radiation pattern of the acoustic elements. Results of experiments with a low-voltage-controlled high-voltage switch array verify the viability of aperture control and channel mapping multiplexing with monolithically integrated electronics.

We conclude with early results of a 1.25D (i.e. an elevation aperture controlled) array. At the time of abstract submission, images have not yet been generated, but water-tank tests of cross-talk below 30 dB and acceptance angle commensurate with element size demonstrate the viability of the array for clinical imaging.

U3-E-2 511AB 10:45 a.m.

A NOVEL METHOD FOR FABRICATING CAPACITIVE MICROMACHINED ULTRASONIC TRANSDUCERS WITH ULTRA-THIN MEMBRANES

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Production of ultra-thin membranes facilitates the development of miniature Capacitive Micromachined Ultrasonic Transducers (CMUTs). Potential medical imaging applications of such transducers include 3D ultrasound imaging, intravascular imaging and intracardiac echocardiography. In this paper, we introduce a novel method, in which several emerging technologies are combined, for the fabrication of a new generation of CMUTs with ultra-thin membranes. The process involves a combination of Atomic Layer Deposition (ALD) and micro-fabrication techniques. First, we define a 25 nm tungsten layer and a 100 nm Al_2 O_3 layer on a polished silicon wafer, the upper wafer, using ALD. ALD is a self-limiting binary reaction process with superior characteristics than surface micromaching, including angstrom-level control of deposition thickness, potential to use a large variety of materials, and excellent surface quality for deposited layers. The Al_2 O_3 layer forms the membrane and the tungsten layer forms the upper electrode for these capacitive transducers. Subsequently, a 0.5 μm gold layer is deposited on the Al_2 O_3 layer by vapor deposition and then patterned to create circular cavities, each with a diameter of 20 μm. Then the upper silicon wafer is bonded with another silicon wafer, the bottom wafer, which has a uniform 0.5 μm gold layer on the front surface and a SiO_2 layer on other surfaces, by gold diffusion bonding technology at a temperature of 100 C. Finally the upper silicon wafer is removed by KOH wet etching and the transducer is wired for experimental operation and characterization. CMUTs fabricated by this method were characterized by a first-order electro-mechanical model and equivalent circuit analysis. Simulation results show that this new fabrication method provides another avenue for optimizing CMUT performance, especially in power savings, sensitivity and potentially increased reliability. An optical interferometric system is used to investigate experimentally the thermo-mechanical behavior of the membrane. Lastly, finite element models are currently being developed to further refine the mechanical modeling. Initial results comparing theoretical and experimental results will be presented.

This work was supported in part by grants from NSF (EECS 0225405) and NIH (HL 072738). L.L. would also like to acknowledge the help of M. K. Tripp from the MEMS group, University of Colorado.

U3-E-3 511AB 11:00 a.m.

CMUTS WITH DUAL ELECTRODE STRUCTURE FOR IMPROVED TRANSMIT AND RECEIVE PERFORMANCE

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In this paper we report the use of a dual electrode structure to improve the performance of capacitive micromachined ultrasonic transducers (cMUTs). In the dual electrode structure, separate transmit and receive electrodes are embedded either in the same cMUT membrane or in the dielectric substrate. This configuration has two primary advantages. First, the maximum pressure amplitude during transmit mode can be significantly increased. By locating the transmit electrodes near the edges of the membrane, leveraged bending increases the maximum displacement without collapsing the membrane. As shown experimentally by Hung et al, with an optimized electrode structure, a rectangular membrane can be actuated by 90% of the gap without collapse [1]. This corresponds to nearly 9dB improvement in the transmitted pressure using the same cMUT membrane at a cost of a higher DC bias. We have fabricated a 0.3mm by 0.65mm rectangular cMUT element consisting of 20μm wide and 100μm long and 0.8μm thick rectangular silicon nitride membranes. The transmit electrodes were 4μm wide and located 2μm from the edges, whereas the 4μm wide receive electrodes were at the center. With this non-optimized structure, we measured a 2.5dB increase in maximum output pressure at 5MHz with edge electrode excitation with only a 7% increase in the collapse voltage as compared to traditional center electrode actuation. The second advantage of a dual electrode structure is the reduction of dead zone during pulse echo operation. Since the DC bias of the electrodes can be controlled independently, the receive electrode can be biased to near collapse immediately after transmission for optimized receive operation. Our measurements also show that the parasitic capacitance introduced by the transmit electrode is negligible, hence should not introduce any degradation in the receive performance. In addition to experimental results, we will discuss the design optimization of cMUTs with dual electrodes. [1] E.S. Hung and S.D. Senturia, Extending the travel range of analog-tuned electrdostatic actuators, IEEE JMEMS, 8, pp. 497-505, 1999.

We would like to thank the Whitaker Foundation for supporting this research.

U3-E-4 B8 11:15 a.m.

OPTIMIZED MEMBRANE CONFIGURATION IMPROVES CMUT PERFORMANCE

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An improvement in CMUT performance was achieved by membrane configuration optimization. CMUTs with three different membrane configurations: square, rectangular and tent, were designed and fabricated using a newly developed process based on the wafer-bonding technique. Paired tests showed that improved transmission (TX) and reception (RX) performance could be achieved by using tent or rectangular membranes instead of conventional square membranes in the CMUT.

A CMUT with a fixed element size and a certain operation frequency, can have its performance improved by an optimized membrane design. The improvement originates from three factors: 1) an increased average membrane displacement for a given pressure loading, 2) an increased average membrane deflection relative to the maximum membrane deflection, 3) an increased fill factor.

Since the performance difference between CMUTs with square and hexagon shaped membranes was relative small, a squareCMUT with 88 μm by 88 μm membranes was selected to represent the conventional design. A rectCMUT with 72 μm by 540 μm rectangular membranes and a tentCMUT with 540 μm by 540 μm tent membranes anchored with 15 μm square support posts (70 μm pitch) were designed for comparison. The designs were such that all CMUTs worked in the same frequency region. All membranes were made from 1 μm thick single crystal silicon while the support walls in the squareCMUT and rectCMUTs were 5 μm wide. The fill factor of the square-, rect- and tentCMUTs were 89%, 94% and 95%, respectively. A FEM simulation predicted that, at 20 VDC, the pre-collapsed average membrane displacement relative to the maximum membrane displacement for the three designs would be 30%, 46% and 52%, respectively.

The ultrasonic characteristics of the CMUTs were obtained by broadband pitch-catch and pulse-echo tests. The experimental TX and RX results were normalized, to ensure a fair comparison, by the electric field intensity. In both TX and RX, the rectCMUTs and tentCMUTs showed a higher output pressure and sensitivity through the entire bias range than the squareCMUTs. The performance improvement gained by the new designs varied with bias. As an example: in TX, at 20 VDC, the output pressure per input voltage of the rectCMUTs and tentCMUTs were 46% and 44% higher than that of the squareCMUT, respectively. The measured max transmission efficiency was 22 kPa/VAC at 90 VDC with the tentCMUT. In RX, at 20 VDC, the sensitivity of the rectCMUT and tentCMUT were 43% and 65% higher than that of the squareCMUT, respectively. The TX and RX spectra of the designs were slightly different in shape, but had a similar uncorrected fractional bandwidth ($\sim$125%).

Since the optimized devices had fewer sub-cells with independent cavities than the conventional design, the optimized CMUT yields were potentially more sensitive to fabrication defects than that of the conventional devices. A newly developed process based on the wafer-bonding technique improved their yields over that of conventional surface micromachining. No difference in yield was observed between the three designs.

U3-E-5 511AB 11:30 a.m.

PZT-DRIVEN, MICROMACHINED, TWO-DIMENSIONAL MEMBRANE ARRAYS

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Ultrasonic actuation is an attractive solution for high-density microfluidic systems with low volume pumping requirements in possibly different directions and at different locations on the chip. In order to realize the actuator part for such a function, a two-dimensional array approach seems most relevant. To pursue this approach, we made an array of 20x20 active pixels with 250μ pitch from a 0.5mm thick slab of piezoelectric ceramic (PZT) by dicing. The fluidics part of the device, which is to be fabricated on a separate wafer and to be bonded over the ground electrode on top of PZT, is mainly an array of silicon nitride membranes. Pumping can be obtained, by phase driving the individual pixels located inside a specific channel. Backside DRIE is used to make these structures and to leave silicon islands of about the same cross sectional area as the PZT pixel. These serve as pillars, which engage the motion of the array to the membrane.

2-D Transducers arrays of similar dimensions and fabrication method are used for ultrasound imaging. [1] Rather differently from previous efforts, flip chip bonding is used to bond bottom die and the array after electroplating eutectic solder bumps on metal pads of the bottom die. [2] In addition, alignment marks are laser drilled on the PZT plate, before dicing. This makes the manual alignment of both the top and the bottom dies possible. Currently, the bottom die has only patterned aluminum over nitride serving for routing and bonding pads. If the pixel dimension can be made small enough to render a CMOS chip that is as large as the PZT array feasible, then three dies, namely CMOS, PZT array and the top die can be stacked together. Such a technology enables compact packaging of complex fluidic systems with control electronics. On the other hand, since standard IC foundries would not normally deposit or coat any special thick film on bumped CMOS dies, characterization of solder as a backing material is crucial. We are aiming to present these characterization results in addition to the results of standard array performance tests like impulse response, uniformity, and cross coupling.

References [1] Fiering, J.O.; Hultman, P.; Lee, W.; Light, E.D.; Smith, S.W.; High-density flexible interconnect for two-dimensional ultrasound arrays Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on, Vol. 47, Issue: 3, May 2000, pp:764 -70

[2] Edward K. Yung and Iwona Turlik, "Electroplated Solder Joints for Flip-Chip Applications", IEEE Trans on Comp. Hybrid. & Man. Tech., IEEE Transactions on, Vol.14 No 3, September 1991, pp: 549-59

This work was supported by DARPA-MTO under the BioFlip program, contract #F30602-00-2-0572.

U3-E-6 511AB 11:45 a.m.

MICROMACHINED PIEZOELECTRIC HETEROSTRUCTURE USING EPITAXIAL $PB(MG_{1/3}NB_{2/3})O_3$-$PBTIO_3$ FILM ON SI FOR ULTRASOUND TRANSDUCERS

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Ultrasound transducers have been widely used in medical imaging. Especially, micromachined ultrasound transducers, where micromachined membranes are driven by either capacitive or piezoelectric actuation, are intensively investigated for phased arrays in high frequency acoustic imaging. In piezoelectric micromachined ultrasound transducer (pMUT) structures, piezoelectric thin films such as $Pb(Zr_xTi_{1-x})$ (PZT) are coated on substrates. However, due to the difficulty in the growth of high quality epitaxial thin films, pMUT has been fabricated using polycrystalline PZT. In a previous work polycrystalline PZT was deposited using a sol-gel method on $Pt/SiO_2/Si$ membrane substrates and obtained longitudinal piezoelectric coefficient d_{33} of 62 pm/V and its corresponding transverse piezoelectric coefficient e_{31} of 11 C/m^2. These properties of polycrystalline PZT runs far short of its single crystal counterpart. Besides, new piezoelectric materials such as $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (PMN-PT) are reported to have much higher piezoelectric properties. In this work, we successfully deposited high quality epitaxial thin films of PMN-PT on both silicon and SrTiO3 substrates up to the thickness of 4 μm. The d_{33} and e_{31} values were determined to be over 1200 pm/V and 29 C/m^2, which are the highest values among piezoelectric thin films ever realized. Based upon high quality epitaxial growth technique, we will propose piezoelectric membrane structures on top of $SrTiO_3$/SOI and discuss results on the evolution of 3-dimensional (in-plane and out-of-plane lattice parameters) strain state in the piezoelectric thin film after making membrane structure and effects of membrane geometries on piezoelectric properties and frequency responses.

Session: U4-E

PHYSICAL ACOUSTICS I
Chair: S. Zeroug
Schlumberger-Doll Research

U4-E-1 513AB 10:30 a.m.

COMBINED RADIATION PRESSURE FIELD IN A DUAL-FREQUENCY ULTRASOUND SYSTEM

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The radiation force incident on an object in an ultrasound field is often utilized to create local displacements used for making elastographic measurements. This force is proportional to the target properties like absorption and reflection as well as the squared pressure of the ultrasound field. In particular, in a dual-frequency radiation force set-up, the objective is to create a pressure field which beats in time in order to produce a cyclical radiation force which could be used to make dynamic measurements of target mechanical properties. This study looks at the combined pressure field from two ultrasound transducers in a dual-frequency system to determine the radiation pressure field pattern which would be incident on an object in the focal plane. The pressure fields from a concentric element transducer as well as two separate elements with intersecting foci are analyzed. First, the combined pressure field is calculated using a computer simulation of the summed linear fields. Then, the simulation is shown to be in close agreement with experimental measurements of the pressure fields. Finally, the simulation is expanded to compute the radiation pressure for various target sizes and transducer geometries. We present the first direct experimental measurements of the cyclical radiation force from a dual-frequency system. With a 1mm diameter target, we record a magnitude on the order of 1.4 μN which oscillate at frequencies less than 1 Hz using a dual frequency concentric ring transducer (8 cm radius of curvature, 10 cm diameter) driven at 20 W electrical per element at a frequency of 1.7 MHz + Γf. Then, the we demonstrate that the summed linear pressure field with its grading lobe pattern results in a radiation pressure field which varies greatly depending on the geometry of the transducers and the target size. For example, there is a decrease in radiation pressure as target size increases of up to 97% for target diameters ranging from $1/4\lambda$; to 20λ. In some cases, the resulting radiation force on the target may not cause a cyclical displacement in time that is measurable as has been previously assumed in the literature. Knowledge of the combined pressure field will allow for optimization of the dual-frequency set-up so that the pressure field variation in time is conducive for radiation force experiments.

U4-E-2 513AB 10:45 a.m.

PERFECTLY MATCHED LAYER FOR FDTD COMPUTATIONS IN PIEZOELECTIC CRYSTALS

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The Finite-Difference Time-Domain (FDTD) method has become a very powerful tool for the analysis of propagating electromagnetic waves. It involves the discretization of Maxwells equations in both time and space and leads to a numerical solution of the wave propagation problem in the time domain. The techniques main benefits are that it permits the description of wave propagation in non-uniform media, it can easily accommodate a wide range of boundary conditions, and it can be used to model non-linear effects as well as the wave behaviour near localized structures or material defects. In [1], the FDTD method was presented and applied to mechanical wave propagation in piezoelectric crystals. To our knowledge, this was the first time that the FDTD method was applied to wave propagation in a general anisotropic medium. However, its use was shown to be limited because the large reflection artefacts generated by the computational boundaries interfered with the desired wave propagation. In this paper, we present an implementation of a finite-thickness Perfectly Matched Layer (PML) that reduces the acoustic wave reflection artefacts to less than 0.5% in piezoelectric crystals. In the PML, spatial derivatives in directions tangential and normal to the boundary are treated separately and the underlying differential equations are modified to induce attenuation in the normal direction. The result is a layer that presents a matched boundary to the computational region and permits its modelling as if it were infinite in extent.

1. P. M. Smith and W. Ren, Finite-difference time-domain techniques for SAW device analysis, *2002 IEEE Ultrasonics Symposium Proceedings*, Munich, Germany, pp. 313-316, 8-11 October 2002.

This work was supported in part by grants from the Natural Sciences and Engineering Research Council of Canada.

U4-E-3 513AB 11:00 a.m.

NUMERICAL AND EXPERIMENTAL STUDY OF THE RESONANT BEHAVIOR OF N ELASTIC SHELLS EMBEDDED IN WATER

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Resonances of a single thin hollow cylindrical aluminum shell embedded in water are well known. At low frequencies, they are due to external circumferential A-waves (also called Scholte-Stoneley waves), which can easily couple close enough identical shells. Such a coupling has already been shown [Lethuillier et al., Ultrasonics 41, 655-662, 2003] in the so-called "eclipse configuration", that will

be the reference configuration for us. The eclipse configuration corresponds to aligned shells, a plane wave incident in the direction of the shells alignment, and an observation direction corresponding to backscattering. In this configuration, all A-wave resonances of a single shell are split into N resonances, with N the number of shells. This has been explained by the presence of N-1 local waves (i.e. waves with propagation paths including less than N shells), and of one global wave, with a propagation path including all shells. Here, we present an extension of these results to geometries that break at least one symmetry. This can be done by changing either the incidence direction or the disposition of the shells, as observation is still done in the backscattering direction. When the incidence direction is no more parallel to a symmetry axis of the system, each resonance observed in the reference configuration splits into two new ones for specific incidence angles. The amplitude of each new resonance depends on the incidence angle. The other dispositions of shells we have studied are the equilateral triangle, the square and the regular pentagon. In all cases the presence of almost all resonances may be explained in a similar way to the eclipse case. Whatever the disposition of the shells, there is a critical distance dc between the shells, over which no coupling may be observed. As the distance d between the shells is decreased from dc, each resonance of a single shell splits into M ones. M-1 are due to local waves and one to a global wave. The frequency positions of the resonances related to local waves decrease with d, while those related to the global wave increase. However, all M resonances remain close to the original single shell resonance. In addition to those M resonances, there may be another one, which cannot be explained, neither in terms of global waves, nor in terms of local ones. Its frequency position increases hyperbolically as d decreases. If all shells are replaced by rigid cylinders, the M resonances disappear while the last one remains. Nevertheless, its frequency position, at a given distance d, depends on the thickness of the elastic shells, just as well as the frequency positions of the M other resonances. A discussion of the possible physical mechanisms giving rise to the last resonance is done.

U4-E-4 513AB 11:15 a.m.

ELASTIC WAVES IN DEVIATED BOREHOLES IN FORMATIONS WITH TRIAXIAL STRESSES

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A new three-dimensional finite-difference formulation of equations of motion for elastic waves in prestressed formations has been used to calculate synthetic waveforms at an array of receivers in a liquid-filled borehole. These equations describe the influence of borehole hydrostatic pressure as well as triaxial formation stresses on elastic waves produced by either a monopole or dipole transmitter placed on the borehole axis. The synthetic waveforms are processed by a slowness-time coherence (STC) and modified matrix pencil algorithms for isolating both non-dispersive and dispersive arrivals in the wavetrain. Computational results for the formation compressional, fast-shear, and slow-shear slownesses

obtained from synthetic waveforms in a wellbore with deviations of 0, 30, and 60 degrees from the vertical are consistent with the rotated stresses referred to the hole measurement axes. Compressional slowness changes are primarily affected by changes in the stress along the propagation direction. In contrast, shear slowness changes are equally affected by stress changes either in the propagation or radial polarization direction. We note that a decrease in the axial stress is largely compensated by an increase in the circumferential stress (parallel to the slow-shear polarization) with increasing well deviations. Consequently, the slow-dipole dispersion at low-frequencies is largely unaffected with increasing well deviations. We have also demonstrated that a decrease in shear slowness caused by a uniaxial stress applied parallel to the propagation direction is the same as that applied parallel to the radial polarization direction. This is in agreement with analytical results.

U4-E-5 513AB 11:30 a.m.

INFLUENCE OF PERIODICAL STIFFENERS ON THE ACOUSTIC RESPONSE OF A FINITE CYLINDRICAL SHELL

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Previous studies on the acoustic scattering from air-filled finite cylindrical shells immersed in water have been carried out. They have shown the influence of circumferential and guided waves at variable incidence. The resonance modes depend on the dimensions of the finite shell (length, thickness, radius). More recently, experiments have investigated the influence of ribs on the scattering processes and these results have been supported by a theoretical calculation.

The present paper highlights the influence of periodical radial stiffeners on the acoustic response of a cylindrical shell. This one, made of stainless steel, is characterized by its length L = 75cm, outer radius a = 5cm, and radius ratio b/a = 0.98. The ribs, made of the same material, present a length lr = 1mm, a thickness hr = 5mm, and a spacing d = 1.5cm. The cylinder end sections are closed by disks.

Experiments are carried out in monostatic configuration at variable incidence. Thus, the shell describes a rotation respect to the normal of its axis and signals are acquired at each position. Thanks to the dimensions of the tank, the choice of emission frequencies is not too restricted (50 kHz - 200 kHz). Experimental results display a certain number of features associated with helical, Bragg and Bloch-Floquet waves scattering. The results, discussed in time and frequency domains, are compared to experimental results acquired for a shell presenting a similar ribbed structure (b/a = 0.97, lr = 1.5mm, hr = 1cm, d = 1cm), and to theoretical results.

U4-E-6 513AB 11:45 a.m.

PROPAGATION OF NONLINEAR ACOUSTIC SIGNALS THROUGH INHOMOGENEOUS MOVING MEDIA

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Nonlinear propagation of intense acoustic waves through inhomogeneous medium is an important problem for many modern applications including sonic booms in a turbulent atmosphere, explosive waves in a fluctuating ocean, and intense ultrasound and shock waves in biological tissue. Two different types of inhomogeneities are of importance: scalar inhomogeneities (spatial distribution of sound speed and density), for example, due to temperature variations in the medium or variations in tissue type; and vector inhomogeneities (spatial distribution of mean velocity), for example, due to the presence of vortices or flow in the medium. In all of these problems the combined effects of inhomogeneities, diffraction, and nonlinear propagation determine the peak and average characteristics of the acoustic field. A complete theoretical model that includes all the above mentioned phenomena is very complicated for analysis, thus most results to date have been obtained for the simplified models. Approximations include nonlinear geometrical acoustics models, linear propagation of harmonic waves, and consideration of only scalar types of inhomogeneities. The problems of propagation of broadband nonlinear signals in inhomogeneous, especially moving, media are not yet studied in details. In this work, a new nonlinear parabolic wave equation with inclusion of both scalar and vortex inhomogeneities is presented. Numerical solutions of the equation for an axisymmetric and fully three dimensional formulation, arbitrary initial periodic or single shock waveforms are described. Typical problems of linear and nonlinear propagation of acoustic signals in media with thermal or vortex inhomogeneities are investigated in order to better understand how the combined effects of inhomogeneities, diffraction, and nonlinear propagation determine the overall peak and average parameters of the acoustic field and to distinguish the impact of scalar- and vector-type inhomogeneities on the wave propagation. It is shown, that, for example, the presence of thermal inhomogeneities induced by high intensity focused ultrasound in tissue do not significantly effect the spatial characteristics of the acoustic field under conditions, typical for ultrasound surgery. It is also shown that theoretical predictions of the acoustic field in the medium with vector-type of inhomogeneities can be quite different, if the inhomogeneities are treated as the scalar ones, i.e. only the component of the flow velocity along the propagation distance is taken into account, or both transverse and longitudinal components are considered.

Work was supported by ONRIFO, NATO, NIH Fogarty, and CRDF grants

Session: U5-E

NDE AND IN-PROCESS MONITORING

Chair: D. Yuhas
Industrial Measurement Systems Inc.

U5-E-1 512C-H 10:30 a.m.

OBSERVATION AND CONTROL OF SOLIDIFICATION PROCESSES BY ULTRASONIC PULSE-ECHO TECHNIQUE

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For solidification of metals and semiconductors the solidification velocity and the thermal gradient at the interface are the most relevant parameters. They are crucial for the formation of well-defined microstructures. During the last years we have developped an ultrasonic pulse-echo technique to observe and control the solidification velocity in various applications. This paper shows the principle set-up of the technology and gives an overview of the solidification processes that it can be used for. In all the processes used the solidification takes place in a unidirectional thermal gradient so that there exists a cold end of the sample that remains solid and to which the ultrasonic transducer can be attached. This ultrasonic transducer is used as generator and receiver of a guided wave which is reflected by the solid-liquid interface. During the directional solidification of the sample the time-of-flight of the signal increases in accordance to the increasing distance the wave has to propagate while the solid part of the sample grows longer. The time-of-flight differences are evaluated phase-selectively and allow for a resolution of the relative position of the solidification front of 1/500 of the sample diameter. This technique was used for several solidification processes and materials. Divers kinds of experiments were performed in a Bridgman-Stockbarger furnace. This gradient furnace consists of a cooling device at the bottom, a heating zone at the top and an isolating baffle zone in between. The liquid metal cooling allows for keeping the ultrasonic transducer at the lower end of the sample at a constant temperature of about 30 °C while further up melting and solidification take place. With this furnace we accomplished unidirectional solidification experiments with different alloys. These experiments showed that a constant furnace velocity does not automatically imply a constant solidification rate. As the real solidification velocity is crucial for the materials' properties we therefore developped an online process control that allowed us to influence the solidification velocity in-situ, either by controlling the furnace velocity or by adjusting the furnace temperature. Furthermore the technique was used in a float-zone device used for single crystal growth of doped Silicon. In a float-zone process a part of the sample is molten by radiation. Underneath and above this zone the sample remains solid. For well-defined resolidification of the sample the float-zone is moved upwards. In this process the transient growth and the relation between solidification velocity and the striations patterns caused by

doping are of high relevance for the quality of the grown crystal. The ultrasound technology allows for identifying such correlations. The variety of solidification processes to which we adapted the ultrasonic pulse-echo method demonstrates the feasibility and benefit of this technique for various industrial processes, especially for directional solidification of metallic alloys and float-zone growth of single crystals.

U5-E-2 512C-H 10:45 a.m.

ULTRASONIC IN-SITU MONITORING OF SOLIDIFICATION AND MELTING BEHAVIORS OF AN ALUMINUM ALLOY

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In both research and production involving solidification of materials, it would be beneficial to realize an in-situ, real-time characterization of the material behaviors during solidification process. This paper presents a newly developed high temperature ultrasonic sensor and its application to in-situ observation of aluminum alloy during solidification and melting in temperature up to 1073 K. The ultrasonic sensor mainly consists of a conventional piezoelectric transducer and a titanium buffer rod as an acoustic waveguide. The length is 300 mm. The side surface of the titanium buffer rod is coated with a thermal sprayed titanium layer in order to improve the wave guidance ability in molten aluminum. This sensor, owing to the unique characteristics of titanium, is highly expected to provide not only high acoustic coupling to molten aluminum but also high corrosion resistance. Aluminum alloy used here is eutectic alloy (Al-12.6%Si) that is widely used for die-casting in industries. The possible chemical reaction at the outer wall of the titanium rod has been evaluated for long time immersion up to 16 hours in the molten aluminum alloy. It is demonstrated that the titanium buffer rod has superior sustainability and wettability to the molten aluminum alloy. Using the ultrasonic sensor, pulse echo measurements have been performed with the aluminum alloy in temperature range from 473 K to 1073 K. A steel reflector is assembled at the probing end of the sensor to make time-of-flight measurements. The changes of the longitudinal velocity in the aluminum alloy during solidification and melting have been successfully monitored as a function of temperature. The longitudinal velocity shows a rapid and a significant jump from about 3900 m/s to 5600 m/s around the eutectic point 850 K at which the solidification occurs. In addition, the behavior of the amplitude of reflected echoes around the eutectic point is discussed in relation to solidification phenomena. Furthermore, an attempt to monitor the solid-liquid interface during directional solidification and melting of the aluminum alloy has been made by controlling temperature gradient in a furnace. A clear reflected echo from the solid-liquid interface of the aluminum alloy has been observed. The movement of the reflected echo due to the growth of the solid-liquid interface has also been monitored during cooling process. Thus, it is

demonstrated that the developed ultrasonic sensor using a titanium rod is a promising tool for molten aluminum monitoring.

This work is supported by the Grant-In-Aid for Scientific Researches by JSPS (B14350397). The authors are grateful to T. Okuno of Toyota Motor Co. for his considerable assistance in this work.

U5-E-3 512C-H 11:00 a.m.

REAL-TIME MONITORING OF FABRICATION PROCESS OF MICROFLUIDIC PLASTIC DEVICES USING MINIATURE ULTRASONIC SENSORS

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A microfluidic device, consisting of one or more channels with at least one dimension less than 1mm, has attractive features such as small sample requirement and low power consumption, realizing a lab-on-a chip device. Polymer injection molding technique is a promising candidate to fabricate disposable microfluidic devices with low-cost and in mass production. However, polymers need to be selected and modified in order to meet the requirements of narrow process windows involved with their flow, solidification and microstructure development in micron size channels. Because of this complexity real-time process monitoring is desired to improve the quality of the molded part and optimize the process. Ultrasonic method is chosen because of its ability to probe the properties of polymers within the mold.

We have developed miniature ultrasonic sensors for real-time monitoring of a microfluidic device fabrication using a 30-tons BOY injection molding machine. A thick piezoelectric film ultrasonic transducer is fabricated onto one end of 4mm-diameter and 12mm-long steel buffer rods using a sol gel spray technique. The sol gel is composed of fine PZT powders and PZT solution. The top electrode size is 2mm in diameter. Operating ultrasonic frequencies are available in the range from 10 to 30MHz by controlling film thickness in order to monitor devices with thin thickness. Two spiral like V grooves with a depth of 0.5mm and with a periodicity of 0.8mm are machined on the steel rod periphery in order to reduce the trailing echoes generated by the finite diameter of the rod and thus enhances a signal-to-noise ratio (SNR) of the desired signal. Ultrasonic signals reflected at the probing end with the SNR of more than 30dB have been achieved. The probe developed has the identical external shape of a KISTLER temperature and pressure sensor so that it can be installed into the injection molding machine without modification of the mold. The sensor can operate continuously at 200°C without ultrasonic couplant and cooling. The two sensors are installed into the mold near the gate and at the end of the mold cavity. A material used in the experiments is low viscosity polycarbonate with a DVD grade. Clear ultrasonic signals in the molded part having 1mm-thickness have been obtained. Molten polymer flow front arrival, flow velocity, solidification, shrinkage of the molded part and part detachment from the mold are monitored.

Monitoring of completion of micro-channel development on a thin plastic plate is also discussed.

U5-E-4 512C-H 11:15 a.m.

SUPER-RESOLUTION IN SITU ULTRASONIC MONITORING OF CHEMICAL REACTIONS

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Compression wave ultrasound could provide an effective and non-invasive means to monitor chemical reactions either in the laboratory or under process conditions. In this paper we report how the method was used as a sensitive probe for an acid-base titration aqueous aluminium chloride into potassium hydroxide in aqueous solution. The experimental set-up consisted of an EDOS liquid handling unit, a pH/temperature monitor (Radiometer, Denmark), and an ultrasonic pulse-echo spectrometer built in-house; the spectrometer probe was immersed in the chemical reactor. The time course of the titration, the timing of recordings of the temperature and pH in the vessel, and the recording of the ultrasonic waveforms were all under computer control. A range of derived ultrasonic propagation variables was investigated in relation to their suitability for reliable monitoring of the reaction progress. Most were rendered significantly variant either by electronic noise [1] or by bubbles and other inhomogeneities in the reacting mixture. A key aspect of the work was therefore to find a robust parameter with which to monitor the reaction. Estimates of ultrasonic group velocity based on [2] gave the most reliable means to track the chemical reaction. Very high precision was required in these estimates, achieved in part by careful synchronising of the ultrasonic pulser with the received signal sampling process in order to minimise frame jitter [3]. In addition, a novel algorithm was developed to identify reliably clusters of data that related to given states in the progressing reaction; it enabled us to make estimates of ultrasonic wave group delay within a standard deviation of 0.3ns with a sampling interval of just 3.1ns. This precision was far beyond the nominal resolution of the signal recorder. With the ultrasonic system thus optimised we were able to track very small changes in the reacting mixture down to less than 300 ppm of reagent uptake over timescales that were several orders of magnitude less than what is possible using conventional monitors such as the pH probe. We conclude that high precision ultrasonic group velocity measurements provide, for the first time, an effective means to monitor and ultimately control acid-base titrations in a process context.

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U5-E-5 512C-H 11:30 a.m.

EVALUATION OF ULTRA-LOW EXPANSION GLASSES BY THE LINE-FOCUS-BEAM ULTRASONIC MATERIAL CHARACTERIZATION SYSTEM

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The line-focus-beam ultrasonic material characterization (LFB-UMC) system is applied to evaluate ultra-low expansion glasses (C-7971 Corning Co.). Characterization is made by measuring propagation characteristics (viz., velocity and attenuation) of leaky surface acoustic waves (LSAWs) and leaky surface-skimming compressional waves (LSSCWs) using an LFB ultrasonic device through V(z) curve analysis. In order to obtain their absolute values, it is necessary to calibrate the system using a standard specimen whose bulk acoustic properties, viz., independent elastic constants and density, are measured with high accuracy. Bulk velocities have to be measured in the frequency range, in which the LFB-UMC system is used, because velocities of glass materials exhibit velocity dispersion in general. By replacing the LFB ultrasonic device with plane-wave (PW) ultrasonic devices, longitudinal and shear velocities were measured in the frequency 100-300 MHz for a C-7971 specimen, and the density was measured. Longitudinal and shear velocities were 5739.82 m/s and 3629.77 m/s, respectively, and the velocity dispersions were very small, which can be neglected.

Characterization is demonstrated for three kinds of C-7971 specimens extracted from different lots. The LSAW velocity for the standard specimen was 3306.05 m/s, and the reproducibility of 50 repeated measurements was ± 0.14 m/s ($\pm 2\sigma$, σ: standard deviation). TiO_2 concentrations were analyzed to 7.3 wt% by an X- ray fluorescence analysis. Using the results for the C-7971 specimen and a synthetic silica glass (C-7980, Corning Co.) specimen, sensitivity and resolution to TiO_2 concentration by LSAW velocity measurements were obtained as -16.45 (m/s)/wt% and ± 0.010 wt%, respectively. And, those to thermal expansion coefficient were obtained as -230.96 (m/s)/ppm and ± 0.72 ppb, respectively. A maximum velocity difference of 2.29 m/s was detected among three specimens, and a maximum velocity variation of 3.92 m/s was detected on a specimen. These velocity changes correspond to the TiO_2 concentration changes of 0.139 wt% and 0.238 wt%, respectively, and to the thermal expansion coefficient changes of 9.92 ppb and 16.97 ppb, respectively. When angular dependences of the LSAW velocities were measured, a maximum difference of

2.00 m/s was detected for a specimen. It might be caused by a striation associated with the glass production process. A determination method of bulk wave velocities, viz., longitudinal and shear wave velocities, using measured LSAW and LSSCW velocities also developed: ratios of LSAW velocity to shear velocity and LSSCW velocity to longitudinal velocity were 0.9108 and 1.0010, respectively. This ultrasonic system and method are very effective for evaluation and selection of glass substrates, and evaluation and control of the production processes.

U5-E-6 512C-H 11:45 a.m.

TRANSMISSION OF ACOUSTIC WAVES THROUGH PIEZOELECTRIC PLATE: MODELLING AND EXPERIMENT

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Piezoelectric materials represent one of the basic components of ultrasonic transducers. Characteristics of the devices are directly linked to the material elastic and piezoelectric properties, which are therefore important to identify. They can then be used as input data for simulation codes intended to modelling the transducer behavior.

One of the common methods of the Non-Destructive Evaluation implies generating ultrasonic plane waves in a plate immersed in water. Their transmission coefficients are related to the plate properties, and the comparison between the experimental data and simulated transmitted fields enables characterization of the material.

This work deals with the direct transmission problem. The derivation of the angular spectrum of the transmission coefficient through a piezoelectric plate is based on the octet formalism of piezoacoustics [1, 2], and the concept of the plate impedance and admittance [3, 4]. Specifically, we introduce a particular version of the admittance matrix that incorporates any type of electrical boundary conditions, and so the transmission problem is then described in the same way as in a pure elastic case. Moreover, this admittance matrix is furnished with certain symmetries. The ensuing formula for the reflection or transmission coefficient is therefore similar to that obtained for an elastic plate in the literature (for example, see [5]), except that it is further simplified due to the admittance-matrix properties. The numerical computations prove to be robust without any limitation in anisotropy or frequency up to more than 100 MHz.mm.

The simulated results are compared to experimental data obtained by means of a classical transmission setup: the sample is fixed to a rotation stage and placed between two ultrasonic transducers. The acoustic signals transmitted through the sample at different angles are then collected and the transmission spectrum is obtained by selecting their amplitudes at a given frequency.

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Session: U6-E

BONE CHARACTERIZATION

Chair: K. Wear

FDA

U6-E-1 512A-F 10:30 a.m.

AXIAL TRANSMISSION TECHNIQUES FOR BONE ASSESSMENT: AN IN VITRO COMPARATIVE STUDY

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The objective of this study is to compare three different approaches using ultrasonic axial transmission in vitro.

Forty-one fresh human radii with soft tissue removed were investigated. Measurements of the ultrasound velocity of the fastest signal were performed with a commercial device (V1, Sunlight Omnisense TM, 1.25 MHz), a prototype based on 1MHz bi-directional axial transmission (V2), and a prototype low frequency (200 kHz) device (V3), which provided in addition the velocity (V4) of a slower guided wave. Site-matched pQCT measurements provided bone properties, such as cortical thickness (CTh), cross-sectional area (CSA), and bone mineral density (BMD). All measurements were taken at the same location, corresponding to the clinical site of measurement. The velocity values obtained correlated significantly with each others except V1 and V4 (r ranged from 0.43 to 0.74; all $p<0.01$). The highest correlation ($r=0.74$) was obtained between V1 and V2. This result was expected as the two devices measure the velocity of the first arriving signal at similar frequencies. Correlations (r) between ultrasound measurements and bone properties are summarized in the table. The relatively low to moderate correlation between different velocities suggest that the velocities may not reflect bone properties at exactly the same location in the samples due to differences in the emitter-receiver configurations of the probes. As expected, the high-frequency devices (V1 and V2) are less sensitive to CTh, CSA and trabecular BMD than the low-frequency device because high frequency waves detect only a thin upper layer of the cortex (approximately 1 to 1.5 mm) compared to the low frequency wave. Our results suggest that different axial transmission approaches may reflect different bone properties. Therefore, a multi-frequency technique might be useful in probing different bone properties at the same time (e.g., cortical thickness and BMD).

Correlation between ultrasound mesurements and bone properties

	Cortical BMD	Trabecular BMD	Cross-sectionnal area	Cortical thickness
V1	0.50***	0.22	0.10	0.19
V2	0.72***	0.47**	0.2	0.36*
V3	0.40**	0.21	0.31*	0.33*
V4	0.67***	0.74***	0.52***	0.72***

*p<0.05;**p<0.01;***p<0.001

U6-E-2 512A-F 10:45 a.m.

APPLICATION OF THE KRAMERS-KRÖNIG RELATIONS TO MEASUREMENTS OF ATTENUATION AND DISPERSION IN CANCELLOUS BONE

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Ultrasonic (US) assessment of fracture risk in osteoporotic patients is based on measurements of broadband ultrasonic attenuation (BUA) and speed-of-sound (SOS) of cancellous bone found at peripheral sites. Cancellous bone is known to exhibit dispersion over clinically relevant frequencies, which along with frequency-dependent attenuation can lead to discrepancies in estimates of SOS depending on the time-of-flight (TOF) estimation technique. An improved understanding of the relation between attenuation and dispersion in cancellous bone could benefit numerical and experimental investigations of the effects of these properties on estimates of SOS. One approach for the study of attenuation and dispersion involves the Kramers-Krnig (K-K) dispersion relations. Discrepancies between measured and K-K predicted dispersion in cancellous bone have generated uncertainty as to the appropriate form of the K-K relations for application to cancellous bone. We consider here a subtracted form of the finite-bandwidth K-K relations that requires knowledge of the US properties over only the experimental bandwidth. Compensation for artifacts introduced by limiting the K-K integrals to the experimental bandwidth can be achieved through an

appropriate choice of a subtraction frequency. We validate this form of the K-K relations with *in vitro* measurements of cancellous bone. Cancellous bone specimens (n=10) obtained from the proximal end of four bovine tibia were cut into cubes (15 mm sides) and prepared with the axis of measurement along the mediolateral (ML) and superoinferior (SI) directions. Marrow was removed prior to measurement. Apparent densities ranged from (96 to 534) kg/m^3. US measurements were performed in a water bath (23 °C) using a pair of planar transducers (2.25 MHz, 0.5" diam.) aligned coaxially. Transducers were connected to a pulser/receiver, and signals were digitized with a 100 MHz 8-bit digitizing oscilloscope. The SOS was determined from changes in the TOF of the signal between a reference water path and a path with the specimen inserted. The TOF was estimated using both peak and threshold values of the signal envelope. The attenuation coefficient and phase velocity were calculated from Fourier analysis of the US signals. Finite-bandwidth K-K analysis of the attenuation coefficient predicted the corresponding phase velocity. The usable bandwidth was approximately (0.5 to 3.0) MHz. Measurements of cancellous bone were found to be consistent with the assumptions of the K-K relations. Good agreement was observed between the measured and K-K predicted dispersion (Pearson's r=0.99) for all ML and SI specimens. Dispersion correlated well with apparent density for ML specimens (Pearson's r=-0.95) but less so for SI specimens (Pearson's r=0.61). Discrepancies between the peak and threshold SOSs corresponded to specimens of higher density ($>$250 kg/m^3). This was due in part to several factors including frequency-dependent attenuation, large dispersion ($\sim$100 m/s), or the presence of a fast and slow wave.

U6-E-3 512A-F 11:00 a.m.

ULTRASONIC WAVE DISPERSION AND ATTENUATION IN A PERIODICALLY TWO-LAYERED MEDIUM

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Osteoporosis is a metabolic bone disease characterized by reduced bone mass and deteriorated microstructure of bone tissue. Broadband ultrasound technique is a promising tool to characterize bone tissue and assess bone quality. Bone is a porous, anisotropic and anelastic medium. There were attempts to use Biots porous theory to model cancellous bone. However, Biots theory has many controlling parameters making it difficult to apply in practice. It has recently been suggested that a periodically two-layered medium might provide an alternative to model cancellous bone. The stratified theory predicts the three sound waves (two fast and one slow waves) similar to those of the Biots theory. The stratified theory has the advantages over the Biots theory in its simplicity. Each layer is characterized by only four quantities: thickness, sound speed, density and attenuation coefficient. In this work, we use numerical method to simulate

wavefield propagation through a stratified cancellous bone model. The model is a 2 cm thick periodically two-layered structure with ten and twenty periods respectively. In each period, the ratio of the thickness of bone-mimic layer and that of marrow-mimic layer is 7:13. The model can be elastic or anelastic. The speeds of sound in the bone-mimic layer and marrow-mimic layer are 3200 m/s and 1500 m/s respectively. A broadband Berlage pulse with a dominant frequency of 0.9 MHz was used to simulate an ultrasonic pulse traveling through the model. Based on our preliminary work on elastic cases, the simulated signal displayed strong reverberation after the main transmitted arrival, demonstrating strong multiple scattering within the stratification. The frequency spectrum shows periodic passing and stopping-bands. Within the primary passing band, the phase velocity decreases with frequency and the attenuation increases mildly with frequency. Within the stopping bands, wave transmission is prohibited but the medium supports a constant phase velocity and there is maximum attenuation. The first cut-off frequency (at which the first passing band ends and the first stopping band starts) increases apparently with the decrease of the thickness of the two-layered period. It is interesting that these results could be quite accurately predicted using an approximation theory, which does not consider any multiple scattering within the stratification. Comparison of the results using both theories is also presented.
This research was supported by a grant from the Natural Science and Engineering Research Council of Canada. Financial support in term of studentship was provided by the University of Alberta and Capital Health.

U6-E-4 512A-F 11:15 a.m.

CHARACTERIZATION OF HUMAN FEMORAL TRABECULAR BONE IN VITRO USING TRANSMISSION AND BACKSCATTER ULTRASOUND MEASUREMENTS

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An important limitation of quantitative ultrasound measurement (QUS) methods that are available today is their restricted ability to measure only peripheral skeletal sites. However, the risk of fracture may be best predicted by analyzing the site where the fracture occurs (femur or the spine). This work was motivated by the development of QUS techniques to measure the hip. The goal of this study is to investigate the relationships of QUS measurements in transmission and reflection to BMD and micro-architecture measured on human proximal femur. One-centimeter thick slices were cut through the proximal femur of thirty-eight specimens removed from fresh cadavers. Two-dimensional ultrasonic scans were performed using a pair of 1-MHz focused transducers to measure QUS parameters including normalized BUA (nBUA), SOS and broadband ultrasonic backscatter (BUB). BMD was determined using QCT. Non overlapping ROIs (leading to 660 different ROIs) were selected for quantitative analysis on both QUS and QCT images. Finally, 8-mm diameter cylindrical cores were extracted

from 31 specimens. Their micro-architecture was derived using synchrotron radiation micro-tomography (SR μCT). Thirty-seven cylindrical cores were investigated (6 were taken from the neck and 31 from the great trochanter). All QUS parameters were significantly ($p<10^{-4}$) correlated to BMD (nBUA: $r^2=0.7$; SOS: $r^2=0.75$; BUB: $r^2=0.44$). Most of the micro-architectural parameters were significantly correlated to QUS parameters except the degree of anisotropy and the degree of mineralization. The higher correlations were found for BV/TV (nBUA: $r^2=0.84$; SOS: $r^2=0.83$; BUB: $r^2=0.50$). In forward stepwise multiple regression analysis BV/TV remained the main determinant of QUS parameters variability. Only for SOS, additional parameters (BS/BV and Tb.Sp) could explain a significant increment of 10% of SOS variance. These results suggest that parameters reflecting bone quantity explain most of the variability of BUA and SOS parameters, in agreement with results previously obtained at the calcaneus. In contrast, 50% only of the variability of BUB could be explained by BMD or BV/TV and no additional variability of BUB could be explained by other micro-architectural parameters. Further studies are required to clarify the reason for this moderate relationship of BUB to bone material or structural properties.

U6-E-5 512A-F 11:30 a.m.

ACOUSTIC MICROSCOPY FOR DETECTION OF OSTEOPOROTIC BONE PROPERTIES

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Bone is a tissue highly adapted to its load-bearing function and changes its properties according to the biomechanical need. It is known that bone mass is changing with age and the amount of bone loss is correlated with the incidence of fracture in osteoporosis. A decrease in bone mineral density of one SD increases the fracture risk by more than two times. But there is any evidence that exist factors influencing the skeletal fragility independent of bone mass summarized in clinical terms as bone quality. It comprehends mechanical properties of the material bone itself such as elasticity and strain resistance. Only little is known on these intrinsic elastic properties. The high anisotropy of bone, the porosity and function-related structures make it extremely difficult to measure and describe its mechanical properties in detail with testing procedures commonly used in materials science such as bending test or torsion test. Acoustic microscopy can deliver information of more complex and detailed nature using high frequency transducers. For bone investigation we found the acoustic impedance as the most suitable parameter. Frequencies up to 2 GHz gain a spatial resolution of about 0.5μm allowing morphological study at the level of cellular structures. For quantitative analysis at high frequencies a smooth and plane surface is essential. In bone remains an unavoidable surface roughness sufficient to influence the reflected sound waves. To exclude these disturbing effects we developed the image processing software Multi Layer Analysis (MLA). METHODS: Specimens from human iliac crest biopsies with different clinical grades of osteoporosis were embedded in polymer resin, milled and polished up to a surface roughness of 0.5 μm for further investigation. With the acoustic microscopes SAM 100Ex and SAM 2000 (Kraemer Sc. Instr.) acoustic impedance was measured at 50 MHz and 200 MHz. The measurements were taken in distilled, degassed water at a controlled temperature of 25°C. By scanning the sample in x,y-direction a grey scale image is gained in amplitude contrast. For correct data acquisition and device control we used a software tool (ELIPS) for automatical grabbing of consecutive images in decreasing z-positions. MLA calculates focussed output images finding the V(z)-maxima for every site of measurement. The acoustic parameters were correlated with histological severity of osteoporosis. RESULTS: SAM images elastomechanical properties of bone tissue in a two-dimensional distribution. At high frequencies the spatial resolution is comparable to light micropcopy and delivers concomitant morphological information. SAM therefore delivers a unique quality of mechanical information. In contrast to results of common mechanical testing in our study bone was barely found to change its mechanical properties according to the clinical severity of the osteoporosis. We registered a small decrease of osteoporotic specimens in comparison with healthy persons, but there was no significant change with the severity of the disease.

U6-E-6 512A-F 11:45 a.m.

IMPACT OF MATERIAL AND STRUCTURAL BONE PROPERTIES ON 1-MHZ VELOCITY MEASUREMENT IN HUMAN FOREARMS

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The ultrasonic axial transmission technique allows investigating skeletal sites such as the cortical layer of long bones (radius, tibia, phalanges). We investigated in vitro the relationships between 1 MHz axial transmission speed of sound (SOS) measurements at the radius and site-matched measurements of cortical thickness (C.Th), intracortical porosity (POR), tissue mineralization (MIN) and BMD using synchrotron radiation microtomography. SOS measurements were based on bi-directional axial transmission, performed with a 1 MHz proprietary probe on 39 excised human radius. The highest correlations between SOS values and bone parameters (R2(SOS/POR) = 0.28, p<10-3, R2(SOS/MIN) = 0.38, p<10-4, R2(SOS/BMD) = 0.57, p<10-3) were found for bone parameters assessed in a 1 mm thick periosteal region of the cortex, rather than through the whole cortex. The observed moderate correlation between SOS and C.Th values (R2(SOS/C.Th) = 0.20, p<10-2) disappeared when controlled for other variables. This moderate correlation may be partly explained by 3-D finite difference modeling indicating that that the signal velocity reflects bone properties over a

limited depth of about half a wavelength. The two best multilinear predictive model, including either BMD alone or the pair of dependent variables MIN and POR (all assessed in the periosteal cortex), were equivalent in predicting SOS values (R2(SOS/POR,MIN) = 0.59, R2(SOS/BMD) = 0.57, both p<10-5). For the first time, the respective adjusted contributions of intracortical porosity (-24 m/s.%-1) and tissue mineralization (-3.5 m/s.(mg/cm3)-1) to SOS values were assessed. The sensitivity of SOS to porosity, after adjustment for mineralization, is in good agreement with 3-D finite difference simulations. These results suggest potential sensitivity of axial transmission SOS values to changes in cortical bone status under different pathological conditions or treatments affecting porosity and/or tissue mineralization. These results also indicate that measurements currently performed in clinic around 1 MHz should be sensitive mainly to periosteal regions of the cortex. Different pathological conditions or treatment may affect multiple bone conditions (mineralization, porosity, cortical thickness) and the various effects may add up to contribute to changes in SOS values. In this context, new techniques combining several ultrasonic measurements, involving several frequencies or several propagation modes for instance, must be developed with the aim to identify and quantify specific changes of these bone properties.

Session: FE1-E

RELAXORS
Chair: T. Takenaka
Science University of Tokyo

FE1-E-1 513CD 10:30 a.m.

OPTICAL PROPERTIES OF EPITAXIAL PLZT THIN FILMS FABRICATED BY A SOL-GEL METHOD

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INTRODUCTION $(Pb_{1-x}, La_x)(Zr_{1-y}, Ti_y)_{1-x/4}O_3$ [PLZT x/1-y/y] is well known as a ceramic with a high transparency and high electric-optic (EO) coefficient. Because of such these attractive optical properties PLZT is one of the candidate materials for future optical devices. A controllable refractive index, low birefringence and a high EO coefficient are required for the device applications, such as waveguide and so on. In this work, the composition dependence near morphotropic phase boundary (MPB) of TE- and TM-mode refractive indexes, and the EO properties of the epitaxial PLZT thin films grown on Nb-doped $SrTiO_3$ [Nb-STO] (100) substrate fabricated using the sol-gel method were investigated.

EXPERIMENTAL The sol-gel precursors were synthesized from lead acetate trihydrate, lanthanum isopropoxide, zirconium n-propoxide, and titanium isopropoxide. 2-methoxyethanol was used as a solvent. Sol-gel precursor solutions close to MPB compositions were prepared: PLZT 0/52/48, 3/55/45, 6/60/40, 8/65/35, 9/65/35 and 10/65/35. These sol-gel precursors were spin-coated onto Nb-STO (100) substrates. Subsequently the PLZT film was annealed with an oxygen flow in an infrared furnace for crystallization. The above process was repeated to obtain epitaxial PLZT thin films whose thickness was over 2 μm. The prism coupling method was used for TE- and TM-mode-refractive index measurements. Light with a wavelength of 1550 nm was used. To measure change of the index as a function of an applied dc electric field, a 10-nm-thick tungsten layer was deposited by sputtering as the upper electrode. Voltage was applied between the tungsten electrode and Nb-STO substrate.

RESULTS AND DISCUSSION Heavily La doped PLZT requires a high crystallization temperature; therefore, depending on the La content, the annealing temperature was varied over the range of 625 to 750 °C. The PLZT thin films had a perovskite single phase and were highly (001) oriented. These films were confirmed epitaxially grown on the Nb-STO substrate by XRD pole figure measurements. The refractive index decreased from 2.45 to 2.40 as the La content increased from 0 to 10 atom%. This indicates that the refractive index can be controlled up to 2 % with the PLZT composition. Birefringence decreased from 410^{-3} to 510^{-4} as La content increased, because the crystal structure decreased tetragonality. The PLZT crystal structure became pseudo-cubic as the La content increased and approached 10 atom%. The EO coefficient increased from 25 pm/V to 45 pm/V as the La content increased from 0 to 9 atom%. This behavior is almost same as PLZT bulk ceramics [1]. PLZT bulk ceramics have a polarization dependence [1], but only small polarization dependence of the EO coefficient was observed in these results.

REFERENCE (1) G.H. Haertling and C.E. Land, J. Am. Ceram. Soc., 54 [1], p. 1 (1971).

A part of this work was belongs to Photonic Network Project which OITDA contracted with New Energy and Industrial Technology Development Organization (NEDO).

FE1-E-2 513CD 10:45 a.m.

RELAXOR FERROELECTRICITY IN EPITAXIAL SRTIO$_3$ THIN FILMS ON DYSCO$_3$ SUBSTRATES

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Strain can be a dominating factor in properties of ferroic thin films. Of particular interest is $SrTiO_3$, which exhibits a permittivity approaching 20,000 as the temperature is lowered to about 4 K. To examine the effects of strain, epitaxial $SrTiO_3$ thin films were grown on $DyScO_3$ substrates by molecular beam epitaxy. These films were highly strained due to the coherence of the film to the substrate. The films exhibited good structural epitaxy with x-ray rocking curves of less than 0.34° in ω. The $SrTiO_3$ films show an in-plane maximum dielectric constant of near 18,000 and a transition temperature of 250 K, over 100 K above previously reported temperatures. The $SrTiO_3$ films also exhibit relaxor ferroelectricity that was well fit by a Vogel-Fulcher equation over eight orders of magnitude in frequency with a characteristic frequency of 1 x 10^{13} Hz and activation energy of 0.05 eV. However, this relaxation behavior may be linked to the diffusion of Sc from the substrate into the films. These films also develop clear hysteresis loops below the T_{max} with remanent polarizations up to 10 $\mu C/cm^2$ at 77 K.

FE1-E-3 513CD 11:00 a.m.

DIELECTRIC RELAXATION IN FERROELECTRICS WITH DIFFUSE PHASE TRANSITION

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One of characteristics for relaxor ferroelectrics is that the T_m of the dielectric maximum shifts towards higher temperature with frequency increasing at low frequency range of 10^2 10^6 Hz, which has been ascribed to the flipping or rattling of the spontaneous polarization in the nano-polar regions. The dielectric relaxation behavior of relaxor ferroelectric 70PZN-15PT-15BT can be eliminated through thermal annealing. The data of spontaneous polarization with temperature demonstrate that the increasing section of dielectric constant peak for the annealed sample stems from the nano-polar regions, which is analogous to the unannealed one. Therefore, the shift of T_m towards higher temperature at 10^2 10^6 Hz could not be produced by the spontaneous polarizations response of the nano-polar regions. The experimental data provide a hint that domain-wall movements and orientations of various dipoles parasitized around polar-regions are the most possible origins causing the shift of Tm at 10^2 10^6 Hz.
The work described in this paper was supported by the Fund of National Natural Science Foundation of China (Project No. 50272052). The dielectric and ferroelectric measurements were done in Department of Physics and Materials Science, City University of Hong Kong.

FE1-E-4 513CD 11:15 a.m.

ELECTROSTRICTIVE PROPERTIES IN PR DOPED (BA,SR)(TI,AL)O_3 CERAMICS

W. XU-SHENG*[1], Y. HIROSHI[1], N. KEIKO[2], and X. CHAO-NAN[1,2], [1]PRESTO, Japan Science and Technology Agency, [2]National Institute of Advanced Industrial Science and Technology.
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Barium titanate was the first perovskite-type ferroelectric and piezoelectric materials developped and widely used ever since its discovery 60 years ago, though it was replaced by lead titanate zirconate later [1]. Recent years, with the growing demand of global environmental protection, the lead-free and heavy metal-free materials have attracted much attention. Barium titanate ($BaTiO_3$) and barium strontium titanate [(Ba,Sr)TiO_3] are environmental friendly materials and have shown excellent microwave dielectric properties. $Ba_{1-x}Sr_xTi_{0.99}Al_{0.01}O_3$ (x=0.2 0.7) doped with 0.2 mol% Pr ceramics were prepared by solid-state reaction technique and the dielectric and electrostrictive properties were characterized. The X-ray diffraction and dielectric-temperature measurement showed that the pure phase of perovskite solid-solution was formed in each sample and the ferroelectric (tetragonal)-paraelectric (cubic) transition temperature (Tc) decreased with x increase. The strain-electric field measurement at room temperature showed that the largest strain was obtained in the samples of x=0.2 and 0.3 (Tc is about room temperature) to be 0.06% induced by 30 kV/cm. Quite large strains were measured in the samples of x=0.4 and 0.5 in cubic symmetry state. Far higher to Cuire point, the electrostrictive strain can be observed for the samples of 0.6 and 0.7. The electrostriction in cubic paraelectric phase $(Ba,Sr)Ti_{0.99}Al_{0.01}O_3$ was discussed by using polar microregoin or nanoregion concept used in relaxor ferroelectrics [2]. [1] B. Jaffe, W. R. Cook and H. Jaffe, *Piezoelectric Ceramics*. (Academic Press, London, 1971). [2] L. E. Cross, Ferroelectrics, 76, (1987) 241.

FE1-E-5 513CD 11:30 a.m.

MONOLITHIC BULK ELECTRO- AND ACOUSTO-OPTIC DEVICES BASED ON DOMAIN INVERTED FERROELECTRICS

H. W. J. GNEWUCH*[1], C. N. PANNELL[2], and J. H. LEHMAN[3], [1]School of Physical Sciences, University of Kent, [2]Gooch and Housego Group, Optronic Laboratories, Inc., [3]NIST/815.01.
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We report advances in bulk electro-optic and acousto-optic components based on the exploitation of anisotropy and induced inhomogeneity of crystalline materials. The controlled introduction of inhomogeneity in ferroelectrics by means of electric field poling at room temperature has been used for about a decade now to realize monolithic bulk quasi phase-matched structures for optical frequency conversion. However it is less well known that the resulting "superlattices" offer unique opportunities for electro-optic (EO) and acousto-optic (AO) device fabrication. For example, we have shown that an EO Bragg-modulator based on superlattices reduces drive power by 70% and switching time by a factor of 5 compared with a conventional (single-domain) transverse EO retarder-modulator and acousto-optic Bragg cell, respectively. The same design has also been employed as an electrode-less electric field sensor, owing to the fact that quadrature was achieved without any bias. Moreover, for AO devices we have demonstrated that with the introduction of a transducer array based on acoustic superlattices, instead of a conventional thin plate piezoelectric transducer bonded to an acoustic transmission medium, at least two more degrees of freedom for its design, namely the number of periods and chirp, and one additional acoustic wave excitation scheme are introduced. This allows, for instance, improved broadband impedance matching, the exclusion of matching layers, and a transducer-free optical path. These broadband acoustic transducers have been successfully used as part of monolithic bulk acousto-optic tuneable filters (MBAOTFs), for which the ferroelectric material is also used as the optical transmission medium. Several topologies have been built and analysed. In one design an acoustic longitudinal wave excited in the "crossed-field" scheme, in which the applied electric RF-field is normal to the propagation direction of the acoustic wave, is used to couple two collinearly propagating optical waves of orthogonal polarization. The device showed excellent filter characteristics between 1300 nm and 1600 nm with moderate conversion efficiency. Improved drive power demands were achieved in a MBAOTF, which uses acoustic shear waves instead of longitudinal waves, resulting in an improved acoustic figure-of-merit. The excitation of shear waves was accomplished by exploiting the anisotropy of the material through the efficient conversion (98%) of a longitudinal wave at an appropriate angle at the crystals surface. In a third topology the MBAOTF is optimised in as much as it uses a shear wave with maximised relative conversion efficiency and acoustic beam direction parallel to the wafer surface, thus providing a long interaction length. Moreover, due to the rather small wafer thickness acoustic wave diffraction is an important issue, this is analysed and reduced by appropriate electrode design.

Session: FC1-E
OPTICAL STANDARDS AND APPLICATIONS
Chair: J. Ye
University of Colorado

FC1-E-1 511CF 10:30 a.m.

THE OPTICAL LOCAL OSCILLATOR PROBLEM: A 40 DB REDUCTION OF VIBRATIONAL SENSITIVITY VIA A NEW OPTICAL CAVITY DESIGN

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The new millenium has brought remarkable advances in our ability to compare frequencies in the rf and optical domains, clearly revealing that not enough of the clever techniques common in the rf standards systems have yet been adopted, adapted, and implemented by the optical frequency community. Many attractive optical transitions have been identified, with phase lifetimes from molecules in the millisec domain, to many ions in the $\sim$s region, to 1000 s for Sr^+ and even beyond for Yb^+. However most of the projected joy awaits development of suitable optical local oscillators of adequate stability and narrow linewidth: The fundamental issue of any standard is the local oscillator used for interrogation of the resonant sample. Also, several known problems are exacerbated by the short optical wavelength and the resulting enhanced phase-modulation. For example, miniscule laboratory vibrations leaking onto the optical reference cavity of a cavity-stabilized laser ordinarily lead to resolved optical sideband structure on the optical carrier. By now, several major labs have already demonstrated Hz-level ($<10^{-14}$) linewidths, via massive and highly expensive vibration-reduction installations. With a new idea, we are demonstrating similar linewidth performance on top of an ordinary optical table in an open laboratory environment. The new concept is essentially a better mounting geometry whereby symmetry can be defined and used to achieve a major reduction of the cavity length variation, for a given vibrational amplitude of the mounting flange. Basically, the short reference cavity should be vertical, rather short and fat, probably football-shaped, and - most critically - symmetric above and below its midplane from which is mounted in a pendular fashion. Vertical accelerations generate tensile and compressional strains of nearly-equal and cancelling magnitudes. Compared with resting the entire weight on the bottom of the structure, we readily achieve a 40 dB reduction of the vibrationally-induced *differential* length changes. Horizontal accelerations of the base are strongly filtered by the pendulum mounting, and also operate with a much-reduced sensitivity coefficient.

A second major concern is predictability of the frequency in time. Ideally one would prefer a drift rate or zero. We find good results with ULE material for the cavity spacer where drift- rate well below 10 milliHz/s at 5.6 $\times 10^{14}$ Hz can often be enjoyed for hours – after a number of somewhat subtle thermal variations are suppressed. An extremely attractive attribute of this nanotechnology material is that its internal mixed-phase structure leads to a stationary, shortest length with a basically pure quadratic expansion coefficient of $\sim 1 \times 10^{-9} \cdot$ (T-T_0)h stabilities below 100 μK, leads to sub-Hz projected thermal stability. Our immediate application of this technology is to the attractive transition in ^{87}Sr $^1S_0$ – $^3P_0$ at 698 nm.

FC1-E-2 511CF 10:45 a.m.
(Invited)
NOISE PROPERTIES OF FEMTOSECOND LASERS AND PHOTODETECTORS AT INFRARED FREQUENCIES

E. N. IVANOV*[1], S. A. DIDDAMS[2], and L. HOLLBERG[2], [1]University of Western Australia, [2]National Institute of Standards and Technology.
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Demodulation of ultra-short light pulses with photodetectors is accompanied by excess phase noise at the harmonics of pulse repetition rate in the spectrum of the photocurrent [1]. This noise originates from power fluctuations of the detected pulse train and, if not compensated for, can seriously limit the accuracy of time transfer from optical to microwave domain.

By making use of an infrared femtosecond laser, we measured spectral density of the excess phase noise, as well as power-to-phase conversion for different types of InGaAs photodetectors. Noise measurements were performed with a novel type of a dual-channel readout system with channels separated by a fiber coupled beam splitter. Stabilization of the average power of the femtosecond pulse train resulted in strong suppression of the excess phase noise in both channels of the measurement system.

Noise properties of optical beat notes which result from the non-linear interaction between pulsed and CW light were studied. Based on this study, an alternative technique for extracting a microwave signal from the optical frequency synthesizer is proposed.

References:

1. E. N. Ivanov, L. Hollberg and S. A. Diddams, Analysis of Noise Mechanisms Limiting the Frequency Stability of Microwave Signals Generated with a Femtosecond Laser, in IEEE Journal of Selected Topics in Quantum Electronics, vol. 9, no. 4, pp. 1059- 1065, July-August, 2003.

This work is jointly supported by Australian Research Council and National Institute of Standards and Technology

FC1-E-3 511CF 11:15 a.m.

"MAGIC" WAVELENGTHS FOR OPTICAL FREQUENCY STANDARDS ON COLD ATOMS

V. OVSIANNIKOV[1] and V. PAL'CHIKOV*[2], [1]Department of Physics, Voronezh State University, [2]Institute of Metrology for Time and Space at National Research Institute for Physical-Technical and Radiotechnical Measurements. Corresponding e-mail: vitpal@mail.ru

The use of the forbidden optical transitions of atomic systems with two outer electrons has been proposed as the basis for an ultrastable optical clock on Mg, Ca, Sr and Yb atoms [1-3]. In our recent work [3], we have examined in detail the effect of the "light shift cancellation" on the singlet-triplet s-p transitions in Sr atoms, which adjust the dipole polarizabilities for the probed electronic states in order to cancel light field perturbation effects on the measured spectrum. In particular, we have estimated the light shift as a function of the trapping laser wavelength in the vicinity of the crossing point ("magic" wavelength). We have also demonstrated, that the contribution of the higher-order light shifts can be reduced to less than 1 mHz. In this paper, we will further demonstrate the applicability of this approach by extending our study to the determination of the "magic" wavelengths for Mg, Yb and for the first time Hg atoms on forbidden transitions between the ground state and the triplet P-states with J=0,1,2. In the calculations of the dynamic Stark effect we have used the general theory [4] for consecutive estimates of "scalar", "asymmetric" and "tensor" parts of polarizabilities for linear and circular polarization of the trapping laser radiation. For the accurate calculations of these quantities we have applied the Fues' model potential method. In this way the quite simple presentation for the Green's function enables us to evaluate the contribution of the higher excited states which are neglected in the finite-sum approach. The present study indicates good prospects for the optical clocks on the forbidden transitions in Mg, Yb and Hg atoms employing the "light shift cancellation technique".

References

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FC1-E-4 511CF 11:30 a.m.

FREQUENCY TRANSFER OF OPTICAL STANDARDS THROUGH A FIBER NETWORK USING 1550-NM MODE-LOCKED SOURCES

K. HOLMAN*, D. JONES, and J. YE, JILA, NIST and University of Colorado. Corresponding e-mail: kevin.holman@colorado.edu

With the advent of optical atomic clocks and the associated superior short-term frequency stability, transfer of signals linked to such clock/frequency standards over an appreciable distance with minimal loss of stability has become an important research subject. Using femtosecond frequency combs produced by mode-locked lasers for this purpose allows simultaneous transfer of optical and radio frequency (RF) signals, both phase locked to the optical frequency standard. Optical transfer is realized by detecting the absolute positions of the transferred comb lines, whereas RF transfer is achieved by simply using a fast photodiode to detect the repetition frequency of the transferred laser pulses. The phase coherence of a mode-locked Ti:sapphire laser linked to an optical standard has been transferred to a 1550-nm mode-locked source, which is necessary for distribution over optical fiber networks. We have studied the transfer instability for such a 1550-nm source over a fiber network.

Of course RF signals can be transferred via direct amplitude modulation on an optical carrier. The approach we have taken in this work utilizes a phase stabilized 1550-nm mode-locked laser source for simultaneous distribution of optical and radio frequency standards over a 7-km installed fiber network. The transfer instability for the repetition rate of a 1550-nm mode-locked fiber laser is determined by comparing the pulse rate detected after transmission through a roundtrip of a fiber network with that of the pulses before transmission. To minimize the detection instability, it is critical to minimize the light power incident on the photodetector while maintaining a sufficient signal-to-noise ratio (*SNR*). The stretching of the pulses caused by the fiber dispersion decreases the *SNR* of the detected harmonic. By minimizing the pulse spectral bandwidth, the amount of stretching is reduced, maintaining a sufficient *SNR* without needing to greatly increase the incident light power on the detector. The measured instability is the same as that for optical-carrier transfer over the fiber network, and is nearly an order of magnitude better than that for RF transfer through modulation on an optical carrier, as summarized in the table below.

A natural extension of this work in the time domain is to determine the rms timing jitter introduced during the transfer process. This will be an important step towards exploration of tight synchronization of remotely located pulsed lasers and radio frequency sources. We have also begun investigating optical transfer of frequency standards using mode-locked pulse trains. Preliminary results indicate there is no difference between cw and mode-locked schemes when measured locally. However, due to time gating and other effects we expect mode-locked pulses could offer a significant advantage over long transmission distances. We will present further work on these topics as well as implementation of stabilization loops for both microwave and optical frequency transfer using mode-locked sources.

Instability for RF Transfer

RF Source	**1-second Allan Deviation**
modulated cw	2e-13
cw optical transfer	2.6e-14
mode-locked fiber laser	2.6e-14

The current address for D. Jones is Dept. of Physics and Astronomy, University of British Columbia, Vancouver, B.C. V6T 1Z1 Canada. Funding for this work is supported by ONR, NASA, NIST, and NSF. K. Holman is a Fannie and John Hertz Foundation graduate fellow.

FC1-E-5 511CF 11:45 a.m.

APPLICATION OF MODE-LOCKED LASERS TO NANOTECHNOLOGY

L. ARISSIAN[1,2] and J. C. DIELS*[1,2], [1]University of New Mexico, [2]Center of High Technology Materials.
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We have demonstrated active stabilization of the frequency comb of a mode-locked laser, both in frequency and repetition rate. We present progress towards the absolute stabilization of such a laser (i.e. a time and length standard combined in the same instrument) using coherent interactions with atomic vapors, and the application towards the measurement of displacements with sub-nanometer resolution. The accuracy provided by atomic transitions is used to complement the stability of a mode-locked laser locked to a reference cavity. We will discuss a basic difficulty that arises from the requirement that an error signal has to be found in the atomic system for both the laser repetition rate (about 100 MHz) and the optical frequency (10^{14} Hz). While a Lambda level structure shows simultaneous resonances at both frequencies, we will show how quantum interferences present a challenge to the task of finding a method of absolute calibration.

By applying these techniques to ring cavities as well as linear cavities with two pulses/cavity round-trip, we show a method to design the most sensitive phase detectors. In a bidirectional pulsed ring laser the pulses are separated in space/time. Therefore, the cavity length difference between counter-circulating pulses can be changed mechanically, electrically, magnetically or optically. By interfering the two outputs corresponding to each intracavity pulse, one converts the phase difference $\Delta\Phi$ between the counter-rotating perimeters into a frequency $\Delta\nu = \Delta\Phi/\tau_{RT}$.τ_{RT} is the cavity round-trip time. Since the measurement of the beat note $\Delta\nu_b$ has typically a resolution of 1 Hz in an unstabilized laser, the sensitivity of a measurement of the cavity length difference Δ P = P $\Delta\nu_{ms}$ /ν (where ν is the optical frequency of the light) is of the order of 0.0001 A. It is therefore possible to map phonon waves, measure field induced changes of index, nonlinear indices of refraction, perform phase spectroscopy on atomic transitions.

A sensitivity to phase differences of 10^{-7} radian between the paths seen at each round-trip by the two circulating pulses has been demonstrated, in the case of a unstabilized optical parametric oscillator (OPO) fs ring. The sensitivity to periodic displacements can be enhanced by more than three orders of magnitude by applying our stabilization technique to the ring laser or linear laser with 2 pulse/cavity round-trip.

The intracavity pumped optical parametric oscillator has the unique advantage of independent control of wavelength and repetition rate. The repetition rate of the pulses are determined by the length of the pump cavity, while the OPO wavelength is set by the length of the secondary ring or linear cavity.

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Session: FC2-E

CHEMICAL SENSORS
Chair: J. Hines
Microsensor Systems, Inc.

FC2-E-1 511DE 10:30 a.m.

DESIGN CONSIDERATIONS FOR HIGH SENSITIVITY GUIDED SH-SAW CHEMICAL SENSOR FOR DETECTION IN AQUEOUS ENVIRONMENTS

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Guided shear horizontal surface acoustic wave (guided SH-SAW) devices coated with a polymer waveguiding layer and/or chemically sensitive layer have been investigated for the detection of analytes in liquid environments in our previous work. Experimental and theoretical exploration of design considerations for optimizing these devices for liquid phase detection is the focus of the current work. Using dual delay line geometry on LiTaO3, guided SH-SAW sensors are designed and analyzed. The reference line, used to correct for changes in environmental conditions such as temperature fluctuations, is coated with a waveguiding layer of poly(methylmethacrylate) (PMMA). The sensing line is coated either with a

polymer such as poly(isobutylene) (PIB) that functions as both the waveguiding layer and the chemically sensitive layer (3-layer model) or with a PMMA waveguiding layer below the partially chemically sensitive layer (4-layer model). Experimental measurements show that for a given total thickness of polymer layers on the sensing line, the 3-layer model provides higher sensitivity than the 4-layer model. However, the 4-layer model is shown experimentally to be more stable with lower noise. Increased sensitivity when using the 4-layer model can only be achieved through rigorous selection of the guiding polymer layer and chemically sensitive layer, considering both mass loading and viscoelastic effects. Theoretical analysis of the 4-layer model, focusing on the thickness-density product of each layer and assuming negligible difference in viscoelasticity between the two coating layers, suggests that an optimal combination of waveguiding and chemically selective layers can be easily achieved for polymer materials. The combination which has the same total thickness-density product as the single layer in the 3-layer model results in similar sensitivity. Appropriate selection of the partially selective chemical layer to optimize sensitivity is also a critical design factor, particularly in sensing polar analytes in aqueous sensing applications. An attenuated total internal reflectance Fourier transform infrared spectroscopy (ATR-FTIR) methodology for screening the potential effectiveness of new polymer coatings for these devices is being developed. The ATR-FTIR methodology provides an accurate determination of trends for partitioning of analytes from water into polymer coatings. Comparing these trends with the guided SH-SAW devices responses provides sensitivity prediction as well as further insight into the effects of mass loading and viscoelastic properties on sensor response.
This work was partially supported by NSF Grant Nos: ECS-9876366, ECS-0110381 and CHE-0074962.

FC2-E-2 511DE 10:45 a.m.

MACROSCALE AND MICROSCALE RESONANT SENSORS FOR THE DETECTION OF ILLICIT SUBSTANCES

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In the 1980's work with surface acoustic wave (SAW) resonant gas sensors started at the Naval Research Laboratory (NRL). Through the years improved sorbent polymers have been developed at the NRL and other institutions, and SAW device technology has matured in large part because of the interest in cellular phone markets. Combining these improvements into SAW based systems, the resulting SAW chemical detectors can now be bought commercially.

Recognizing though some of the technology limitations, the NRL has continued to develop SAW based sensor technology to improve some of its characteristics. In an evolution of SAW based detectors, an improved system, pCAD, has been developed which offers a significant improvement in signal kinetics, and offers the potential for improved selectivity. The improved performance with pCAD is achieved by incorporating new chemoselective polymer coatings, by improving the sensor manfold design, and by operating the pneumatics in a pulsed fashion to alternate between two different pressure states, to accelerate vapor or gas sorption kinetics.

As a further evolution of resonant based sensing, various forms of micromachined resonant based sensors have been developed and examined. These sensors offer the potential to allow detector systems to be miniaturized and include on chip electronics, with the cost/reliability benefits that silicon based technologies offer. Early based SAW detectors were large shoe boxed sized instruments, and commercial systems today are hand held, whereas, the micromachined sensor systems offer the potential to shrink detector systems to palm sized, badge, or watch sized type detectors. As an example micromachined transducer technology, a number of microcantilever devices have been investigated at the NRL, with devices ranging from off the shelf cantilevers with custom designed electronics to custom cantilever designs and associated electronics.

Two main microcantilever designs have been explored including (i) a COTS Piezolever^{TM} device incorporating a single piezoresistor that is driven acoustically, and (ii) a custom design that is electrostatically actuated and piezoresistively sensed. The first generation electrostatically actuated cantilever, sensor manifold, and breadboard breadboard electronics/system has been developed. The data for an isothermal vapor concentration ramp demonstrated that the device provided reversible frequency shift responses at 0.1 mg/m^3 or at 20 ppb. The sensitivity of this first generation device is therefore comparable with the relatively mature SAW based technology.

The presentation covering this body of work will provide a retrospective look at the evolution of SAW based resonant chemical sensors, and reflect on the future prospects of micromachined resonant based chemical sensors.
This work was supported in part by DTRA, TSA, ATF, and ONR

FC2-E-3 511DE 11:00 a.m.

STRONG-AXIS BENDING MODE VIBRATIONS FOR RESONANT MICROCANTILEVER (BIO)CHEMICAL SENSORS IN GAS OR LIQUID PHASE

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The use of microcantilevers as transducers in physical and bio-chemical sensing systems has increased in recent years. In fact, the large ratio of surface area to mass makes the microcantilever extremely sensitive to surface processes. For bio-chemical detection, the microcantilever is covered with a bio-chemically sensitive coating which aims to selectively adsorb the analyte or molecule of interest. The adsorbed molecules can then be detected by monitoring the mechanical resonant frequency. As with all frequency-output sensors, the resolution of microcantilever sensors is mainly determined by the mechanical quality factor. Since chemical sensors operate in either a gas or liquid medium, the quality factor of the resonant microstructure is not as high as that of classical microelectromechanical systems (MEMS) operating in a vacuum. When the coated cantilevers are placed in air, the resonant frequencies are reduced typically by a few percent, whereas the quality factors exhibit reductions of three orders of magnitude from their values in a vacuum. Immersion in liquid results in even greater changes to the frequency response, with resonant frequencies and quality factors being an order of magnitude smaller than their corresponding values in air. The reduced value of the quality factor, due to losses in the surrounding liquid, directly affects the resolution of these types of sensors. The aim of this paper is to study different bending vibration modes in order to minimize the losses in the surrounding medium, thus maximizing the quality factor and the resolution of the bio-chemical microsensor. Using Saders model, the expression for the quality factor is analysed for the case of immersion in a viscous fluid. It is demonstrated that the strong-axis flexural mode may have certain advantages over the more conventional weak-axis bending (WAB) mode in enhancing the sensor resolution. Intuitively, it seems that the losses due to the presence of the fluid should be smaller for strong-axis flexural vibrations because the surface area perpendicular to the motion is smaller. In this paper, we demonstrate that in the strong-axis bending (SAB) case the losses are indeed smaller and that the sensor resolution may be improved, even for the case in which the WAB and SAB devices have identical resonant frequencies. To our knowledge this point has not been emphasized in the literature, perhaps because the WAB mode is the mode associated with the more mature AFM technology. Based on preliminary comparisons, we believe that more attention should be given to the possibility of improving microcantilever sensor design by exploring alternate vibrational modes, specifically the fundamental mode associated with strong-axis bending which can be excited with capacitive forces as for other MEMS (i.e. physical microsensors and microactuators).

FC2-E-4   511DE   11:15 a.m.

A MULTI-RESONANCE ACOUSTIC INTERFACIAL BIOSENSOR (MAIB) FOR MONITORING A FORMATION PROCESS OF BIOLOGICAL THIN FILMS

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Interfacial phenomena in biological processes have been of growing interest in the last decade. In particular, biological thin films and their formation processes have become increasingly important. Biological thin films play significant role in development of biosensors where they provide selective interfaces for detection of various biochemical analytes. Other applications biological thin films find in biotechnology, waste water treatment systems, the food industry, and medical area. In this work, a thickness-shear mode multi-resonance acoustic interfacial biosensor (MAIB) is proposed to study the deposition processes of thin film of collagen and albumin. These two materials form two different types of overlayers. Collagen forms anisotropic and polycrystalline thin films, and albumin forms amorphous films. The whole deposition processes including initial liquid stage to final solid thin film stage were investigated. The theoretical analysis of MAIB has been developed to model the sensor response. When acoustic shear wave (ASW) is excited into liquid media it does not propagate but rather penetrates over a relatively short distance. The penetration depth is function of viscoelastic properties of the film and the frequency of acoustic wave. The responses of the MAIB depended on interfacial processes and could be related to biological, chemical, and physical phenomena. Such processes as interfacial mass accumulation or changes in elastic and lossy modulus were measured and monitored in real time using MAIB. The MAIB responses (or signatures) were obtained at the fundamental, 3rd, 5th, and 7th harmonic resonant frequencies (10, 30, 50 and 70 MHz). As a result, the viscoelastic properties of thin films at the different distances from the surface of the MAIB were measured. The changes in the MAIB resonant frequencies and attenuation were monitored during the deposition processes and compared with the theoretical results. Interestingly, the harmonic responses of MAIB were different, which indicated the processes of non-uniform spatial processes during the film formation. Also, the MAIB responses showed qualitatively different signatures for collagen and albumin thin films. Finally, the responses of MAIB were compared with images obtained with optical microscope, SEM, and AFM in order to correlate macroscopic MAIB data with microscopic structures and morphological features of thin films. In conclusion, a multi-resonance acoustic interfacial biosensor (MAIB) has exhibited an attractive measurement features for study the kinetics of biological thin film formation processes in real time with high sensitivity and high temporal resolution.

This study has been performed with the support of the NSF under the grant No. 0242662.

FC2-E-5 511DE 11:30 a.m.

AN ACOUSTIC WAVE SENSOR FOR MEASURING SOOT CAUSED LUBRICATING OIL THICKENING

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Soot caused oil thickening is known to be one of the major failure modes for lubricants operating in heavy duty diesel (HDD) engines. Typically, when oil is contaminated with increasing amount of soot - a combustion by-product in diesel engines, the oil starts losing lubricating functions due to the viscosity increase caused by soot agglomeration. Sensors that could monitor soot agglomeration and help to predict soot caused oil degradation are therefore of both environmental and economical interest in optimizing oil change intervals as well as protecting engines.

Acoustic wave sensors have been reported in applications of online monitoring of oil viscosity changes. However, studies have shown that soot agglomeration is a very complicated process. It depends not only on the absolute soot level, but also the state of the soot and the interaction between soot and oil. Poorly dispersed soot tends to agglomerate at much lower soot levels compared to the well dispersed soot. It is found that while viscosity increase is a good indication of the severe soot agglomeration, monitoring only the viscosity change is difficult to provide information of early soot agglomeration as oil degrades.

In the current study, a novel acoustic wave sensor was developed with a thickness shear mode (TSM) quartz resonator and a permittivity sensor which measured the capacitance change between the ground electrode of the TSM resonator and an additional electrode. The capacitance change was then used to modulate the series resonance frequency of a second quartz resonator. In this case, both the electrical and mechanical properties of the sample can be measured by the two frequency outputs of the sensor simultaneously. Two series of oil drain samples from different engine tests were obtained which were known to have well and poorly dispersed soot respectively. The samples were analyzed first with the laboratory instruments and then tested with the developed sensor. Both the viscosity and permittivity output of the sensor were recorded during the test.

The results showed that for the same level of well and poorly dispersed soot samples, viscosity increase measured by the TSM resonator was similar and fairly linear with the soot concentration. However, the permittivity output of the sensor showed a different response pattern to different soot samples. For example, it was observed that 1.5% poorly dispersed and 2.6% well dispersed soot samples caused similar response in the sensors permittivity output. This result agrees with the fact that soot particles are electrically charged when interact with oil additives. It suggests that different soot agglomeration stages might be differentiated through combining both the viscosity output and the permittivity output of the sensor. Owing to the advantage of simultaneously monitoring both the electrical and mechanical property changes of oil and the potentially low cost of the technology, the developed sensor is expected to find applications in both the laboratory study of soot caused oil thickening and online HDD oil condition monitoring.

FC2-E-6 511DE 11:45 a.m.

RESONANT PROPERTIES OF CERAMIC RESONATORS COATED WITH PLASMA POLYMERIZED STYRENE FILM

S. KUROSAWA*[1], H. AIZAWA[1,2], M. MATSUMOTO[1], J.-W. PARK[1,3], H. KAIDA[4], H. SAKAGUCHI[4], and J. INOUE[4], [1]National Institute of Advanced Industrial Science and Technology (AIST), [2]New Energy and Industrial Technology Development Organization (NEDO), [3]The University of Tokyo, [4]Murata Mfg. Co., Ltd.
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The ceramic resonators (CR) utilize the mechanical resonance of piezoelectric ceramics, typically of lead zirconate titanate (PZT), which provide various vibration modes depending on the resonance frequency. Recently, quartz crystal microbalance (QCM) techniques have found widely applications in chemical- and biosensor. The high-frequency QCM shows the high-mass sensitivity, but it has narrow working range for mass loading [1]. The CR is expected that it shows the similar property such as QCM, even though mass loading effect on CR is not investigated. In this study, the resonant properties of CR coated with plasma-polymerized styrene film (PPSF) as mass loading were examined and compared with that of QCM device. We tested three of 4 MHz CR (thickness shear mode) and two of 9 MHz QCM (thickness shear mode) as a reference for PPSF coated experimental under several plasma-polymerization conditions (100 W of RF power at 13.56 MHz, 100 Pa of monomer pressure, and every 5 min of polymerization times within 60 min and then 10 min until 270 min) [2]. The resonant properties and oscillation frequency of both resonators were measured by the impedance analyzer and universal counter. The shift of resonance frequency is proportional to polymerize time until 270 min (ΔFr (Hz) = 350 [polymerization time (min)] for CR, and ΔFr (Hz) = 2494 [polymerization time (min)] for QCM, respectively). The shift of resonance frequency for CR is 7.13ng/Hz and for oscillating frequency is 7.03 ng/Hz. PPSF coated CR was shown lower frequency shift than QCM for mass loading (about 0.14). The shift of resistance and Q-value for mass loading were not found on CR, but those were found on QCM. It implies that the low Q-value property of CR cause small resistance shift for mass loading. More detail experimental results and discussion will be reported at 2004 IEEE Conference.

References [1] S. Kurosawa, et al., Proc. 2001 IEEE IFCS (2001) 462-464. [2] S. Kurosawa, et al., Thin Solid Films, 374, 2 (2000) 262-267.

Session: U1-F

BLOOD FLOW II
Chair: H. Routh
Philips Research

U1-F-1 510AC 1:30 p.m.

QUANTITATIVE REAL-TIME BLOOD FLOW ESTIMATION WITH INTRAVASCULAR ULTRASOUND IN THE PRESENCE OF IN-PLANE FLOW

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Previously, we presented the flow estimation error introduced by in-plane flow using a slow-time FIR (finite impulse response) filter-bank method to quantitatively measure blood flow through the image plane of an intravascular ultrasound (IVUS) imaging system. There exists a monotonic relationship between blood flow velocity and the normalized second moment of the slow-time spectrum for flow orthogonal to the imaging plane of a side-looking catheter array. However, in the presence of an in-plane flow component, this monotonic relationship changes. The slow-time spectra shift and spread as the in-plane and out-of-plane components of the flow vary respectively. These two effects cause the normalized second moment to increase, resulting in flow overestimates. Applying appropriate tilts to slow-time signals, however, the slow-time spectrum shifts back to DC and the orthogonal estimation method can be used. We present a method to correct this overestimation and accurately estimate blood flow through the image plane in real-time. Initially, the flow angle at each point within the flow field is calculated. Knowing the flow angle at each particular location, a tilted slow-time signal is obtained and its normalized second moment computed. That value is then used to estimate the flow speed using the same monotonic relationship between the slow-time normalized second moment and flow speed observed for orthogonal flow. To accurately estimate flow angles, we use a modification of the filter-bank algorithm, applying slow-time filter coefficients in a tilted arrangement and studying the slow-time spectral energy as a function of tilt. An 8-point slow-time spectral estimate is used to compute the normalized second moment and thus correct the overestimation introduced by the in-plane component of the flow. Independent simulations show that for blood flowing at angles between $\pm 6^\circ$ and $\pm 15^\circ$ at a speed of 70cm/sec, flow would be overestimated by as much as 14.82% and 72.24% respectively using the direct filter-bank approach. However, this overestimation error can be corrected using the modified method presented here, reducing the estimation error by a factor of 28.9 and 34.64 for those angles respectively. This significant correction in the flow estimation makes this real-time method suitable to quantitatively measure flow in most IVUS application where the catheter's imaging plane is not usually orthogonal to the flow direction.

Work supported in part by the NIH (HL-47401)

U1-F-2 510AC 1:45 p.m.

ECG-TRIGGERED RETROSPECTIVE COLOUR FLOW IMAGING

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Colour flow imaging using high-frequency (>20MHz) ultrasound permits measurement of flow in small vessels, and increases the blood to tissue signal level relative to flow imaging at lower frequency. Using a high-frequency single-element transducer, colour flow imaging of blood velocity in small animals such as mice has been accomplished by sweeping the transducer over a region of interest [Kruse et al., IEEE T. Ultrason. Ferr., 45, 1437-1440, 1998]. This technique, however, has the following limitations: 1) tissue clutter artifacts are induced by the sweep velocity, limiting the ability to detect low flow rates; 2) pulse-trigger decorrelation artifacts occur when visualizing pulsatile flow if the rate of flow velocity change is large relative to the transducer sweep rate; 3) the accuracy of flow velocity estimation is limited because few RF lines per location are acquired. ECG-triggered retrospective colour flow imaging is a new approach designed to overcome these limitations and is especially well suited to flow analysis in rapidly moving structures such as the mouse heart. It uses a 40 MHz single-element transducer positioned at a number of lateral locations, in combination with an ECG trigger, to generate the colour flow mapping. ECG-triggered retrospective colour flow imaging eliminates sweep-velocity induced tissue clutter artifacts, pulse-trigger decorrelation artifacts when visualizing pulsatile flow, and it increases the number of RF lines acquired at each location, which in turn serves to increase the accuracy of blood velocity estimates. Swept-scan colour flow imaging and ECG-triggered retrospective colour flow imaging have been compared by imaging a phantom with a 5-Hz sinusoidally varying velocity profile, and by imaging blood flow in the mouse carotid artery. With the swept-scan technique, good estimation of velocities above 10 mm/s was achieved, while with the retrospective technique, good estimation of velocities above 2 mm/s was achieved. Pulse-trigger decorrelation artifacts were also examined for each technique. Multiple frames of the swept-scan colour flow mapping showed that the locations of velocity components were incoherently positioned within each frame. Multiple frames of the ECG-triggered retrospective colour flow mapping, however, showed a gradual velocity change between frames, with coherent positioning of the velocity estimates across each frame. Effective frame-rates of 1000 fps were achieved, with higher frame-rates possible, compared to 4 fps for the swept-scan method. The retrospective colour flow technique permits imaging of blood flow at high frame rates, with high spatial and temporal resolution, which is essential to the visualization and quantification of pulsatile flow in small animals with high heart rates.

CIHR, NCIC, ORDCF, VisualSonics Inc.

U1-F-3   510AC   2:00 p.m.

CLUTTER-FREE DOPPLER DETECTION OF SIGNED VELOCITY BASED ON LEGENDRE SERIES EXPANSION

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The clutter of stationary objects can suffer Doppler velocimetry in two ways. Firstly, its echo amplitude, which is normally orders of magnitude higher than that of the moving objects of interest, can simply exceed the input dynamic range of the velocimeter. Secondly, the cross-talk from the clutter into the velocity range of the moving object, which is small in ratio, can be large in amplitude compared to the signal of the moving object. The former is no longer crucial for a contemporary ultrasonic Doppler velocimeter using high-resolution analog-to-digital converters at the front end, but the latter is still a crucial problem especially for a Doppler velocimeter with small packet size such as that for color flow mapping. A widly-used technique to solve this problem is a moving-target-indicator (MTI) filter at the front end of the velocimeter to reduce the amplitude of the clutter. The polynomial regression filter has a steep low-frequency cut-off characteristic, coming from the fact that the low frequency component of the n-th order Legendre polynomial reduces in proportion to the n-th power of the frequency. However, its use as such an MTI filter is limited because it produces large phase errors up to $\pm\pi$ near the cut-off frequency when used in combination with an autocorrelation velocity estimator or a Fourier-transform velocity analyzer. A clutter-free velocimetry based on Legendre series expansion, which can fully utilize the unique low-frequency characteristic, has been conceived. A set of complex I/Q Doppler signals with a packet size of N+1 is expanded into a series of 0 to N-th Legendre polynomials. Among the obtained Legendre coefficients, those lower than a certain order number, M, are abandoned to eliminate the clutter. Complex Legendre coefficients, C($\pm$n), are then formed by linearly combining the remained even and odd order Legendre coefficients of order numbers different by one, L(n-1) and L(n), as C($\pm$n) = L(n-1) $\pm$ j L(n) and C($\pm$n) = L(n) $\pm$ j L(n-1) for an odd and even number, n, respectively, where j is the basic imaginary unit. The spectrum of the signed velocity can thereby be obtained from the absolute magnitudes of C($\pm$n) (M $\leq$ n $\leq$ N) in a similar way as the velocity spectrum is obtained from the absolute magnitudes of complex Fourier coefficients in Fourier-transform Doppler velocimetry. The efficacy of the proposed velocimetry was tested in color flow mapping with a prototype scanner. The velocimeter demonstrated tissue-motion-free detection of blood flow in portal veins and coronary arteries at a significantly higher sensitivity than a conventional autocorrelation velocimeter with an MTI filter.

Authors thank to Mr. Tsuyoshi Mitake for his support in the implementation of this method to a prototype scanner.

U1-F-4 510AC 2:15 p.m.

REAL-TIME SIMULTANEOUS ASSESSMENT OF WALL DISTENSION AND WALL SHEAR RATE IN CAROTID ARTERIES

G. BAMBI, T. MORGANTI, S. RICCI, F. GUIDI, and P. TORTOLI*, University of Florence.

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A novel ultrasound (US) system has been developed to make possible the real-time assessment of both blood velocity profile and wall displacements in human arteries. The system consists of a modified US machine and a custom PC add-on board based on a high-speed digital signal processor (DSP board). The US machine is a Megas system (Esaote SpA, Florence, Italy) whose software has been customized to make possible the simultaneous selection of two independent M-lines in the B-mode display. With respect to the artery of interest, such lines must be set at optimal angles for wall detection and blood velocity detection, respectively. When switched into M-mode, the system fires the elements of the linear array probe in such a way that US bursts are alternatively transmitted into one of the two selected M-line directions. Demodulated quadrature echo signals backscattered along both such lines are sent to the DSP board, which allows the corresponding blood velocity profile and wall displacement (or distension) waveforms to be displayed in real-time on the PC screen. Wall displacements are detected through the modified 2D-autocorrelation algorithm, while the blood velocity profile is estimated through spectral analysis. From this profile, the wall shear rate (WSR), i.e. the spatial velocity gradient close to the blood-wall interface, is extracted. The system has been preliminarily tested in the common carotid arteries of 10 young healthy volunteers (age 26-39). In each case, the most appropriate M-line directions, approximately 2 cm below the bifurcation, were rapidly found by observing in real-time both the velocity profile and the near and far wall displacement waveforms. In each subject, the diameter distension was measured over a minimum of 3 beats. The average distension was 490 μm (range 420-690 μm), with a typical standard deviation within measurement epochs of 30 μm. The relative distension ranged from 6,3% to 10,2%. The asymmetry observed in the velocity profiles, suggested to separately measuring the WSR in correspondence of the near (NWSR) and far (FWSR) walls. The following average values were obtained: NWSR - peak: 1159 s-1, - min: 294 s-1; FWSR - peak: 1045 s-1, - min: 276 s-1. The typical standard deviation within measurement epochs was 39 s-1 for the peak values and 9 s-1 for the minimum values. Several examples, simultaneously showing the dynamic variation of WSR and wall distension during the cardiac cycle, will be presented. Such results propose the US system as a promising tool toward the goal of assessing the relation between the dynamic properties of the wall and the shear stress associated to different flow patterns.

This work was supported by the Italian Ministry of Education, University and Research (MIUR-COFIN 2002)

U1-F-5   510AC   2:30 p.m.

COMPLEX BLIND SOURCE SEPARATION FOR ADAPTIVE TIME DOMAIN-BASED PHASE FILTERING

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Complex Blind Source Separation (CBSS) is presented for adaptive phase filtering in the time domain. Adaptive phase filtering is pertinent to many ultrasonic imaging applications, including noise reduction, clutter rejection, elastographic imaging, and Acoustic Radiation Force Impulse (ARFI) imaging. In application to ARFI imaging, CBSS phase filtering is particularly useful for segregating physiological motion from elastic tissue and fluid responses to applied radiation force. We demonstrate the utility of CBSS phase filtering using examples of ARFI-induced blood streaming in the peripheral vasculature.

Hypothesis: In the context of physiological motion, CBSS phase filtering is effective for separating vessel wall, elastic tissue, and blood fluid responses to acoustic radiation force in the peripheral vasculature. *Methods*: Raw RF data was collected using ARFI M-mode imaging sequences from the jugular vein of a healthy, male volunteer performing the Vasalva maneuver. The imaginary component of the RF data was computed *via* the Hilbert transform; the complex data was arranged into ensembles of 7-50 transmit-receive (TXRX) beams for CBSS phase filtering. After filtering, phase-shift estimation was employed using ensembles of 2-10 TXRX beams to measure radiation force-induced blood streaming. Similar RF data was acquired without the application of radiation force, phase filtered with CBSS, and processed with phase-shift estimation for axial velocity measurement. *Results*: CBSS basis functions spanning elastic tissue signal subspaces show phase inflections of 0.02°–0.17°, which are indicative of the corresponding tissue's displace-and-recover response to radiation force. Complex CBSS basis functions spanning the blood signal subspace exhibit phase angles that consistently increase over time of ensemble acquisition to 10°–30°, which signify sustained blood displacement away from the transducer. CBSS basis functions computed from data acquired with no applied radiation force show no significant phase inflection and no sustained phase change over the ensemble acquisition. Following CBSS phase filtering, velocity estimation reveals radiation force-induced blood streaming. The induced streaming velocities peak in the range of 0.3-16 cm/s at the focus location inside the vessel lumen and diminish to 0.1-4 cm/s at the distal vessel wall. No significant axial velocity component is measured in the data collected with no applied radiation force. *Conclusion*: These results demonstrate that CBSS is efficacious for adaptive time domain-based complex phase filtering. The temporal directionality of the complex signal spanned by a CBSS basis function is encoded in the phase signature of the basis function's time projection. Therefore, the diverse displacement directions of physiological motion and of elastic tissue versus fluid in response to radiation force yields sufficient CBSS blood signal isolation for measurement of ARFI-induced blood streaming.

This work was supported by NIH grant R01-HL-50104. We thank Siemens Medical Solutions, Ultrasound Division, for their hardware and in kind support.

U1-F-6 510AC 2:45 p.m.

REAL-TIME BLOOD MOTION IMAGING - A 2D BLOOD FLOW VISUALIZATION TECHNIQUE

L. LØVSTAKKEN*[1], S. BJÆRUM[2], D. MARTENS[2], and H. TORP[1], [1]Department of Circulation and Medical Imaging, Norwegian University of Science and Technology, [2]GE Vingmed Ultrasound AS.
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The conventional methods of color flow imaging (CFI) utilize the Doppler frequency shift to distinguish between blood and tissue signal, and is only sensitive to the velocity component along the ultrasound beam. Blood Motion Imaging (BMI) is a new method for visualizing blood flow with ultrasound, capable of displaying both axial and lateral flow direction. BMI is based on preserving and enhancing the speckle pattern originating from blood flow scatterers, similar to the B-flow technique (GE Medical Systems). However, the speckle image frames are acquired at much higher frame rates, and slow motion replay makes it possible to visually track the blood movement from frame to frame. A real-time implementation of BMI has been developed to work in a GE Vingmed Vivid 7 ultrasound scanner, and its performance is under evaluation. Input data was complex demodulated data (IQ-data) obtained using packet acquisition as in conventional CFI, and interleaving techniques were used to be able to image a larger spatial region almost simultaneously. Several speckle image frames were calculated and displayed for each CFI frame. This was essential for proper perception of movement due to the rapid decorrelation of the blood flow speckle pattern. BMI was combined with conventional CFI and Power Doppler techniques by modulating the color overlay images with the speckle pattern images. To allow the human eye to follow the speckle pattern corresponding to the rapid blood movement, the pattern has to be shown in slow motion. This was possible in real-time using packet acquisition and interleaving techniques. The speckle pattern images within an interleave group are acquired at the PRF (pulse repetition frequency) of the imaging system, but are displayed at a lower frame rate (FRS), over the time it takes to record the entire CFI frame. This means that the speckle pattern display has been slowed down by a factor of PRF / FRS. Frame interpolation was used for the color and tissue images to ensure smooth display in-between frames. The slow motion factor can thus be controlled by the PRF, and an investigation was carried out using the GE M12L 12 MHz linear probe to find suitable slow motion factors in vascular applications based on different blood flow velocities and frame rates. When for example imaging a healthy carotid artery, velocities of up to 60-100 cm/s were measured using PW-Doppler. The PRF was varied from 0.35-12 kHz, and results showed in this case that a PRF of 1-2 kHz was appropriate. With a packet size of 10, a high-pass FIR filter of order 4 (6 speckle images), and a frame rate of 11, the slow motion factor ranges from 9 to 18. In other words, the blood flow scatterers are moving 9 to 18 times as fast as they appear on screen. In conclusion, the real-time BMI modality has shown its usefulness in indicating blood flow direction, both axial and lateral. The speckle movement also made it easier to separate true

blood flow from wall motion artefacts. Results from preliminary investigations regarding its clinical usefulness in vascular and cardiac applications will follow in the near future.

Session: U2-F

CELLS AND CARDIAC
Chair: M. Sherar
University of Toronto

U2-F-1 510BD 1:30 p.m.

TOWARDS UNDERSTANDING THE NATURE OF HIGH FREQUENCY BACKSCATTER FROM CELLS AND TISSUES: AN INVESTIGATION OF BACKSCATTER POWER SPECTRA FROM DIFFERENT CONCENTRATIONS OF CELLS OF DIFFERENT SIZES

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During cell death a series of structural changes occur within the cell. We have shown that cell ensembles and tissues undergoing structural changes associated with various cell death pathways can be detected using high-frequency ultrasound. In our effort to better understand the nature of backscatter from collections of cells (which emulate tissues), we have collected raw RF backscatter data from cells of two different sizes in solutions for a series of concentrations or in pellet form.

Human acute myeloid leukemia cells (AML-5, 10-15μm in diameter) and transformed prostate cells (PC-3, 20-30μm in diameter) were imaged either in suspension or in pellet form. Images and radiofreqeuncy data were acquired using a VS40B ultrasound instrument (VisualSonics Inc., Toronto, Ont) and 20MHz, 30MHz and 40MHz transducers with -6dB bandwidths approaching 100%. The cells were either imaged in degassed phosphate buffered solution in which their volumetric fraction increased from 0.0025% to 2%, or in pellet form by using a swinging bucket centrifuge.

It was found that the backscatter power (as measured by the mid-band fit) increased by 3 dB for both cell types in dilute solutions for which the volumetric fraction was doubled up to a specific point (which was dependent on cell size). The backscatter power for the two cell types for the same volumetric fraction was in general comparable. In pellet form however the backscatter power from the prostate cell pellets was 12-14dB greater than the AML cell pellets. A comparison of the spectral slopes strongly suggests a change in the scattering source contributions when the cells are in pellets: the spectral slope was negative for all concentratopns of prostate cells imaged at 40MHz, but positive when

measured in pellets. This is consistent with an increased contribution to the backscatter of smaller sized scatterers (such as the cell nucleus) that manifests itself only when the cells are in pellets but not in solution. These data will be compared to theoretical predictions and their significance discussed.
The authors would like to acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada, the Whitaker Foundation, the Canadian Institutes of Health Research and the Canada Foundation for Innovation.

U2-F-2 510BD 1:45 p.m.

EVALUATION OF THE LAYERED STRUCTURE OF AORTIC VALVE CUSPS USING HIGH-FREQUENCY ULTRASOUND

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High-frequency ultrasound techniques have been developed for estimating dimensions of histological layers in heart valve cusp specimens. Ultrasound images of fresh, whole porcine aortic valve cusps were acquired within 12x8x8 mm^3 volumes using a VisualSonics Model VS40 micro-imaging system operating at a 40 MHz center frequency. The system employed a mechanically scanned, single-element circular transducer that provided 40x70 μm^2 in-plane spatial resolution at the 6 mm focal depth. Specimens were centered within the depth of focus during imaging. Two image volumes were obtained from each of six left coronary cusps. One image volume was acquired after the specimen had been submerged in room temperature coronary perfusion solution (CPS) for 100 minutes, then a second volume was acquired after submersion in distilled water for 100 minutes. Ten B-mode images intersecting a 3.3-mm wide region in the central portion of each specimen were selected for analysis. Nonlinear median and morphological filters were applied to reduce speckle variance and increase the contrast between tissue layers. A two-dimensional discrete dynamic contour (DDC) deformable model, which describes a contour as a set of vertices connected by edges, was implemented to identify the boundaries of the fibrosa, spongiosa, and ventricularis layers of the cusps. In the DDC algorithm, the user defines a preliminary contour by selecting three or four landmark points near each tissue boundary. The model deforms the contour to obtain a detected boundary by minimizing an energy function computed from the local curvature of the contour and the gradient of the image gray level. Layer cross-sectional areas enclosed by the detected boundaries were calculated as well as the fraction of the total area of the cusp occupied by each layer. The significance of variations in the cross-sectional areas and area fractions of the tissue layers in CPS and water were evaluated using paired t tests. The total cross-sectional area increased from 5.86 ± 1.37 mm^2 (mean $\pm$ standard deviation) in CPS to 9.22 ± 2.97 mm^2 in water. The areas of the fibrosa, spongiosa, and ventricularis each increased by statistically

significant ($p < 0.05$) amounts when submerged in water. The spongiosa underwent the largest dilation, from 1.76 ± 0.57 mm^2 in CPS to 3.31 ± 1.50 mm^2 in water, which corresponded to an increase in area fraction from $30 \pm 6\%$ to $35 \pm 5\%$. This change was accompanied by a decrease in the area fraction of the fibrosa from $35 \pm 4\%$ to $30 \pm 6\%$. The mean area fraction of the ventricularis remained 35% in both fluids. The changes in layer dimensions are attributed primarily to absorption of water by the spongiosa. These results demonstrate that high-frequency ultrasound is an effective method for characterizing the structure of valve cusps. Such measurements are essential for estimation of mechanical properties of natural and bioprosthetic valve tissues.
I would like to thank my advisor, Dr. Lacefield for his guidance and advice to my paper. I would aslo like to acknowledge Joy Dunmore-Buyze for preparing the tissue specimens and her very helpful proposals.

U2-F-3 510BD 2:00 p.m.

THE RESPONSE OF REGIONAL INTEGRATED BACKSCATTER LEVELS AND REGIONAL STRAIN TO INOTROPIC STIMULATION AND ACUTE ISCHEMIA

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Introduction: Integrated backscatter (IB) and its cyclic variation (CV) are echocardiographic parameters often used for myocardial tissue characterization. To date, several hypotheses on the origin of CV have been proposed. One hypothesis, is that IB is directly related to regional scatterer density while its CV could be induced by scatterer rearrangement due to local myocardial strain. The purpose of this study was to further test this hypothesis by simultaneously recording the response of the cyclic changes in IB and the response of myocardial strain to alterations in regional deformation induced by inotropic stimulation and acute ischemia.

Methods: In twenty closed-chest pigs, radio frequency (RF) M-mode data were acquired from a parasternal transducer position using a Toshiba PowerVision 6000 at baseline (BL). In ten animals, acute myocardial ischemia was then induced by inflating a PTCA balloon in the left circumflex coronary artery for 20 seconds. RF data from the ischemic region of the posterior wall were taken during and immediately following the ischemic episode. In the remaining ten animals, data sets were acquired during incremental dosis of dobutamine infusion (5-10-15 and 20 microg/kg/min). For all data sets, myocardial velocities were estimated using a cross-correlation method. Subsequently, the posterior wall was manually segmented on the reconstructed M-mode images avoiding specular reflections occurring at the endo- and epicardial borders. The instantaneous strain rate was then calculated as the slope of a linear fit through all velocity estimates within these borders, while regional radial strain (S) was calculated as the temporal integration of the strain rate curve. Finally, IB was calculated as the average squared RF amplitude within the myocardial borders. For all stages, the radial strain and the IB curves were averaged over all animals and the mean negative radial strain (NRS) was plotted on top of the mean IB curve. Finally, a quantitative analysis was done by comparing the response of CV and maximal S values between stages using ANOVA.

Results: At baseline, NRS and IB paralleled and were minimal at end-systole. During acute ischemia, post-systolic thickening was observed which resulting in a time-shift of both the NRS and the IB trace. At reperfusion, both the NRS and IB patterns returned to baseline with a minimum at end-systole. The response of CV to dobutamine parallelled the strain response with an initial increase followed by a subsequent decrease at higher levels ($p<0.05$; see table).

Conclusions: Not only did CV show a similar response to dobutamine as Smax but also did ischemia result in a similar time-shift of both curves. These observations are in concordance with the IB-strain hypothesis.

	Baseline	5	10	15	20
CV (db)	9.07±1.98	9.41±2.53	9.54±2.47	10.51±1.53	9.34±2.54
Smax (%)	66±18	74±18	77±23	82±27	70±23

This work was supported by the Fund for Scientific Research – Flanders (FWO-Vlaanderen)

U2-F-4 510BD 2:15 p.m.

SILICON BASED ULTRASONIC MICROPROBES FOR CARDIAC SIGNAL RECORDING

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Cellular mapping of physioelectrical activities in cardiac tissues is highly desirable for the study of mechanism and development of cardiac arrhythmias. Important information can be obtained for prediction and prevention of arrhythmias, especially ventricular arrhythmiaone of the leading causes of mortality in the United States. In this paper we present ultrasonically actuated silicon microprobes to reduce insertion force and minimize tissue damage. Probe tips with multiple recording sites were successfully inserted into canine heart tissue and cardiac signals in two dimensions were recorded. To our knowledge, this is the first ever in-vitro cardiac signal recordings by micromachined silicon electrode array at this scale. Silicon based microprobes have been reported for electrical activity recording in neural tissues (Wise, 1970). They provide high spatial resolution, reduced tissue damage, and ease to integrate with microelectronics. However, these thin probes do not have enough rigidity to go in the much denser and harder cardiac tissues and easily buckle and break. Thicker probes provide greater rigidity but the increased probe size causes more damage to the tissue being investigated

and may affect their physioelectrical activities. Integrating ultrasonic actuator with silicon microprobe preserves all the advantages of microprobes while reduces the force required to penetrate and cut cardiac tissues, enabling use of thinner and less invasive microprobes. The device consisted of a silicon ultrasonic horn actuator [Lal, 1996] with a longitudinal $\lambda/2$ resonance at 75kHz. Two 100μm5mm tips were defined at the small end of the horn. The thickness of the tips (70μm) was defined by DRIE on front side and the probe is released by wet etching from the backside. A dummy probe without tip was bonded to the probe for symmetry and reducing bending mode of the tips. PZT4 plates were bonded to the device for ultrasonic driving. The device is clamped to a customized PC board at resonance node. The PC board also provides metal pads for electrical connection from the Au electrodes on the probe through wire bonding. Penetration and cutting force measurements show that both forces reduced as ultrasonic driving voltage increased. Cardiac signal recording was conducted on in-vitro canine heart infused with Diacetylmonoxime to reduce the muscle contractions but still allow normal electrical activities. The probes successfully penetrated the tissue at 6 10Vpp driving voltage and both spontaneous fibrillation and externally stimulated rhythmic signals were recorded with qualities comparable to those obtained by conventional metal wire probe. Signals from different recording sites were compared and phase/morphology difference can be used for later reconstruction of physioelectrical wave propagation in the heart. Furthermore, signals recorded with/without the presence of ultrasound showed little difference other than some easily filtered high frequency noise, indicating the low voltage ultrasonic driving posed no significant modification on heart cells electrical activities.

U2-F-5 510BD 2:30 p.m.
(Invited)

MECHANICAL PROPERTIES OF SINGLE CELLS—MEASUREMENT POSSIBILITIES USING TIME RESOLVED SCANNING ACOUSTIC MICROSCOPY

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The coupling between biochemical and mechanical processes inside cells, particularly cardiac cells, is of fundamental interest in biology and medicine. To have a clear understanding of the electromechanical processes during cell motility and cell contraction, the viscoelastic properties of biological cells need to be measured. The technique used for measuring viscoelastic properties of the cells should also be a dynamical one, because a relatively fast variation of the viscoelastic properties must be detected. Several techniques are available for mechanical characterization of the biological cells: optical tweezers, atomic force microscopy or with integrating techniques, such as magnetic beat displacement and microindentation. None of these techniques allow a mapping of the variation of the viscoelastic properties of the whole cell with micrometer resolution.

Scanning acoustic microscopy (SAM) allows the study of elastic properties of biological cells. However, conventional SAM is too slow to trace fast variations of the cardiac cells during vibrations, and low frequency time-resolved SAM used in biology and medicine does not provide enough resolution to study the elasticity of a single cell. In this report we present the primary results obtained by the time-resolved, high-frequency acoustic microscope on quantitative measurements of the local mechanical properties of single cultured cells in vivo. A Fourier spectrum approach is applied to determine dispersion of the sound velocity and attenuation inside the cells. The potential of our approach is discussed through the investigation of the contraction apparatus in cardiac muscle cells.

Session: U3-F

TRANSDUCER MODELING
Chair: R. Lerch
University of Erlanger

U3-F-1 511AB 1:30 p.m.

THE EFFECT OF PILLAR MISALIGNMENT ON THE UNDERWATER PERFORMANCE OF HIGH FREQUENCY MULTILAYER 1-3 PIEZOCOMPOSITE TRANSDUCERS WITH ACOUSTIC MATCHING AND BACKING LAYERS

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The use of multilayer piezoelectric ceramics in ultrasonic transducers is common and multilayer 2-2 connectivity piezocomposites have also been reported in the literature. However, multilayer piezocomposite transducers with 1-3 connectivity have not yet been fully documented and the effects of issues such as pillar misalignment still have to be clarified. In previous work, we described a qualitative analysis based on a simply 2-layer piezocomposite element operating in air without any ancillary acoustic components such as matching and backing layers. Such simple elements are useful to highlight undesirable effects and we showed that pillar misalignment led to extraneous modes through twisting of the pillars. In practice, however, these elements would include the ancillary components, and the effects of acoustic loading must also be taken into account. Therefore, we have now extended our previous work to quantify the influence of pillar misalignment for a complete transducer operating in a water environment, including matching and backing layers. To evaluate the performance of the device, our analysis now includes measurements of the transmit-receive function more closely related to the performance of the device in practical situations, as well as previous electrical impedance data. We present results from full 3D finite

element analysis, incorporating unidirectional and bidirectional pillar misalignments from 0% to more than 25%, validated with data from prototype two-layer 1-3 piezocomposite transducers tested in air and underwater at frequencies between 2 and 4 MHz, and comment on the difference in degree of acceptable pillar misalignment compared with the previous, simpler elements.
Jean-Franois Saillant is supported by Imasonic and French national funding. Sandy Cochran is supported by a UK EPSRC Advanced Fellowship.

U3-F-2 511AB 1:45 p.m.

APPLICATION OF OPTIMIZATION TECHNIQUES TO FINITE ELEMENT ANALYSIS OF PIEZOELECTRIC DEVICES

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Finite Element Analysis (FEA) has become an integral part of research and design of piezoelectric devices for application in many fields including biomedical imaging, therapeutics, non-destructive testing and SONAR. Continuing improvements in both software and hardware capabilities can now allow for models on a scale comparable to typical piezoelectric devices, while increasing device complexity results in clear inadequacies of simpler models. A typical FEA design cycle will consist of an initial design to be simulated, the results of which will be analysed by the engineer who then adapts the model, for numerous iterations. When all specifications are met, the device can move to the prototyping stage.

While for systems with limited numbers of variables this can be a straightforward procedure, more complex systems and designs requiring high performance in multiple measurable quantities such as impedance, bandwidth and sensitivity, can prove somewhat more challenging. In such cases it is possible that the use of optimization techniques will yield superior results. However, both the optimization method used, and the optimization criteria chosen can be critical to the success or failure of the design effort. Replacing expensive engineer hours with cheaper CPU hours can result in better devices and free the engineer for more productive tasks.

This paper details optimization and its application to FEA of piezoelectric devices. The mathematical optimization methods and their benefits will be discussed, and their use in the simulation of several ultrasonic devices using the FE package PZFlex will be demonstrated. Choice of optimization parameters and goals will be discussed, and suggestions for when such techniques are appropriate will be made.

U3-F-3 511AB 2:00 p.m.

INVERSE CALCULATION METHOD FOR PIEZOCOMPOSITE MATERIALS CHARACTERISATION

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Due to their high permittivity and their low acoustic impedance, the piezocomposite materials are increasingly used for ultrasound imaging probes for medical or N.D.T. applications. The determination of elastic, dielectric and piezoelectric homogenised constants needs to be considered for the optimisation and the performance evaluation of the piezocomposite. All parameters are indeed required for the modelling of piezocomposite devices by finite element models or analytical approaches. Inverse problem method enables the determination of parameters by solving data fitting in the least square sense. The full determination of effective electro-acoustic tensor [c, e, ϵ] is then performed from displacement field measurement obtained in air compared to the simulated one. For the modelling of the plate, the piezocomposite is considered as a homogeneous medium with the same symmetry class than the ceramic phase, 6mm. The mechanical response is calculated using well known analytical approach where the source is introduced from the electrical boundary conditions of the plate. Mechanical losses are taken into account. Calculations are performed in the spatial frequency (k) and time frequency (ω) domain: the ω-k domain. The tested piezocomposite material is manufactured under the form of a classical array without backing and matching layers. Mechanical displacements are produced by pulsed electrical excitation source. The experimental ω-k diagram of the displacement is obtained from the 2D Fourier transform of the x-t diagram of the measured displacement. The sensitivity of the ω-k response of the displacement to each parameter is studied. Results are then used to define, for each material property, the optimal ω-k area which brings out the most information. The numerical inversion scheme used to reconstruct the material properties from the ω-k diagram of the displacement is described and first validated from theoretical displacement fields. We show that the regression procedure is successful, while the initial values of material properties stay ten percent around the real values. Experimental results are presented and discussed for four different configurations using piezocomposite structures with different piezoceramics and filler materials type. Using these results, an acoustic performance evaluation for the different piezocomposite configurations will be realized.

U3-F-4 511AB 2:15 p.m.

MODELING OF THE TEMPERATURE INCREASE IN ULTRASONIC TRANSDUCERS

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With the development of therapeutic ultrasound, where high power ultrasound in pseudo continuous regime is applied to the patient, it has become necessary to model and determine the temperature behavior of the probe. Indeed, thermal increase of the transducer can cause damage to the matching layers or to the piezoelectric element itself, and eventually lead to the destruction of the probe. The aim of this work is to develop a model that can predict the temperature rise of an ultrasonic transducer in the steady state. The temperature increase in a transducer is mainly related to the attenuation of the acoustic waves propagating into its components. The temperature profile is non uniform and it can be calculated from thermal properties of constitutive materials of the transducer and from energy conservation law. Its amplitude depends on the acoustic power dissipated in each part of the transducer. Here, analytical expressions of the dissipated powers are derived from the one-dimensional Mason model in which mechanical and dielectric losses are included. The dissipation terms, which correspond to acoustical energy converted into heat, are normalization factors of the thermal source profile in the transducer. Coupled with thermal diffusion equation, these results allow to calculate the two dimensional temperature field in an axisymmetric ultrasonic transducer in electrical harmonic or pulse regime, but in thermal steady state. In particular, simulations of the temperature field of a piezocomposite-based single-element transducer dedicated to ultrasonic surgery are presented and discussed for different conditions of use. Two soft PZT-based transducers with a diameter of 20 mm operating respectively at 1 MHz and 4 MHz were fabricated to validate the theoretical results. First, dissipated power as a function of frequency for a transducer operating in air is determined from transient temperature measurements. Then, steady state temperature measurements are performed along the edge of the transducer, from the front layer to the backing. These measurements show a good agreement with theoretical predictions. The results show that an increase of 10 °C inside the transducer can be reached for 0.1 W electrical power excitation. Furthermore, it is shown that diffraction correction inside the backing has to be taken into account to obtain agreement between theory and experiment. In conclusion, this model is expected to be a useful tool for ultrasonic transducer and system designers, particularly when high power levels are used. It can also be applied to diagnostic systems, for which the temperature of the probe front face must be controlled for the comfort of patients.

U3-F-5 511AB 2:30 p.m.

A METHOD FOR THE MEASUREMENT OF THE K FACTOR IN LOSSY PIEZOELECTRIC MATERIALS

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The most important property of a piezoelectric material for practical applications is its ability to generate and to detect stress waves, i.e. to convert electrical energy into mechanical energy and vice versa. As it is well known, the electromechanical coupling factor k fully characterize this energy conversion. In previous works we demonstrated that, like in static conditions, it is possible to define the k factor in dynamic situations (k_w) as ratio of energies: for a piezoelectric element in free oscillation, mechanically and electrically insulated, k_w was defined as the square root of the ratio of the converted electrical energy to the total energy involved in a transformation cycle, i.e. the kinetic energy. We also showed that k_w is proportional to the static material coupling factor (k_m) of the considered 1-D vibration mode and the proportionality coefficient does not depend on the mode. We extended this definition to lossy materials ($\mathbf{k}_w$), obtaining the same result, i.e. $\mathbf{k}_w$ is a complex quantity proportional to the complex static material coupling factor ($\mathbf{k}_m$); the proportionality coefficient is the same of the case without losses and does not depend on the vibration mode. In this paper we describe a method to measure the k factor of lossy materials, based on the $\mathbf{k}_w$ definition. By using the 1-D model of a piezoelectric element vibrating in the length longitudinal mode, we show that $\mathbf{k}_w$ can be evaluated by measuring the velocity $\mathbf{u}$ on the element external surfaces orthogonal to the wave propagation direction, and the voltage $\mathbf{V}$ across the element. The velocity and the voltage must be measured by supplying the piezoceramic with a current generator, working at the element electrical antiresonance frequency $\mathbf{f}_p$. As several authors proved, for lossy materials, $\mathbf{f}_p$ is a complex quantity and therefore what is the working frequency of the supplying generator? In order to answer to this question, we used the 1-D model of the length extensional mode to compute the velocity $\mathbf{u}$ and the voltage $\mathbf{V}$ at the frequencies $f_r = \mathrm{Re}[\mathbf{f}_p]$ and $f_a = \mathrm{Abs}[\mathbf{f}_p]$ and therefore we computed $\mathbf{k}_w$ at these frequencies, varying the mechanical (Q_m) ad electrical ($tan\ \delta$) losses of the material. The $\mathbf{k}_w$ values ($\mathbf{k}_{wm}$) computed at the two frequencies are only slightly different and therefore both can be used to measure this parameter. In order to test the proposed measurement method, we computed $\mathbf{k}_{wm}$ varying Q_m and $tan\ \delta$; we found that, for values of $Q_m \geq 10$ and for any $tan\ \delta$, $\mathbf{k}_{wm}$ is practically equal to $\mathbf{k}_w$, while for $Q_m < 10$ the discrepancies between $\mathbf{k}_{wm}$ and $\mathbf{k}_w$ cannot be neglected. The inaccuracy of the measurement for very high mechanical losses is due to the dependence of $\mathbf{f}_p$ on these losses, while the measurement is independent on the dielectric losses because $\mathbf{f}_p$ is independent on $tan\ \delta$. In any case the measurement is inaccurate only when $Q_m < 10$ and therefore for mechanical losses that are not shown by any real piezoelectric material.

U3-F-6 511AB 2:45 p.m.

FEA AND EXPERIMENTAL CHARACTERIZATION OF LANGEVIN TRANSDUCERS WITH COMPARABLE LONGITUDINAL AND LATERAL DIMENSIONS

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The Langevin transducer is generally designed to vibrate along its length in pure thickness–extensional mode. This vibration mode can be excited by realizing the lateral dimensions less than a quarter of the longitudinal wavelength and can be adequately analyzed with the Mason one-dimensional theory. In order to extend the analysis to transducers with any length to diameter ratios, analysis tools able to describe also the radial modes and the coupling between radial and thickness modes are required.

In this work a 3–D finite element analysis of the Langevin transducer has been carried out in order to evaluate potential performances and suitability to applications of transducers with diameters comparable to or greater than the total length. In order to validate the result obtained by simulations, several transducers with different aspect ratios have been constructed and experimentally characterized.

The analyzed structure is composed of two piezoceramic disks sandwiched between two identical steel cylinder-shaped masses. The frequency spectrum, i.e., the map of the resonance frequencies, has been computed by varying the aspect ratio G between mass thickness and diameter, and has been compared with that obtained by measurements carried out on several physical samples. The comparison between computed and experimental results has shown that the model is able to predict in a fairly good way the frequency behavior of the transducer for any aspect ratio, even if slightly higher resonance frequency values for samples with lateral dimensions comparable to greater than the total length than those experimentally achieved are observed.

In order to investigate the dependence of transducer's performances on its aspect ratio, several transducers, all designed to work at the same frequency, have been simulated. For each transducer the product γ between the mean displacement and the area of the radiating surface has been computed. Results have shown that the maximum γ value is obtained for G=0,6 i.e. for a transducer with comparable longitudinal and lateral dimension. In order to experimentally validate this result two Langevin transducers with G=0.6 and G=1.4, respectively, have been designed to work at the same frequency (60 Khz). The map of the displacement of their radiating surfaces have been mesaured, by means of an interferometer technique, by driving the two transducers with the same voltage (60 V peak to peak). Even if the transducer with G=1.4 has shown an higher mean displacement than that with G=0.6, due to its higher radianting surface the latter has shown a γ value that is 85 % greater than that obtained with the former. Possible applications where to exploit such a transducer configuration are pointed out and discussed.

Session: U4-F

PHYSICAL ACOUSTICS II

Chair: H. Engan

Norwegian University of Science and Technology

U4-F-1 513AB 1:30 p.m.

GUIDING, BENDING AND FILTERING OF ACOUSTIC WAVES IN A TWO DIMENSIONAL PHONONIC BAND GAP MATERIALS

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A great deal of research effort is currently being devoted to the study of acoustic or elastic waves propagation in periodically structured materials, such as the so-called phononic crystals. They are made of two- or three dimensional periodic repetitions of different solids or fluids which exhibit absolute stop bands in the transmission spectrum of acoustic waves. The location and width of these band gaps result from a large contrast in the value of elastic constants and/or mass density of the constitutive materials. In this work, we demonstrate experimentally that the guiding and the bending of acoustic waves can be achieved in a tight space in highly confined waveguides constructed by removing rods from a perfect two-dimensional phononic crystal. Also, we show that the interaction between guided and localized modes affects the waveguide transmission by introducing a zero transmission at specific frequency of the defect. In particular, this interaction allows introducing a secondary bandgap within the full bandgap of the initial structure. In our experiments, the ultrasonic crystal is an artificial crystal composed of a two-dimensional periodic array of an acoustic scattering material (steel) immersed in water. The choice of steel and water as the composite materials is based on the strong contrast in their densities and elastic constants. The square lattice constant is 3 mm and the scatterers diameter is 2.5 mm, resulting in a filling fraction of 55 %. For this arrangement, there is a full band-gap extending between 250 kHz and 325 kHz in which acoustic waves are not allowed to propagate in the crystal. We first consider straight and bended waveguides, simply built by removing one or several rows of cylinders along the propagation direction. We measure a full transmission of acoustic waves for certain frequencies within the phononic crystal stop-band, which indicates that the wave is well confined within the waveguide and is guided with weak losses. Isolated or periodic stubs are then grafted along the waveguide. The localized stub modes interfere with the propagating waveguide modes and cancel the transmission at definite frequencies. These properties could be used to design novel ultrasonic waveguides and filters.

U4-F-2 513AB 1:45 p.m.

MEASURING PERMEABILITY OF POROUS MATERIALS VIA ACOUSTIC TRANSMITTED WAVES

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A low frequency acoustic transmission method is proposed for measuring permeability of porous materials having a rigid frame. Permeability is an important parameter required for the acoustical characterization of air-saturated porous materials like plastic foams and fibrous or granular materials. The proposed method is based on a temporal model of the direct and inverse scattering problem for the diffusion of transient low frequency waves in a homogeneous isotropic slab of porous material having a rigid frame. This time domain model of wave propagation was initially introduced by the authors (Z.E.A Fellah and C. Depollier, J. Acoust. Soc. Am., Vol. 107, 683 (2000)). The viscous losses of the medium are described by the model devised by Johnson et al. (D.L. Johnson, J. Koplik, R. Dashen, J. Fluid. Mech, Vol. 176, 379 (1987)). Working in the temporal domain, we derive reflection and transmission scattering operators for a slab of porous material from the responses of the medium to an incident acoustic pulse. The permeability is then obtained from the expressions of these operators. We will present experimental and numerical validation results of this method. This method has the advantage of being simple, rapid and efficient.

U4-F-3 513AB 2:00 p.m.
(Invited)

MATERIAL PROPERTY MEASUREMENT IN HOSTILE ENVIRONMENTS USING LASER ACOUSTICS

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Acoustic methods are well known and have been used to measure various intrinsic material properties, such as, elastic coefficients, density, crystal axis orientation, microstructural texture, and residual stress. Extrinsic properties, such as, dimensions, motion variables or temperature are also readily determined from acoustic methods. Laser acoustics, employing optical generation and detection of elastic waves, has a unique advantage over other acoustic methodsit is noncontacting, uses the sample surface itself for transduction, requires no couplant or invasive sample surface preparation and can be utilized in any hostile environment allowing optical access to the sample surface. In addition, optical generation and detection probe beams can be focused to the micron scale and/or shaped to alter the transduction process with a degree of control not possible using contact transduction methods. Laser methods are amenable to both continuous wave and pulse-echo measurements and have been used from Hz to 100s

of GHz (time scales from sec to psec) and with amplitudes sufficient to fracture materials. This paper shall review recent applications of laser acoustic methods to determining material properties in hostile environments that preclude the use of contacting transduction techniques. Example environments include high temperature (>1000C) sintering and molten metal processing, thin film deposition by plasma techniques, materials moving at high velocity during the fabrication process and nuclear high radiation regions. Recent technological advances in solid-state lasers and telecommunications have greatly aided the development and implementation of laser acoustic methods, particularly at ultra high frequencies. Consequently, laser acoustic material property measurements exhibit high precision and reproducibility today. In addition, optical techniques provide methods of imaging acoustic motion that is both quantitative and rapid. Possible future directions for laser acoustics shall be discussed drawing from examples in materials science, microelectronic and nuclear fields.
This work was sponsored by the U.S. Department of Energy, Office Basic Energy Sciences, Materials and Engineering Physics under DOE Idaho Operations Office Contract DE-AC07-99ID13727

U4-F-4 513AB 2:30 p.m.

FORWARD MODELING FOR ULTRASONIC LEAKY-LAMB WAVE-BASED IMAGING THROUGH A HIGHLY CONTRASTING STEEL CYLINDRICAL LAYER

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At last years conference, we introduced an ultrasonic leaky Lamb-wave technique to image through a cylindrical steel layer (a highly contrasting layer) with immersion transducers. The technique allows for detection of scatterers/interfaces and evaluation of the mechanical properties of materials bonded to the steel layer. Its primary application arises in the evaluation of cementing jobs in cased oil wells to assess whether or not cement has indeed been placed in the annulus between steel casing and rock formation and provide imaging of the formation wall (through casing and cement sheath). We present here a forward simulation model for this measurement that allows for a further understanding of its physics, its design optimization, and help in the interpretation of the acquired data. The analytical model represents the single-frequency (cw) receiver voltage as a spectral integral of propagating cylindrical functions weighted by the reflectivity function of a layered elastic media the transient response is synthesized through a fast Fourier transform. The reflectivity function is manipulated to yield the total voltage as a sum of contributions one of which is due to reflection from the (cement-formation) interface being imaged. The quantitative model accounts for most important parameters that establish the amplitude and phase of the acquired signal: the finiteness and alignment angle of the transmitting and receiving transducer apertures, the curvature and boundary conditions of the various interfaces the signal interacts with, and eccentering of the imaged interface through an approximate model (to account for the situation that

arises when the casing is eccentered inside the well). The approximate model for the eccentering is derived in the high-frequency regime by a rigorous consideration of the scattering problem from a planar interface between two solids. It is found that the contribution of the scattered/reflected signal from the eccentered interface can be written, in the Kirchhoffs scattering regime, as that of a concentric interface with the incident wavefield and reflectivity function evaluated at a shifted wavenumber. The latter being given in terms of the eccentering parameters.

We will present the forward model and show comparisons with experimental and numerical reference data that help establish its domain of validity.

U4-F-5 513AB 2:45 p.m.

MEASUREMENT OF STATIC AND DYNAMIC RADIATION FORCE ON SPHERES

S. CHEN*[1], G. SILVA[2], R. R. KINNICK[1], M. FATEMI[1], and J. F. GREENLEAF[1],
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Background: Vibro-acoustography [M. Fatemi, Science 280: 82-85] makes images of acoustic emissions from an object vibrated by ultrasound radiation force at audio frequencies (e.g., 10 kHz). The radiation force is produced either by amplitude modulating an ultrasound beam or by interfering two ultrasound beams with slightly different frequency. The radiation force has both dynamic (oscillatory) and static components. Recently, a theory of dynamic radiation force on an object of arbitrary shape has been developed [G. Silva *et al*, abstract submitted to this conference]. This theory predicts that the dynamic and static radiation forces exerted on a sphere have identical magnitude. Here we design an experiment to measure both dynamic and static radiation force on a sphere to verify the theory. **Methods:** For a sphere suspended in water with a very thin thread, the static radiation force deflects the sphere to a new equilibrium position along the ultrasound beam. The dynamic radiation force causes the sphere to vibrate (∼100nm) around this equilibrium position. The static radiation force is balanced by the tension of the thread and gravitational force (corrected for buoyancy) on the sphere, and thus can be calculated from deflection of the sphere [F. Dunn, Acustica 38: 58-61]. The dynamic radiation force can be estimated from the vibration velocity of the sphere [S. Chen J. Acoust. Soc. Am. 112: 884-889]. The force is equal to vibration velocity multiplied by the total impedance of the sphere, which includes its radiation impedance and inertia. **Experiment:** Three stainless steel spheres (radius r = 1.2, 0.85, and 0.64mm) suspended on 10cm long threads were tested in water. Ultrasound with center frequency of 1MHz was used to vibrate the spheres at 100, 200, and 400Hz. The vibration amplitude of each sphere along the ultrasound beam axis is measured by optical vibrometry. The deflection of the sphere is measured with an alignment laser that is perpendicular to the ultrasound beam. The laser is first focused on the sphere at its deflection position. Then the ultrasound is turned off and the position of the laser is moved laterally on a micro-platform

to align with the sphere at its rest position. The deflection of the sphere can be measured with 10 micron resolution. **Results:** The magnitudes of static and dynamic radiation force are equal for all three spheres, tested at vibration frequencies of 100, 200, and 400Hz. The difference between the measured static and dynamic radiation force is 1.35% (r=1.2mm), 2% (r=0.85mm), and 5.4% (r=0.64mm) respectively. **Conclusion:** The method described in this abstract can reproducibly measure both dynamic and static radiation force on a sphere. The measured dynamic and static radiation forces have identical magnitude, with less than 6% difference for the spheres tested.

This work is supported by grant EB02167 from National Institute of Health.

Session: U5-F

ACOUSTIC IMAGING
Chair: L. Kessler
Sonoscan Inc.

U5-F-1 512C-H 1:30 p.m.
(Invited)

ULTRASONIC IMAGING OF FINGERPRINTS USING ACOUSTIC IMPEDIOGRAPHY

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We have recently developed a new method of acoustic impediography and applied it to finger print capture [1]. This method uses the 20 x 25 mm matrix of 1-3 piezo composites as the basic sensor. The ceramic pillars are connected via crosscurrent electrodes lines to multiplexer arrays attached to the four sides of the sensor selecting single or multiple piezo pillars. If a short electrical pulse excites an element with a frequency centered at the 33-serial resonance of the pillar, it will resonate with a damping constant depending on the acoustic load coupled to the element. Since the serial impedance changes with the load attached to the pillar acoustic impedance is estimated from the electrical impedance of the pillar via calibration. Scanning the specimen by addressing each element in the 2D matrix provides an acoustic impedance map of the load. This principle of impediography and its application to finger print capture has been verified with a 64x64 sensor matrix with a pitch of 100 um. In this talk we will also focus on exploring the limits of the method for finger print and other potential applications. Using FE modeling we have analyzed the dynamic range by introducing figures of merits based on parallel and serial resonance. A dynamic range of approx. 60 dB is achieved between tissue and air under the ideal conditions of a single pillar and negligible internal and lateral losses. Varying the pillars aspect ratio improves the dynamic range of the method at a given pitch and fill factor at the expense of electrical capacitance. However, if the pillars are immersed into a real polymer phase such as epoxy the dynamic range drops to 25 dB.: Scanning a 10 um wide air impedance within a tissue like environment yields the PSF of the single element. Modeling also reveals this type if impediography is

more sensitive to a low acoustic impedance (air) embedded in a high impedance, tissue like environment as compared to a high impedance target embedded in a low impedance environment. Assessing the more practical issues of implementation by investigating cross -coupling via electrodes, supporting layers, backing, matching materials it is shown that these influences are of 2nd order and can be neglected if they are well below the particular wavelength. Mutual coupling between neighbor elements affects sensor performance substantially if several elements are addressed in parallel. Initial evaluations of the sensors characteristics for use as an ultrasonic transmitting and receiving array are performed. Combining rows and columns to cross like apertures of 1.6 mm stripe width and 20 mm length yields a reasonable pulse-echo beam pattern. Electronic focusing and beam steering are currently evaluated using Field II [2]. These results will also be reported at the time of the meeting. [1] R.M.Schmitt, W.G. Scott, R.D. Irving Numerical validation of an advanced finger print sensor based on 1-3 piezo-composites. IEEE-UFFC Symposium Proc., Honolulu, Hawaii, 2003, p 1074-77 [2] J.A. Jensen: Field: A Program for Simulating Ultrasound Systems,
Supported by NIST-ATP

U5-F-2 512C-H 2:00 p.m.

HAMSTER KIDNEY CELL ELASTIC PROPERTIES EVALUATED USING ULTRASONIC ATOMIC FORCE MICROSCOPY

A. EBERT*, J. DU, X. WANG, M. SALERNO, W. SCHEUCHENZUBER, and B. TITTMANN, The Pennsylvania State University.
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Ultrasonic atomic force microscopy (U-AFM), as well as, conventional and force-distance curve techniques were used in the study of hamster kidney cell elastic properties. U-AFM operates in contact mode with the addition of an ultrasonic frequency applied to the cantilever. The tip is raster-scanned across the sample surface as the cantilever oscillates at a frequency and amplitude. The change in frequency and amplitude of the cantilever is monitored, where a stiff material will result in different amplitude than a soft material. While U-AFM imaging has been used widely to image inorganic materials, its use in the study of biological specimen is limited despite great opportunity. The main advantage of U-AFM imaging is the information about the elastic property heterogeneity about a sample surface. Biological cell surfaces are not well characterized due to their complex and delicate structure. Information about their structure and function are integral in biotechnological fields, for the development of tissue engineering, medical implants, and biosensors, while also gaining fundamental knowledge of biological cells. U-AFM images of hamster kidney cells were collected at an operating frequency of 36 kHz, which was the main resonance peak of the cantilever. The U-AFM images were compared to conventional topography images obtained simultaneously. The U-AFM image provided higher contrast images of the cell surface compared to conventional topography images. The highest contrast in the U-AFM image was between the edge and center of the

cell. Force-distance curves were also performed on the hamster kidney cells. The force-distance technique provides quantitative determination of elastic moduli at single locations on the sample surface with the use of a model. The application of a nonlinear Hertz model with parabolic tip geometry was utilized to obtain an average elastic modulus of 33 kPa, with a range between 10 70 kPa. The edge and center regions of the cell were compared, where the edge was found to be twice as stiff as the center. A computer model of the cantilever and tip-sample interaction was created using Ansys software to explain the contrast in the U-AFM images. The elastic moduli range determined from the force-distance work was used in the simulation. The cantilever was modeled after the geometry, dimensions, and material properties of the cantilever used in U-AFM imaging, where the tip-sample interaction was modeled by a nonlinear spring represented by the nonlinear Hertz model used in force-distance curves. The cantilever amplitude response to varying elastic moduli was theoretically simulated through a finite element model. The model showed cantilever vibration amplitude and resonance frequency dependence on sample elasticity. The simulations led to the conclusion that the bright features in the U-AFM images were areas of higher stiffness than darker features. This was a result of stiffer materials having greater interaction with the tip ensuing higher cantilever vibration.

U5-F-3 512C-H 2:15 p.m.

MULTI-FREQUENCY ULTRASONIC NDE FOR EARLY DEFECT RECOGNITION AND IMAGING

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Conventional ultrasonic equipment for non-destructive evaluation (NDE) is normally a mono-frequency instrument which makes use of the amplitude and time variations of the input signal due to its scattering, reflection and transmission. One can bear with such an inadequate amount of information as long as the wave-defect interaction is believed to be linear. The nonlinear approach to NDE allows for frequency changes due to non-linear response of the flaw. The nonlinear frequency components acquired are intrinsic signatures of material imperfections and bring along new spectral data to complete the defect detection and location. We report on the observation and NDE application of the ultimate nonlinear spectrum which (beyond the well-known ultra-harmonics and modulation side-bands) comprises the sub-harmonics, ultra-sub-harmonics, and ultra-frequency pairs. The experiments include 20-40 kHz intense acoustic wave excitation and local spectrum measurements with a scanning laser interferometer over 1 MHz frequency range. The new modes produced reveal the distinctive features of the nonlinear resonance mechanism: hysteresis, bistability, and avalanche-like dynamics. Unlike the excitation frequency, their spatial distribution is confined strictly around the sources of nonlinearity (defects) and is used for the multi-frequency C-scan imaging of flaws that are invisible in the

mono-frequency NDE regime. The series of images for various frequency lines is applied to remove background noise and to enhance the object to be identified by linear and nonlinear image processing. The results obtained for the fractured defects (impacts, cracks, delaminations, welded-joints) in a number of materials and components (CFRP, C-C/SiC, alumina ceramic, laser welded aluminium alloys, etc.) demonstrate evident benefits of the cumulative multi-frequency NDE for defect recognition and imaging.

U5-F-4 512C-H 2:30 p.m.

3D ULTRASONIC IMAGING AND CONTOUR DETECTION IN METAL SHEET HYDROFORMING

O. KEITMANN-CURDES*[1], K. HENSEL[1], P. KNOLL[2], H. MEIER[2], and H. ERMERT[1], [1]Institute of High Frequency Engineering, Ruhr-Universitaet Bochum, [2]Department of Mechanical Engineering, Ruhr-Universitaet Bochum.
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The aim of the presented work is to develop an ultrasonic imaging system for contour detection of specular reflecting metal sheets in a hydroforming process. The active fluid medium is a water-oil-emulsion at a pressure of several hundred bar. Due to limited hardware resources, only a sparsely filled array of ultrasonic transducers will be set up in the high-pressure vessel to provide information about the state of forming on-line during the whole process. The disadvantage of a sparsely filled array (21 transducer positions on a 10 cm long linear aperture at 2 MHz) can be mostly compensated by the fact that only specular reflections of the ultrasonic signals have to be considered.

On the last IEEE Ultrasonics Symposium, the general principle of our contour detection algorithm was presented. At that time, only simple contours in the so-called 2.5 D domain could be reconstructed (corner-shaped, cylindrical shaped) with a linear aperture (For example, a circular cylinder is a 2.5 D object corresponding to its 2 D circular cross-section).

In the meantime, the reconstruction algorithm has been extended with respect to two different aspects.

Thus, more complex surfaces in the 2.5 D domain (different radii and slopes within one contour) can be reconstructed by now with a relative axial reconstruction error of significantly less than 1 %. The respective experiments were performed in a 2.5 D experimental set-up with two 2 MHz transducers and two independent traversing units to generate a linear aperture. In this way, data acquisition was obtained and in a first step, image reconstruction was performed with a SAFT (synthetic aperture focusing technique) algorithm. Within the SAFT image, the contour of the metal sheet could be detected by a snake algorithm. This algorithm computed the contour in several iteration steps starting from initial values accounting for energies calculated from image information and parameters of the contour (slope and curvature). Finally, the contour could be represented by mathematic functions with a limited set of parameters (currently 9th order polynomials or bi-cubic splines) as the reconstruction result.

Additionally, the linear aperture was extended to a 2 D aperture with 3 D imaging capabilities and first experiments were performed. Thus, simple contours in 3 D are reconstructable and adequately representable from ultrasonic data acquired with a sparsely filled 2 D array with a satisfactory resolution. First experiments were carried out to find optimized transmitter/receiver positions and numbers to decrease acquisition as well as computing time while keeping the reconstruction accuracy on a high level.

All presented results are based on measured ultrasonic data and will be discussed with respect to reconstruction accuracy, hardware requirements and computing time.

We would like to thank the German Research Foundation DFG (Deutsche Forschungsgemeinschaft, grant ER 94/26-1,2,3 and ME 1831/9-1,2,3) for supporting this project by grants.

U5-F-5 512C-H 2:45 p.m.

OPTIMIZED ALGORITHM FOR SYNTHETIC APERTURE IMAGING

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Synthetic Aperture Imging (SAI) has been used in ultrasonic imaging systems mainly due to its two benefits: first, it is capable of improving the lateral resolution in focal zone, and second, it extends the focal zone resulting in a dynamic focusing effect. However, the success of SAI in practical applications depends strongly on how strictly the assumptions, on which this technique is based are fulfilled. One of the main assumptions is that the diffraction effects of the transducers used to build the synthetic aperture can be neglected. However, the minimum transducer size is often limited by some other requirements, such as, minimum power required for a sufficient signal to noise ratio or minimum area needed for obtaining the desired electric characteristics. Thus the analysis of SAI performance for finite sized transducers is of great interest for its potential users. In this paper we present a novel SAI algorithm based on the range migration concept used in geophysics. The algorithm, which is developed in terms of the wave equation accounts for the beam-pattern of the finite sized transducer used in the synthetic aperture. The 2D Fourier transform is used for the calculation of 2D spectrum of the ultrasonic data. The spectrum is then interpolated to convert the polar coordinate system used for the acquisition of ultrasonic signals to the Cartesian coordinates. After windowing, the transformed spectrum is subjected to the 2D inverse Fourier transform to get the time domain image again. The algorithm is computationally attractive due to the use of 2D FFT. An analysis is presented in the paper where the performance of the proposed algorithm is compared to that of the classical time-domain SAFT with emphasis on the lateral resolution. The analysis is based on numerical simulations of the responses to the scatterers located at different distances from the synthetic aperture created by circular sources. Lateral resolution and side lobes of the algorithms are compared in the analysis. It is shown that the increase of the transducer size generally reduces system resolution but the proposed algorithm

is less sensitive to the source size than the classical SAFT. Similar comparison is also performed on real ultrasonic data acquired using a circular transducer located at various distances from different scatterers in water.

Session: U6-F

THERAPY: THERMAL ABLATION

Chair: L. Crum

University of Washington

U6-F-1 512A-F 1:30 p.m.

MRI-BASED THERMOMETRY AND THERMAL DOSIMETRY DURING FOCUSED ULTRASOUND THERMAL ABLATION OF UTERINE LEIOMYOMAS

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Purpose: We will present our experience with using MRI-based thermometry and thermal dosimetry for guiding, monitoring, and predicting the outcome of focused ultrasound thermal ablation of uterine leiomyomas (fibroids). The purpose was to quantify the agreement between the thermal dose estimates of the size of the treated volume and the imaging findings after the treatments and to measure the variation in the temperature rise achieved during the treatments.

Methods: MRI-guided focused ultrasound was used for thermal ablation in women with uterine leiomyomas. The goal of the treatments was to treat a sub-volume of the fibroid as a palliative treatment. To date, more than seventy patients have been treated at our institution. The ultrasound was produced by phased array transducer integrated into an MRI-compatible system (Exablate 2000, InSightec, Haifa, Israel). Temperature changes were measured with MRI by mapping temperature-induced changes in the water proton chemical shift. These images were used to construct thermal dose maps. The temperature and dose were used online to monitor and guide the treatments. Immediately and six months after the treatment, contrast-enhanced T1-weighted images were used to detect non-perfuse areas induced by the treatment. The lack of inertial cavitation during the sonications was verified by monitoring the acoustic emission during the sonications. The MR temperature images were analyzed again offline using in-house written software to reconstruct thermal dose maps and to evaluate the inter- and intra-patient variation in the peak temperature rise. The areas that reached thermal dose values greater than 240 min at 43°C were compared with those of the non-perfuse areas in post-treatment imaging.

Results: The thermal dose maps underestimated the non-perfuse areas after treatment in most cases. The non-perfuse area was contained within the fibroid volume. Preliminary analysis of 15 treated fibroids in 10 patients found an underestimation of the non-perfuse area (in the images in the focal plane) of 15-75% (mean $\pm$ SD 48 $\pm$ 19%). In some cases, large areas in the fibroids

were non-perfuse that were clearly not targeted by the ultrasound exposures, indicating that at least in some cases that the disagreement was due to secondary vascular changes induced by the thermal ablation at distant locations. Substantial variation (>10°C) in the peak temperature rise was observed, both between patients and within single treatments with the same sonication parameters.

Conclusions: The thermal dosimetry and post-treatment imaging indicates that a larger volume is affected by the treatments than would be predicted by the temperature information alone. However, the fate of this tissue with secondary vascular effects is not currently known. The large variation in measured peak temperature rise strongly indicates the need for online thermal monitoring during focused ultrasound thermal ablation.

This work was funded by NIH grants CA046627-14 and CA67165-06 and from a grant from InSightec

U6-F-2 512A-F 1:45 p.m.

CAVITATION ENHANCES TREATMENT DEPTH WHEN COMBINED WITH THERMAL EFFECT USING A PLANE ULTRASOUND TRANSDUCER: AN IN VIVO STUDY

C. GOLDENSTEDT*, D. MELODELIMA, F. MITHIEUX, S. CHESNAIS, Y. THEILLRE, and D. CATHIGNOL, INSERM Unit 556.
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Until now, high intensity ultrasound has been developed for numerous surgical and medical applications. Interstitial applicators have been designed to treat pathologic tissues while enabling minimally invasive techniques. Although these techniques provide good results, the volume of tissue that can be treated is limited by the size of the applicator. Therefore, in order to increase these volumes, we propose to combine cavitation and thermal effect to enhance the treatment depth. Our recent *ex vivo* studies using a plane transducer have shown that cavitation bubbles permit to increase the depth of the necroses produced by thermal effect. These results led us to set out an *in vivo* study on pig's liver in order to confirm this property into living tissues. After a laparotomy, ultrasound exposures were applied on the surface of the liver. 40 exposures were performed with an endocavitary applicator using a plane ultrasound transducer (3×10 mm^2) operating at 4.75 MHz. This study aims to compare two methods of treatment. The first one produces lesions by thermal effect exclusively. The second method uses cavitation in addition to thermal effect. Cavitation bubbles are initiated inside tissues along the beam axis by a high intensity pulse (60W/cm^2 for 0.5 s). This pulse is followed by a continuous wave exposure, which generates thermal effect. Immediately after treatment, the animal was sacrificed and the exposed areas were sampled to measure macroscopically the depth of the necroses. These samples were then prepared for a histological analysis. The method using cavitation bubbles produced the deepest lesions. At an intensity of 30 W/cm^2 applied for 30 s, the lesions produced with cavitation bubbles were 1.7 times deeper than those produced without cavitation bubbles. Moreover, the geometry of the lesions was reproducible and strechted uniformly from the surface of the liver. The histological analysis has shown that they correspond to coagulation necroses. Thus, these results have shown that the initiation of cavitation bubbles *prior* to the exposure increases the therapeutic depth significantly. Consequently, this method might offer new possibilities with regards to the treatment of greater tissue volumes such as tumours using small dimensions ultrasound transducers.

U6-F-3 512A-F 2:00 p.m.

FEASIBILITY OF MRI-GUIDED TRANSURETHRAL THERMAL THERAPY FOR PROSTATE CANCER

R. CHOPRA*, S. N. BAKER, V. CHOY, S. LOCHHEAD, and M. J. BRONSKILL, Sunnybrook and Women's College Health Sciences Centre.
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Transurethral thermal therapy is a minimally invasive technique that uses a small applicator located in the urethra to heat regions of the prostate gland to the point of thermal coagulation. Medical imaging plays an important role in guiding and monitoring transurethral thermal therapy to ensure adequate heating of the entire prostate gland while sparing sensitive surrounding interfaces such as the rectal and bladder walls. Magnetic resonance imaging (MRI) is particularly suitable for use with transurethral thermal therapy because it enables visualization of the target volume and post-treatment regions of thermal damage. MR imaging also offers the unique ability to measure temperature during a treatment to monitor the spatial heating pattern.

We have developed MRI-compatible multi-element ultrasound heating applicators designed to deliver conformal thermal damage patterns in the prostate. The device consists of multiple planar transducers, each with the capability of operating at multiple frequencies (typically 4.7 and 9.7 MHz). The individual transducers are 4 x 10 mm, with an acoustic efficiency of between 30 and 40% at each frequency. The ability to control the rotation of the applicator, as well as the power and frequency of each element independently, enables the generation of targeted three-dimensional thermal damage patterns.

Three-dimensional Bioheat transfer simulations have been performed to evaluate the ability of this technology to perform conformal thermal therapy in the prostate. Eleven prostate MR exams were obtained, representative of the enlarged size and shape of prostate gland expected in a clinical population. The boundary of the gland was identified, and an optimized spatial heating pattern to cover the entire gland, produced by the heating applicator in the urethra, was calculated. The final thermal damage pattern was defined as the region where peak temperatures greater than 55 $^{\circ}$C were achieved. The output parameters of the applicator (frequency, power, rotation rate) were varied based on the boundary temperature of the prostate gland to simulate active temperature feedback from MR imaging.

Results suggest that this technology can deliver a pattern of thermal damage to the entire prostate gland with a mean overshoot of less than 3 mm between the prostate and thermal damage boundaries. Thermal damage to the rectal wall can be further avoided by cooling the rectum during treatment. Treatment times are longer for larger prostates, ranging from 10 ? 40 minutes. Experiments to validate this simulation control algorithm are currently being performed using a tissue-mimicking phantom.

U6-F-4 512A-F 2:15 p.m.

DETECTION OF IMAGING ACOUSTIC SIGNALS FOR SYNCHRONIZING A COMMERCIAL ULTRASOUND IMAGER WITH A HIGH INTENSITY FOCUSED ULTRASOUND THERAPY SYSTEM

N. R. OWEN*, M. R. BAILEY, P. KACZKOWSKI, and L. A. CRUM, Center for Industrial and Medical Ultrasound, University of Washington.
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Objective: Transcutaneous surgical procedures performed with high intensity focused ultrasound (HIFU) therapy can be monitored in real-time with an ultrasound imager if the HIFU is gated appropriately. Gating the HIFU produces an ultrasound image that is partially occluded with noise. If the gating signal is synchronized with the imaging cycle of the imager, it is possible for the location and total area of the interference to be consistent from frame to frame on the ultrasound image. Synchronization has been achieved with many methods, most requiring some type of modification to the imager. We present a synchronization technique that uses the HIFU transducer to detect acoustic signals from imaging probe. Modifying the imager is not required with this technique. Materials/Methods: The imaging probe and HIFU transducer (d = 33mm, roc=55mm, f = 3.5MHz) are mechanically fixed with coplanar orientation to visualize the HIFU focus. Acoustic signals from the imaging probe are scattered and detected by the HIFU transducer. When viewed with an oscilloscope, the receive signal from each pulse-echo imaging cycle is a collection of pulses that represent excitations of individual elements in the imaging probe. Receive signal amplitude is 20 mV before it is amplified by two non-inverting op-amps with a combined gain of 50 dB. A series diode rectifies the signal and a tuned RC circuit preserves the positive voltage envelope. The rectified signal is amplified by 6 db with another op-amp. Information in the output signal is the frame rate and a phase reference that is consistent from frame to frame. The output signal triggers a logic circuit that generates the control signals for phasing and gating of the HIFU, which is synchronized with the pulse-echo imaging cycle. Results: The detection system has been used to synchronize a HIFU system with 3 imagers: SonoSite 180, HDI 1000, and Terason 2000. In each test, the phasing and gating of the HIFU were controlled, relative to the imaging cycle of the imager, while creating lesions in a gel. When viewed on the display of the imager, the location and total area of interference from the HIFU was determined by settings in the logic circuit. The system remained synchronized when the depth setting on the imager was changed. B-mode imaging was used

in each test. Synchronization was achieved with Color Doppler imaging in a subsequent test. Conclusion: This detection technique can be used to synchronize a HIFU therapy system with a commercial ultrasound imager without modifying the imaging system. Key features of this synchronization method include the ability to control the phasing and duty cycle of the HIFU transmission, relative to the pulse-echo imaging cycle, and the ability to remain synchronized when settings on the imager are changed. This technique offers a simple, low cost method to synchronize a HIFU therapy system with an ultrasound imager for ultrasound-guided HIFU therapy.
This work was supported by the NSBRI.

U6-F-5 512A-F 2:30 p.m.

TEMPERATURE RISE MEASURED NON-INVASIVELY DURING THERMAL THERAPY USING CORRELATED BACKSCATTERED ULTRASOUND

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Background Quantitative knowledge of the spatial distribution of tissue temperature is an essential indicator of thermal therapy progress, and of treatment safety and efficacy. Measured changes in ultrasonic (US) travel time from an imaging transducer to backscattering sites in the heated region can provide clinically useful temperature estimates from which thermal dose throughout the imaged region can be obtained. In this work, it is shown through in vitro experiments that temperature rise can be accurately measured during therapy delivery and post-treatment cooldown phases using RF backscatter data collected with a commercial scanner (ATL HDI 1000). Correlation based signal processing, and spatio-temporal smoothing of the results using the bioheat transfer equation (BHTE) model provide a 2-D temperature image for each backscattered ultrasound frame. **Methods** RF US data was acquired using a software-modified commercial ATL HDI 1000 during and after thermal exposures at 10 frames/second, in three standard tissue mimicking phantoms: gelatin, agar, and alginate, with mucilloid fiber added as needed to enhance backscattering. Initial experiments were performed using a nichrome heating wire embedded in cubic samples of dimensions 5 cm on a side. Electrical power (10 to 15 W) was dissipated in the wire (for 5 to10 s). The experiments were repeated with 3.5 MHz HIFU as the heat source at intensities of 1000-3000 W/cm2 for 1-5 seconds. For each image frame, scatterer location shifts with respect to a preceding frame were measured along each scanline using elastographic correlation processing methods. The measured travel time differences were compared to BHTE simulations of the temperature field in a medium of known K and heat source Q, and with an initial guess for temperature dependent backscattered travel time. Iteration of the model proceeded until the 2-D temperature maps estimated from the data agreed well with the simulation. For validation, four thermocouples were used to independently measure temperature at locations around the heating wire (HIFU focus) and in the imaging plane transverse to

the wire (beam direction). Independent tests were also conducted to obtain the value of thermal diffusivity K, and temperature dependence of 2-way travel time to embedded scatterers using a water bath. **Results** In vitro experimental results show that the mean error in the noninvasive ultrasonic temperature measurements was approximately 1°C compared to thermocouple data readings for the electrical heating experiments throughout the heating and cooling phase. For HIFU exposures, the mean temperature tracking error was approximately 5% shortly after therapy commenced but decreased to approximately 1°C once the BHTE parameters adapted to their correct values using the first few frames. The mean error in noninvasive estimates of the temperature dependence of travel time was less than 5%.

U6-F-6 512A-F 2:45 p.m.

NONINVASIVE LOCALIZED ULTRASONIC MEASUREMENT OF TISSUE PROPERTIES

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High intensity focused ultrasound (HIFU) is a promising modality for image-guided noninvasive surgery. MRI is currently the leading modality for guidance of HIFU due to its excellent quality and temperature sensitivity. Ultrasound guidance of HIFU is limited by the non-quantitative nature of conventional ultrasonic imaging. Several groups have recently investigated the use of elastography and viscoelastic remote palpation techniques for characterization of the state of ablated tissue. Initial reports of remote palpation are promising but true localization of the shear waves to simplify the solution of the inverse problem to obtain the shear elastic modulus is yet to be demonstrated in tissue. Two quantities believed to reflect the state of the tissue after HIFU lesion formation are tissue absorption and blood perfusion. The former has been shown to increase upon lesion formation while the latter is hypothesized to exhibit dynamics depending on the temperature rise, position within the heated volume, and degree of damage to the vasculature. In this paper, we present in vitro and in vivo results for validation of a new localized noninvasive ultrasonic measurement of both tissue absorption and perfusion. The method employs sub-second low-intensity focused ultrasonic beams for generating brief temperature rise on the order of 1 degree C. The RF data from an imaging transducer is processed to produce noninvasive temperature estimate in the localized heated volume using speckle tracking or frequency-domain algorithms. Absorption can be obtained from the initial heating rate while perfusion can be estimated from the initial decay. Due to the small size of the heated spot, the noninvasive temperature estimation can produce results that are virtually free of thermal lensing effects. Furthermore, since the measurements are based on heating and decay rates, only the parameters of the transient bioheat equation (density and heat capacity) are needed for the estimate. Experiments have been performed on ex vivo liver tissue and in vivo MA148 human ovarian carcinoma, grown in a nu/nu immunodeficient mouse. A linear array probe LA522E on a Technos MPX scanner

(Esaote, S.p.A) was used in monitoring the heating field from a 1.5 MHz focused transducer (ex vivo) and a 4 MHz focused transducer (in vivo) with radii of curvature of 63.5 mm and 40 mm, respectively. Temperature profiles were estimated before and after single-shot overexposure lesion formation using the therapeutic transducer. Both ex-vivo and in vivo results have shown a three-fold increase in tissue absorption with the ex vivo results corroborated using direct fine wire thermocouple measurements at the treatment site. The decay rate of the in vivo estimated temperature was observed to increase by two-fold indicating increased perfusion in the tumor surrounding the small lesion. While the opposite effect can be expected in volumetric lesion formation, this is very likely in this single-shot lesion formation experiment.In vivo results show clearly the feasibility of estimating perfusion based on decay rate.

Session: FE1-F

MATERIALS CHARACTERIZATION
Chair: A. Kholkin
University of Aveiro

FE1-F-1 513CD 1:30 p.m. (Invited)

TEMPERATURE- AND ELECTRIC-FIELD-DEPENDENT PHASE TRANSFORMATIONS IN (001)-ORIENTED PMN-40%PT SINGLE CRYSTAL

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Temperature- and electric-field-dependent phase transformations in a (001)-oriented $Pb(Mg_{1/3}Nb_{2/3})_{0.6}Ti_{0.4}O_3$ (PMNT40%) single crystal have been investigated by temperature- and frequency-dependent dielectric permittivity and polarizing microscopy. The permittivity ϵ' exhibits a maximum near 463 K with a shoulder near 446 K and a broad step near 270 K. By using relations of crystallographic symmetry and optical extinction for polarizing microscopy data, we found that the unpoled crystal has tetragonal (T) phase domains with polarizations **P** along the [100] and [010] axes. These domains are 15 to 60 microns wide, and are separated by 90 ° domain walls. They coexist at 200 K with a small fraction of monoclinic (M) phase. As temperature increases toward room temperature, the T phase domain increases rapidly at the expense of the M phase. This may account for the broad peak in ϵ' and decrease in ϵ" near 270 K. The polarizing microscopy indicates that the crystal reaches a cubic phase near 464 K, which is consistent with the dielectric maximum temperature. The E-field-dependent polarizing microscopy results at room temperature show that the polarizations begin to rotate to the tetragonal [001] (T_{001}) direction through the M phase and significantly change near E=11 kV/cm. As E-field increases, the crystal exhibits more T_{001} domain, which is associated with optical extinction at every orientation of the perpendicularly crossed polarizer/analyzer pair.

The crystal becomes entirely T_{001} monodomain near E=33 kV/cm. As E-field decreases to 0 kV/cm, the domain structure shows irreversible behavior. It does not re-establish the broad T_{100} and T_{010} domains described above, but the extinction pattern is consistent with tetragonal microdomains.
The authors express sincere thanks to Dr. H. Luo and H. Cao for the crystal. This work was supported by DoD EPSCoR Grants N00014 02-1-0657 and NSC Grant 91-2112-M-030-006.

FE1-F-2 513CD 2:00 p.m.

NON-LINEAR DIELECTRIC RESPONSE IN 111 AND 100 ORIENTED $0.5PB(YB_{1/2}NB_{1/2})O_3$-$0.5PBTIO_3$ THIN FILMS

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The effective dielectric and piezoelectric coefficients of piezoelectric films depend on the applied electric field strength and frequency. The application of these films in microelectromechanical systems (MEMS) requires an understanding of these nonlinearities for prediction of the device behavior. The AC electric field dependence of the permittivity and piezoelectric response of ferroelectric thin films in sub-switching conditions can be modeled using Rayleigh-type behavior. (1-x)$Pb(Yb_{1/2}Nb_{1/2})O_3$-x$PbTiO_3$ (PYbN-PT) presents one of the highest Curie temperatures (~360°C) near the morphotropic phase boundary (x~0.5) among the relaxor-PT solid solution systems, which makes is a very good candidate for devices with good temperature stability and wide working temperature range. The highest piezoelectric responses in this material are observed for the 100 orientation. In this work, the nonlinear dielectric response of 111 and 100 oriented thin films of 0.5PYbN-0.5PT are reported as a function of AC electric field and frequency. The responses are modeled with a frequency-dependent modification of Rayleigh law as $\epsilon_r = \epsilon_{r,init}(\omega)+\alpha(\omega)E$ where $E_{AC}=E.\sin(\omega t)$ is the AC driving field and $\epsilon_{r,init}$ and α are the reversible and irreversible Rayleigh coefficients. This modified model predicts the dielectric properties of the PYbN-PT films in the intermediate AC field and frequency regions relatively well. Furthermore, 100 oriented films show higher irreversible Rayleigh coefficients than 111 oriented films. The ratio of the irreversible to reversible coefficients is also higher in the 100 oriented films, showing a higher contribution to the dielectric constant due to the irreversible component (movement of the domain walls) in these films with respect to the 111 oriented films. Work on the piezoelectric nonlinearity for these films will also be described.
This work was supported by Office of Naval Reaserch. The authors gratefully acknowledge that some substrates were provided by Dr P.Muralt (EPFL)

FE1-F-3 513CD 2:15 p.m.

CONVERSION OF 45° ROTATED X-CUT $KNBO_3$ PLATES TO Y-CUT PLATES BY COMPRESSION

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Ferroelectric potassium niobate ($KNbO_3$) single crystals are expected as lead-free high-coupling piezoelectric materials. The electromechanical coupling factor of the surface acoustic wave (SAW), k_{SAW}, is as high as 73% for Y-cut $KNbO_3$ plates. Since $KNbO_3$ has a pseudo-cubic structure, the domain state is changeable by a mechanical stress as well as an electric field. To the best of our knowledge, however, there has been no report on domain control by applying a mechanical stress onto $KNbO_3$ crystals. The objective of this study is to convert the 45° X-plate with a high coupling factor for the thickness-extensional mode to the Y-plate with a very high coupling factor for the surface acoustic wave. Both plates are in relation of 60° domain each other. Considering the crystal structure, the 45° X-plate may be converted to the Y-plate by applying a compressive force obliquely to the plate surface. To comfirm this and obtain a better understanding of the domain behaviors, a system consisting of a polarizing microscope combined with a stress application mechanism was constructed for observation and video recording of the domain state during linearly increasing the applied stress. When the stress was about 6.6 MPa, a stripe 60° domain nucleated and evolved as expected. Finally the 45° X-plate was almost converted to the Y-plate in about 10 seconds. The recorded moving pictures will be presented. To confirm this conversion, an X-ray diffraction investigation was performed before and after applying the stress. The conversion was also confirmed by observing the electrical admittance characteristics before and after applying the stress. Although a thickness-extensional mode resonance was originally observed, it turned into the thickness-shear mode resonance, which is a feature of the Y-plate. These results would present a useful suggestion for obtaining Y-domain $KNbO_3$ films.

FE1-F-4 513CD 2:30 p.m.

EVALUATION OF FERROELECTRIC DOMAIN STRUCTURE BY ULTRASONIC ATOMIC FORCE MICROSCOPY

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In transducers and actuators using ferroelectric materials, the ferroelectric domain structure is elastically deformed by the piezoelectric effect. In ferroelectric

memories, the movement of the domain boundary (DB) occurs during switching the polarization state. Therefore, the operation of these devices is probably affected by the elasticity of the domain and the DB as well as the ferroelectricity of them. In order to evaluate the ferroelectric domain structure, piezoresponse force microscopy (PFM) is widely used. However, PFM doesn't provide the information about elasticity. Ultrasonic atomic force microscope (UAFM) has been developed as a nondestructive elasticity evaluation method with the resolution of an atomic force microscope (AFM), which enables the evaluation of stiff materials such as ceramics and alloys by the resonance vibration of an AFM cantilever. Because the elasticity of the sample is evaluated by the resonance frequency, the measurement of the resonance spectrum with high SN ratio is important. Recently, we developed the cantilever holder that reduces the occurrence of spurious modes of the cantilever vibration. In this study, the ferroelectric domain structure in lead zirconate titanate (PZT) was visualized and evaluated by UAFM. An evidence of the lower elasticity at the DB than that within the domain is reported. Commercially available soft bulk PZT ceramics were investigated (sample 1: NEC Tokin Cooperation, N-21, sample 2: Fuji Ceramics Cooperation, C-82). They were annealed above Curie point to remove macro-scale polarization and make a random domain structure. These samples were lapped by diamond slurry. Sample 1 was polished by colloidal silica slurry. An AFM topography with a RMS roughness of 1nm was obtained. After the ferroelectric domain structure was visualized by PFM, UAFM was applied. The elasticity distribution related to the domain structure was visualized by the mapping of the resonance frequency at the 2nd deflection mode. For investigation of DB, sample 2 was polished by alumina paste. The topography with a RMS roughness of 3nm was obtained. In UAFM at the 1st deflection mode, the elasticity distribution due to grains was observed and thin string-like objects were seen within the grains. These objects were clearly observed in UAFM at the 2nd deflection mode, showing lower resonance frequency than that of surrounding area. The string-like objects were identified as the DB by comparing with a PFM image. To evaluate the difference of the elasticity between the domain and the DB, the resonance spectra were evaluated using the cantilever vibration theory. It was found that the contact stiffness of the DB is lower than that of the domain, probably indicating the decrease of the effective elastic modulus. Implication of this finding is that lower elasticity of DB may be related to its higher mobility under stress or electric field. Application of this evaluation to various materials can therefore provide important information for development of efficient ferroelectric materials.

This work was supported by JSPS Reserch fellowship for Young Scientists.

FE1-F-5 513CD 2:45 p.m.

THE DIRECT PIEZOELECTRIC EFFECT IN $[001]_C$-POLED RELAXOR-FERROELECTRIC SINGLE CRYSTALS: CONTRASTING LONGITUDINAL AND TRANSVERSE MODES

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Direct measurements of longitudinal (d_{33}) and transverse (d_{31}) piezoelectric coefficients have been made on cuboid samples of $[001]_C$-poled 0.955Pb[$Zn_{1/3}Nb_{2/3}$] O_3-0.045PbTiO_3 (PZN-4.5PT), 0.92Pb[$Zn_{1/3}Nb_{2/3}$]O_3-0.08PbTiO_3 (PZN-8PT) and 0.68Pb[$Mg_{1/3}Nb_{2/3}$]O_3-0.32PbTiO_3 (PMN-32PT) single crystals. The measurements were made in a Berlincourt-type press over a wide range of dynamic and static bias stresses. In the transverse mode, the response was found to be essentially anhysteretic and d_{31} was independent of the dynamic stress amplitude. In contrast, for the longitudinal mode, the piezoelectric charge-stress behavior is hysteretic. Moreover, the relative hysteresis size and the d_{33} coefficient are both strong functions of bias stress, dynamic stress amplitude and frequency; coupling of the dynamic stress dependency of d_{33} to the charge-stress hysteresis is demonstrated by a quasi-Rayleigh type relationship. The observed hysteretic response could be due to domain switching in the crystals although this would be unexpected for a $[001]_C$-poled rhombohedral crystal. Instead, following the observed difference between transverse and longitudinal behaviors, it is suggested that polarization rotation *away* from the poling direction leads to a hysteretic response.
The authors acknowledge financial support from the Swiss National Science Foundation.

Session: FC1-F

MICROWAVE OSCILLATORS
Chair: J. Searls
Poseidon Scientific Instruments Pty. Ltd.

FC1-F-1 511CF 1:30 p.m.

HIGH POWER MICROWAVE OSCILLATORS WITH INTERFEROMETRIC SIGNAL PROCESSING

E. N. IVANOV*, M. E. TOBAR, and J. TORREALBA, UWA.
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Application of interferometric signal processing to precision noise measurements at microwave frequencies resulted in a real breakthrough in the noise performance of microwave signal sources [1]. Since the initial success, when the phase noise of a X-band oscillator was improved by almost 25 dB as compared to the

previous state-of-the-art, the subsequent progress in the field of oscillator frequency stabilisation was rather slow. This was largely due to the fundamental limitations imposed by thermal fluctuations (Nyquist noise) on the resolution of frequency measurements. The arrival of high power solid-state microwave amplifiers offered an opportunity of lowering the thermal noise limit by simply dissipating more power in the high-Q resonator of the oscillator. By following this approach, another order of magnitude reduction in the intensity of oscillator phase noise has been achieved leading to the construction of a 9 GHz oscillator with spectral density of phase fluctuations equal to 160 dBc/Hz at 1 kHz offset frequency.

This work summarizes the basic stages of the design and tuning of high power microwave oscillators with interferometric signal processing. It also describes the techniques of evaluating the contributions of various noise mechanisms to the oscillator overall phase noise. Finally, it focuses on the approaches to the measurement of very low levels of phase noise.

While working on this project we discovered an excess phase noise with the intensity proportional to the loop gain of the control system stabilising the oscillator frequency. Possible explanations to the origin of the excess noise, as well as the way of circumventing it will be presented.

References:

1. E. N. Ivanov, M. E. Tobar and R. A. Woode, Applications of interferometric signal processing to phase noise reduction in microwave oscillators, IEEE Transactions on MTT, vol. 46, N10, October 1998, pp.1537-1545.

This work is jointly supported by the Australan Research Council and Poseidon Scientific Instruments

FC1-F-2 511CF 1:45 p.m. (Invited)

A REVIEW OF SAPPHIRE WHISPERING GALLERY MODE OSCILLATORS INCLUDING TECHNICAL PROGRESS AND FUTURE POTENTIAL OF THE TECHNOLOGY

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In this paper we present the results of recent progress in the development of Low Phase Noise signal generators based on Sapphire Whispering Gallery Mode Resonators, and look at the future potential of these oscillators to meet the ever increasing demands for precision signal generation and processing.

The paper reviews oscillators which include interferometric signal processing techniques for the detection and reduction of noise in the oscillator, as well as those based on components which intrinsically have low phase noise.

As the industrial and commercial viability of such devices also require that they perform well in real world situations we review the current state of the environmental performance of such oscillators. Standard, commercial off the shelf, non-cryogenic, compact, oscillators made using this technology repeatedly demonstrate phase noise of -144 dBc/Hz 1 kHz, and -170 dBc/Hz 10 kHz from the 10 GHz carrier. These same standard oscillators routinely achieve a g-sensitivity of better than 2 x 10(-10) per g.

Recent results proved a pair of prototype oscillators which had -160 dBc/Hz at a 1kHz offset from a 9 GHz carrier, and we have observed oscillators with g-sensitivities of better than 1x10(-11) per g in two axes.

Simultaneously, effort has been directed at advancing the environmental performance of these oscillators, and oscillators with a start up time of less than 2 minutes to full specification have been demonstrated.

The paper will finish with a summary of the levels of oscillator performance which can reasonably be obtained in the future taking into account known and proven support technologies.

FC1-F-3 511CF 2:15 p.m.

PHOTONIC MICROWAVE OSCILLATOR USING MODE-LOCKED LASER AS THE HIGH Q FREQUENCY DISCRIMINATOR

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It is well known from the general oscillator theory that, given the noise sources in an oscillator, the noise performance is determined by the Q value of the frequency discriminator in the oscillator loop. In the microwave domain, however, there is a lack of convenient high Q devices. Microwave frequency synthesizers multiply quartz oscillator at tens of MHz to GHz. The frequency multiplication inevitably multipies the phase noise at faster rate, limiting the microwave synthsizer phase noise. Dielectric resonators based on sapphire operating on whispering gallery modes represent the only viable approach to very low noise microwave oscillators, but are limited to frequencies in the range of ten GHz. More recently, it has been recongnized that an equivalent high Q in microwave can be achieved using an optical fiber link, as successfully demonstrated in the opto-electronic oscillator. In this paper, we will show that the narrow rf spectral response of a mode-locked laser (MLL) can serve as the high Q frequency discriminator for generating ultra-low phase noise microwave signals.

The mode-locked laser itself is an active optical resonance device. It is most instructive to follow the injection locking picture for understanding the resonant response of MLL as a microwave device used in a closed optoelectronic loop. When one applies an input to the mode-locker, all existing laser modes are modulated with two sidebands. If these sidebands are far away from the laser modes, the modulations die away quickly, and the photoreceiver recovers a weak residual AM modulation signal. As the driving frequency is tuned into the laser mode spacing, it tends to force the laser modes to oscillate in sync with the sidebands, due to the injection locking. This in turn resonantly increases the beatnote output level at the driving frequency. This filter-like response can be treated more analytically. We will show that the small signal response is exactly like a high-Q filter.

Experimentally, we demonstrate the high Q frequency discriminator using an erbium-doped fiber amplifier based fiber ring laser. The equivalent Q of it can be as high as 10^6. With such a setup, we were able to directly generate a 10 GHz microwave signal with the phase noise of -140 dBc at 10 kHz. The system also produces correspondingly low jitter short optical pulse.

FC1-F-4 511CF 2:30 p.m.

NON-INTERFEROMETRIC CARRIER SUPPRESSED CAVITY OSCILLATOR

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Current state-of-the-art microwave oscillators achieve their phase noise performance by utilizing a high-Q cavity resonator as a frequency discriminator for correcting the close-to-the-carrier phase noise in a closed-loop servo [1-3]. The limiting factor of the frequency discriminator at microwave frequencies is the flicker noise in the mixer. Techniques for overcoming this noise were introduced by suppressing the carrier and then amplifying the discriminated frequency noise [3-6]. By operating the mixer in suppressed-carrier mode, the multiplicative effect of the flicker noise can be greatly reduced. Traditionally, high levels of carrier suppression are achieved by using a microwave interferometer in conjunction with critical coupling to the cavity. This paper will demonstrate equal or superior performance to that achieved last year by the high power air-dielectric oscillator [7] without the use of an interferometer. Carrier suppression levels well in excess of 80 dB will be maintained by a new technique (patent pending).

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FC1-F-5 511CF 2:45 p.m.

POUND CIRCUIT - INDUCED FREQUENCY SENSITIVITIES IN ULTRA-STABLE CRYOGENIC OSCILLATORS

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We have analyzed the sensitivity of a Pound oscillator to thermally driven variations in frequency dependent transmission components between an assumed perfect phase modulated RF driver and the stabilizing resonator. Ultra-stable cryogenic oscillators with mixed cryogenic / room temperature architectures generally use a Pound circuit methodology to reduce the impact of variations in thermally unstable parts of the oscillator circuit. Without such a technique, thermal variations in (e.g.) transmission line length would prevent ultra-stable operation. A Pound circuit nominally eliminates these frequency variations by application of a relatively low frequency phase modulation to the resonator drive signal. Because the PM sidebands and the carrier suffer a similar phase delay, the quality of the PM is not directly affected by changes in delay. Thus detection of PM-AM conversion due to oscillator mistuning allows a frequency lock that is nominally immune to such path length variations. However, a consequence of frequency dependencies in transmission components is to induce phase and amplitude variations between the carrier and sidebands involved in the Pound detection process. An evaluation of consequent frequency sensitivities; to first derivative of amplitude with frequency and to second derivative of phase, are used to derive requirements for frequency-selective filters used in the synthesis of the resonator drive frequency, and also VSWR specifications for transmission line components.
This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Session: FC2-F

PHYSICAL SENSORS
Chair: J. Vig
US Army CECOM

FC2-F-1 511DE 1:30 p.m.

STUDY ON THE INTERACTION OF SOLID PARTICLES WITH SURFACES UNDER DIFFERENT AMBIENT CONDITIONS USING PIEZOELECTRIC SENSORS

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Study on the interaction of micro/nano particles with various surfaces under various ambient conditions is critical to many applications, such as microelectronics fabrication, chemical and biomedical engineering, and has been observed growing interest in the last decades. A sensing technique is needed to monitor interfacial phenomena and provide real-time information on the properties of the particles, surfaces and their interaction, such as masses of particles, cleanness of surfaces and binding energy, etc. In this paper, we present a simple and sensitive technique for monitoring of interfacial interactions, which utilizes piezoelectric quartz crystal sensors operating in thickness shear mode (TSM). The interaction of a particle with the surface of a TSM sensor can be described as a system of coupled lossy resonator. Through modeling and measurements of the electrical characteristics of the TSM sensor, information on the properties of the particle and the interaction is obtained. Different interaction forces, such as Van der Waals force, are considered to find the parameters in the coupled model. Effects of ambient conditions on the interaction are evaluated. Experiments have been made to measure the changes in resonant frequencies, amplitudes and phases of 5 MHz and 10 MHz TSM sensors at their fundamental and harmonic frequencies. Polystyrene, brass, chrome steel, ferritic and austenitic stainless steel particles with sizes from hundreds of nanometers to hundreds of micrometers have been used in the experiments. The effects of different ambient media, such as air, deionization water, acetone, etc., on the binding energy, coupling coefficient and lossy factor have been evaluated. The resonant frequency of a TSM sensor with particle/liquid loading is found to decrease or increase depending on a given experimental condition. The response of the TSM sensor depends on the effective coupling coefficient between the particle and the surface. The frequency shift is used to determine the particle size. The results have shown that piezoelectric TSM sensor is capable of real-time monitoring the interfacial interactions of solid particles with various surfaces under different ambient conditions, such as in air, water or electromagnetic field at a particular temperature, humidity and pressure. The obtained results allow the determination of binding energy and the size of particle.

FC2-F-2 511DE 1:45 p.m.

DETECTION OF NANOPARTICLES WITH QCR SENSORS

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Summary This contribution focuses on the detection of nanoparticles in liquid environment with Quartz Crystal Resonator (QCR) sensors. Polymeric nanoparticles and surface modified solid nanoparticles act as model analytes. The interface of the QCR is functionalized with self assembled monolayers (SAM) and Langmuir-Blodgett (LB) films. Ellipsometry, optical profilometry and microscopy are employed as independent methods. Acoustic measurements have

been performed at fundamental and overtone modes. Motivation Acoustic-wave based sensors are known as devices highly sensitive to mass changes on a picogram scale and increasingly used in liquid environment. Those sensors are also known to respond to viscous properties of the liquid environment, viscoelastic properties of the coating material and even interfacial phenomena. Recently, increasing activities can be recognized to apply acoustic measurements as label-free method for detection of proteins, viruses, bacteria, spores or cells. The detection of those "heavy particles" seems to be a simple task. Rigidly bonded, a monolayer of those objects should generate a frequency shift of several to tens of kHz. Experiments, however, show smaller signals, which cannot be explained unambiguously with incomplete coverage and viscoelasticity. We therefore started a systematic investigation of the interaction of nanoparticles with QCR sensors. We have concentrated on interfacial acoustic phenomena, which we believe are representative for the transduction mechanism in the above biosystems. Results The analysis is based on the Generalized Acoustic Load Concept (GALC). To limit the number and range of free parameters within GALC optical methods were applied to determine mainly layer thickness surface and coverage independently. Measurements up to the 9th overtone reveal distinct features, which have not been observed with acoustic chemosensors. We assume that specific features arise primarily from phenomena at the interface between the SAM or LB-film and the nanoparticle. Bond strength has been modified by means of chemical properties of the interface; the acoustic consequences can be analyzed by "acoustic slicing" by means of the harmonics.
The work has been supported by a grant of the Ministry of Education, Saxonia-Anhalt.

FC2-F-3 511DE 2:00 p.m.

MEASUREMENTS OF PARTICLES IN LIQUID USING A SURFACE ACOUSTIC WAVE SENSORS

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Measurements of particles in liquid, suspension and slurry are required in the field of industries, environmental contamination. A surface acoustic wave with a shear horizontal polarized displacement (SH-SAW) can work as a liquid-phase sensor. The SH-SAW sensor, which is fabricated on a 36YX-LiTaO3 substrate, is influenced by mechanical and electrical properties of an adjacent liquid. In this paper, we present the experimental results of paint-water binary mixture solutions with different colors, blue, red and yellow. The paint was chosen as a model for the particle involved solution, because pigment involves in the paint. The 50MHz SH-SAW sensor for simultaneous detection of the liquid mechanical and electrical properties was utilize. A liquid cell was placed on the propagating surface. Distilled water was used as a reference solution. The particles in samples deposited onto the sensor surface. Before measurements, the samples were mechanically stirred to uniformly disperse and then it was injected into the liquid cell. In the measurements, the sensor responses were immediately measured after sample was injected into the liquid cell (Experiment 1). Saturated values of sensor responses due to deposition were also measured (Experiment 2). There were no distinct differences from the results for mechanical properties of Exp.1 and Exp.2, such as viscosity and mass loading. However, there were observed differences from the responses for electrical properties of Exp.1 and Exp.2. In spite of the particles depositing on the sensor surface, the SH-SAW sensor cannot detect as massloading effect. The factors affecting could be as follows: the thin liquid layer exists between surface and particle. Whereas the penetration depth of SH displacement is 80nm for water at 50MHz, the results indicate that the influence of particles could not detect as viscosity effects. On the other hand, the penetration depth for the electric potential is about 12 microns. Therefore, the influence of deposition appears as electrical property change. The differences of colors were appeared in the electrical property measurements. Moreover, interesting facts can be discovered from the results for electrical properties in both Exp.1 and Exp.2. The sensor responses for less or more than 50 wt.% differ from each other. These mean that the liquid conditions are not the same. The paint involves in water below 50 wt.% and water involves in paint more than 50 wt.%. These results were observed for three colors. From the results, we conclude that new knowledge can be obtained from electrical property measurements. The differences of color were also appeared in the electrical property measurements.

FC2-F-4 511DE 2:15 p.m.

AN ACOUSTIC TWEEZER FOR MANIPULATION OF MICRO-AND NANOPARTICLES

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In the last decade there has been growing interest in development of new techniques for manipulation of objects at the micro- and nano-scale levels. Specifically, novel techniques capable of controlling motion of small particles have been intensively researched. In this paper, we present a novel technique allowing levitation and trapping of solid microparticles by using piezoelectric resonant actuators. There are a very few techniques that could be used to manipulate microparticles at the distances on the order of nano- and micrometer from the surface. Such capabilities are of particular interest for applications in the area of nanotechnology where capabilities of moving and assembling small objects are important for effective nano- and micro-scale manufacturing. Up-to-date magnetic tweezers have been used to move and trap magnetic particles and optical tweezers effectively were applied to solid nanoparticles and biological objects such as DNA and cells. Recently, atomic force microscope (AFM)-based techniques have been applied, with limited success, to particle manipulation. Piezoelectric actuators generate an acoustic force field which can be used for effective controlling of motion of a particle immersed in that field. The distribution of that field, and accordingly, mechanical forces, can be controlled by an

appropriate arrangement of the transducers and their phase relationships. In our work we have examined various modes of the acoustic fields for the manipulation purpose. The applied acoustic field was capable to move and trap solid stainless steel particles having the diameter range from 5 to 100 microns over the distance from nanometers to several microns. Actually, the particles were levitated above the surface of the actuator. The maximum of the vertical displacement was about a few microns and the lateral displacement of the particle along the surface was about a few hundreds of microns for the applied acoustic power on the order of about 30 mW. Both the vertical and lateral displacements were controlled by the power level of acoustic wave motion. A preliminary theoretical model describing the motion of a particle in the acoustic field has been developed and favorably compared with experimental data. The obtained results have shown that piezoelectric resonant actuators can implement a concept of acoustic tweezers. In principle, any type of particles, magnetic and non-magnetic, particles having arbitrary optical properties should be manipulated by acoustic manipulation techniques. The proposed acoustic tweezer should find applications in nanotechnology, biomedicine, pharmaceutical and space industries.
This work was support in part by the NSF Grant No. CCR-0304639 and the NTI Grant No. 242072

FC2-F-5 D11 2:30 p.m.

TECHNIQUES TO EVALUATE THE MASS SENSITIVITY OF LOVE MODE SURFACE ACOUSTIC WAVE BIOSENSORS

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With a shear horizontal polarization and a high mass sensitivity, Love mode surface acoustic wave (SAW) biosensors detect and quantify in real-time chemical species sustained in liquid environments. The Love mode is a guided acoustic mode generated in single or multiple layer coatings on a piezoelectric substrate. Love mode biosensors can be tailored in order to achieve desired parameters from both the electrical and sensing points of view. To this end, the fine tuning of these parameters requires a set of proper methods to investigate experimentally the sensing properties and link them with theoretical models that take into account the material characteristics as well as instrumentation and physical effects occurring in the device during a biorecognition experiment.

In this paper, we investigate two experimental approaches that can be used to evaluate the mass sensitivity of Love mode SAW biosensors. The first approach is based on the analysis of the dispersion curve of the sensor, which helps to determine, either by simulation or derivation, the value of the mass sensitivity. In order to obtain the dispersion curve, we have performed a chemical wet etching procedure that enables the continuous monitoring of the transfer function during the etching of the entire guiding layer.

The second approach is based on the addition or removal of layers in known quantities. The mass sensitivity is estimated in different cases: etching of a thin gold layer, copper electrodeposition, surface adsorption of an ionic surfactant or of a biochemical layer.

The results obtained by these techniques are compared to each other and to a theoretical model.

In the theoretical model, the layered structure of the acoustic sensor is described in terms of mechanical transmission lines and the mass sensitivity is calculated using the dispersion relation and the phase and group velocities. The model takes into account the design of the device, the influence of a liquid cell and the parasitic effects linked to the instrumentation. From this model, we extract the theoretical mass sensitivity of a multilayered system.

Future improvements of the model will address Love mode SAW biosensors with piezoelectric, semiconducting or porous guiding layers.

L. Francis thanks the FRIA (Fonds de Formation à la Recherche dans lIndustrie et dans lAgriculture) for its financial support.

FC2-F-6 511DE 2:45 p.m.

LOVE - MODE SURFACE ACOUSTIC WAVE LIQUID SENSORS USING A POLYIMIDE WAVEGUIDE LAYER

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Introduction A means to combine simultaneous refractive index and density measurements on the same sample is highly desirable in the food and drinks industry. Existing measurement methods involve separate sequential samples in a refractometer and a vibrating tube densitometer. A combined measurement solution, with the required small size, high sensitivity and small sample volume, necessitates a microsystems solution.

A SAW Love mode density sensor has been developed. Love modes form by focusing Shear-Horizontal SAWs into a thin waveguide layer, and exhibit high sensitivities with low acoustic losses into a liquid. The sensor incorporates two SAW delay lines, one with a smooth surface and the other patterned to trap the liquid and separate the density from the density - viscosity product, $\rho\eta$.

Experimental Love mode SAW devices were fabricated using HDM PI2545 polyimide waveguide layers spin coated onto Y cut ST-quartz substrates, with 40 μm wavelength IDTs operating up to 125 MHz. Polyimide offers simple and cheap fabrication, with a robust chemically resistant surface. This study is the first to use polyimide in a Love mode sensor. Patterned device corrugations were etched 0.5 μm deep into the polyimide using an O_2 RIE.

Results Investigations monitoring the centre frequency (f) and insertion loss for different thickness polyimide layers were used to characterise the waveguiding effect of the material. Minimum insertion loss occurs with 0.8 μm - 0.9 μm thick layers with an acceptable drop in frequency to around 123.5 MHz. For layers greater than 1.2 μm, no SAW behaviour was evident.

Temperature response of the devices was measured by heating from 20°C through to 60°C and monitoring f at intervals. The temperature coefficient of frequency varies between 0.0035 MHz°C^{-1} (0.7μm) and 0.008 MHz C^{-1} (1.2μm) with temperature independent response estimated to occur with 0.85 μm polyimide thickness.

Device sensitivity tests were made with a range of sucrose, saline, and oil samples, measuring Δf following sample contact on smooth and patterned devices. Δf increases proportionally for small $\rho\eta$ with patterned device response up to 4 times greater than smooth giving a sensitivity up to 69.7 kHz g^{-}1 cm^{-3}. For large $\rho\eta$, high insertion losses reduce SAW oscillations to near background levels, giving no relation.

Conclusions Initial results indicate the suitability of polyimide as a high sensitivity waveguide layer in Love-mode liquid density sensors. The response is proportional for small $\rho\eta$, and reproducible but not proportional for large $\rho\eta$. Temperature tests prove that a temperature independent device response is possible with polyimide.

Further Work Comparisons of the polyimide devices with CVD SiO_2 waveguide layer devices will lead to the development of a multilayer sensor using both materials. We believe this will offer a combination of high sensitivity and low losses and increase the $\rho\eta$ measurement range. Design improvements will reduce the insertion loss and background signal.

The authors gratefully acknowledge the financial support of the project from Index Instruments Ltd, the Durham County Council Science and Technology for Business and Enterprise Programme, and the EPSRC.

Session: U1-G

TISSUE ELASTICITY II
Chair: M. O'Donnell
University of Michigan

U1-G-1 510AC 3:30 p.m.

IN VIVO PROSTATE ELASTOGRAPHY: PRELIMINARY RESULTS

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We report preliminary results from our investigation of *in vivo* prostate elastography. Although physicians often can feel them manually during digital rectal exams (because tumors tend to be stiffer than surrounding tissue), prostate cancers typically are not reliably visualized using any current clinical imaging modality. Thus, an imaging method based on tissue stiffness could be useful in visualizing prostate cancers. Elastography displays a map of strain that results from external or internal compression. It already has shown promise in detecting and identifying breast cancers, and seems to be ideal for imaging prostate cancer because stiffer regions generally exhibit lower strain in elastograms.

We acquired digital radio-frequency (RF) data from patients on operating table undergoing prostate brachytherapy. In our studies, elastography data were obtained before seed-implantation in some cases and after implantation in the other cases. Seed placement is guided by a transrectal ultrasound (TRUS) probe, which is held in a mechanical fixture. The probe can be moved in XYZ directions and tilted. The probe face, in contact with the rectal wall, is used to apply a compression force to the immediately adjacent prostate. Both lateral movement and tilt motion were used to compress the TRUS probe against the prostate gland. Scans were oriented in transverse planes, approximately perpendicular to the urethra. As the deformation force on the rectal wall was continuously increased in each scan plane, we acquired RF data from thirteen subsequent scans at the scanner frame rate. We also used of a water-filled coupling membrane to compress the prostate; increasing the water volume inside the membrane distended it and applied the deformation force to the rectal wall and deformed the prostate. The mechanical fixture incorporated detents enabling the TRUS probe to be introduced into or withdrawn from the rectum in 5-mm steps and obtain elastography data in parallel planes. (This might eventually allow 3-D visualization.) We computed strain using RF cross-correlation analysis (1-D) in conjunction with least squares fitting of the estimated displacement. We currently are exploring advanced methods such as adaptive stretching and deformable meshes to see whether they can improve performance.

The compression method based on fixture displacement produced nice elastograms despite a small compression area that caused strain dissipation with depth. Balloon-based compression also produced promising elastograms. With both approaches, we were able to apply small strain ($< 2\%$) that allowed us to use conventional signal processing to estimate strain. Initial results demonstrate that a majority of cancers (7080% of a growing number of cases, as opposed to 50% for B-mode ultrasound) are visible in prostate elastograms and the cancer detectability is significantly higher with prostate elastography compared to conventional B-mode TRUS imaging.

Supported in part by NIH grant CA84274.

U1-G-2 510AC 3:45 p.m.

ACOUSTIC RADIATION FORCE IMPULSE IMAGING OF IN VIVO BREAST MASSES

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Acoustic Radiation Force Impulse (ARFI) imaging utilizes brief, high energy, focused acoustic pulses to generate radiation force in tissue, and conventional diagnostic ultrasound methods to detect the resulting tissue displacements in

order to image the relative mechanical properties of tissue. In an ongoing clinical study, ARFI images of in vivo breast masses are acquired prior to core biopsy. Matched B-mode and ARFI displacement images are generated for each mass. Data sets are divided based upon biopsy results, and images are evaluated for differentiating features. We previously presented phantom studies demonstrating improved image quality is achieved using multiple, tightly focused mechanical excitations in both the axial and lateral dimensions of a 2-D field of view. PURPOSE: The purpose of this study is to acquire ARFI datasets using multiple interrogation locations (e.g. 4 axial foci x 50 lateral foci) in vivo, in real-time, and to identify differentiable features between different breast mass types in the resulting images. METHODS: A Siemens Antares scanner and a VF10-5 probe were modified and programmed to implement ARFI imaging in a multi-focal zone configuration. Under an IRB approved protocol, patients scheduled for breast core biopsy were recruited for participation. Data was acquired in real-time and processed offline. Matched B-mode and ARFI images were evaluated concurrently. To date, 17 masses have been imaged under this experimental protocol. In addition, single focal zone ARFI data acquired from 52 masses with a Siemens Elegra scanner and a 75L40 transducer were evaluated for consistency of the differentiating features. RESULTS: Of the 69 masses, 22 were malignant, 15 were benign fibroadenomas, 18 were cysts, and the rest were other benign masses (i.e. lymph nodes, fat necrosis, etc.) Structures in matched B-mode images are in good agreement with those in ARFI displacement images, with both modalities demonstrating comparable resolution. In general, in ARFI displacement images, malignant breast masses exhibit increased contrast and improved margin definition over matched B-mode images. They displace less (i.e. they are stiffer) than the surrounding tissue, and in some cases they appear larger than in the matched B-mode images. In addition, some malignant masses exhibit a surrounding ring of uniform, slower recovery time, which has not been observed with benign masses. The cysts and fibroadenomas, in general, exhibit less contrast in ARFI images than in matched B-mode images. In many cases, fibroadenomas are not clearly distinguished from the surrounding tissues in ARFI displacement images. Acoustic streaming is observed in cyst fluid in response to ARFI excitation. CONCLUSIONS: ARFI displacement images portray different, complementary information than matched B-mode images. Some possible differentiating features between malignant and benign breast masses have been identified by this pilot study. Promising features include: displacement magnitude, recovery time, and image contrast. These results encourage further study of breast mass characterization using ARFI imaging.

U1-G-3 510AC 4:00 p.m.

BUBBLE-BASED ACOUSTIC RADIATION FORCE FOR MONITORING INTRAOCULAR LENS ELASTICITY

T. N. ERPELDING*[1], K. W. HOLLMAN[1], T. JUHASZ[1,2], and M. O'DONNELL[1],
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Previously, we demonstrated ultrasonic methods to monitor overall changes in the elastic properties of laser manipulated intraocular lenses. We also presented results using acoustic radiation force on laser-generated bubbles to measure viscoelastic properties of collagen gel phantoms. In the current study, we test the hypothesis that acoustic radiation force applied to laser-generated bubbles can monitor local changes of intraocular lens elasticity during a potential presbyopia treatment. Presbyopia is an age-related condition resulting from increased stiffness of the lens, reducing its ability to accommodate. Laser-induced optical breakdown (LIOB) treatment can increase compliance by applying a loose grid of photodisruption sites within the lens. A real-time elasticity monitoring system is needed to study the outcomes and guide this potential treatment. Optical breakdown occurs when sufficiently high threshold fluence is attained at the focus of femtosecond pulsed lasers, inducing plasma formation and bubble generation. The small transient gas bubbles can be used as targets for acoustic radiation force measurements prior to their ultimate collapse. While ultrasonic speckle is extremely limited within the lens, LIOB bubbles provide strong ultrasound backscatter to measure lens elastic properties. In this investigation, explanted porcine lenses are embedded within a gelatin phantom (5 w/w%) prior to laser treatment. An integrated optical-acoustical system has been constructed enabling simultaneous bubble creation and radiation force experiments. Femtosecond laser pulses (800 fs) are focused into the lens media to form bubbles using variable pulse number (1-3000) and peak powers. A two-element confocal ultrasonic transducer generates acoustic radiation force with the 1.5 MHz outer element while monitoring the bubble displacement within the lens using the 7.44 MHz inner element. The timing of acoustic radiation force application relative to bubble creation is controllable and can occur immediately following laser exposure. Preliminary experiments have demonstrated that bubbles created inside the lens using 1500 laser pulses at maximum fluence (30 J/cm^2) dissolved within 3 hours of laser exposure. A single LIOB bubble created with approximately 16 laser pulses at a fluence of 20 J/cm^2 has shown a maximum displacement of 128 μm using a 3.3 ms acoustic tone burst. Identical experiments performed in collagen gel phantoms of known mechanical properties resulted in larger bubble displacements. These results suggest a higher elastic modulus for porcine lenses, consistent with independent measurements of lens elastic properties. These results advance the development of an *in vivo* technique to monitor changes in lens elasticity during a potential laser presbyopia treatment.
This work has been supported in part by the Whitaker Foundation and the National Institutes of Health grants HL-47401 and HL-67647.

U1-G-4 510AC 4:15 p.m.

ABDOMINAL ACOUSTIC RADIATION FORCE IMPULSE (ARFI) IMAGING

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ARFI (Acoustic Radiation Force Impulse) imaging uses brief (100-160 microsecond) pulses of ultrasound to displace tissue and conventional ultrasonic methods to track the displacements. ARFI imaging of deep-lying tissues (8-16cm) presents unique challenges in generating sufficient radiation forces to measurably displace these tissues and in characterizing these small (typically 0-5 micron) displacements with low PRF tracking pulses. We have created viable ARFI images of realistic tissue phantoms and ex vivo bovine livers down to 10 cm and of the livers and kidneys of six healthy adult subjects down to 11 cm. The images were created using a modified Siemens Antares scanner with a curvilinear array operating at transmit frequencies between 2.5 and 3.5 MHz. Motion filtering was required to remove artifacts due to cardiac/respiratory/transducer motion and transducer heating artifacts. Displacements of liver tissues were on the order of 2-5 microns and kidney tissues moved 1-3 microns. Adjacent fatty tissues moved 20-30 microns. Images show good correspondence with B-mode images, and the capsule, parenchyma, and cortex regions of the kidney are distinguishable in vivo. Radiofrequency ablation sites in bovine livers were well visualized, with lesion sites being displaced 0-1 microns and untreated tissues moving 3-5 microns. Tissue displacements peaked 0.6 to 1.2 ms after application of the radiation force and recovered in 2-3 ms. Our results indicate that ARFI imaging is feasible for applications in liver and kidney imaging and in ablation guidance in these organs. We discuss challenges in transducer heating control, ultrasonic safety, and signal processing related to abdominal ARFI imaging.

U1-G-5 510AC 4:30 p.m.

HIGH FREQUENCY ELASTOGRAPHY FOR IN-VIVO STUDY OF THE MECHANICAL BEHAVIOR OF SKIN

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The aim of this study was to show the value of high-frequency elastography for the in-vivo study of the mechanical behavior of skin, which is affected in many human diseases. Our 20MHz real time sonographer (DERMCUP2020TM) was combined with a device called an Extensiometre, developed by the LMARC laboratory, for in-vivo skin creep and relaxation tests [Patent N° FR03/09220]. The latter device permits the application of a stretching stress in the plane of the skin. We first considered the principal methods used for 2D elastography (gradient and scaling factor methods) in order to estimate the axial and lateral displacements and strain field. We conducted an experimental study with PVA-cryogel phantoms to compare their performance by using simple compression of the phantom with the sonographer probe. A homogeneous PVA-cryogel phantom (E = 8kPa, thickness equal to 14 mm) was uniformly compressed axially to 4%. We assessed a mean axial strain equal to 4.15%±0.8 with the gradient method and 4.2%±0.5 with the scaling factor method. Since the performance of these two methods was similar, we choose the gradient method for its short computing time. Concerning the lateral displacement field due to axial stress

(because of the incompressibility of the media), this displacement field had a central axis of symmetry (where the displacement is nil) and we found maximum lateral displacement of 0.1 mm for 4% of strain. We also obtained elastograms of a two layer (soft and hard, of identical thickness of 2mm) PVA-cryogel phantom with compression stress and stretching stress, the latter stress were applied using the extensiometre. Axial and lateral resolutions of elastograms were 140μm and 0.4mm, respectively. In-vivo experiments were conducted with the extensiometre device on several sites of healthy human skin. We used RF sequences of the real time sonographer (10 RF images/s) to evaluate axial deformation and lateral displacement with cumulating small deformation steps (up to 10 steps), which allowed measurement up to 20% of local strain in the dermis with a correlation coefficient (ρ>0.9). Good correlation coefficients (ρ>0.8) were obtained in the same way, for axial and lateral displacement of subcutaneous fat : e.g. for the forearm external face, about +6% of axial strain occurred in the dermis with 2mm of stretching and $\pm$60μm maximum symmetrical lateral retraction in the dermis and -60μm in hypodermis. For the forearm lateral face, about +10% axial strain occurred in the dermis and -10% in the hypodermis for 4 mm of stretching. Lateral displacement was $\pm$ 0.4 mm in the dermis, -0.4 mm in the hypodermis and +0.4 mm in subcutaneous structures (muscle). The dermis has an original mechanical behavior since its thickness increased in the image plane during the creep test. The behavior of the hypodermis depends strongly on the displacement of the dermis and less significantly of surrounding tissues. These in-vivo results show the potential of elastography for the study of the mechanical behavior of healthy and diseased skin.
This work was supported by the Pierre Fabre Research Institute, Toulouse, France

U1-G-6   510AC   4:45 p.m.

ACOUSTIC RADIATION FORCE IMPULSE (ARFI) IMAGING OF THE GASTROINTESTINAL TRACT

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Currently, the evaluation of lesions in the gastrointestinal tract via transesophageal ultrasound suffers from poor contrast between healthy and diseased tissue. Acoustic Radiation Force Impulse (ARFI) imaging provides information about the mechanical properties of tissue. This method uses brief, high-intensity, focused ultrasound to generate radiation force and conventional ultrasonic correlation methods to track the tissue displacement response. Using conventional linear arrays, we have previously demonstrated that ARFI images can have improved contrast over B-mode images when applied to solid masses in the breast and liver. The purpose of this work is to (1) demonstrate that ARFI imaging can be performed with a transesophageal probe, and (2) demonstrate that ARFI imaging can provide improvements over conventional B-mode imaging of gastrointestinal lesions. **METHODS:** A V5M, 5 MHz linear Acuson transesophageal probe has been modified to perform ARFI imaging using

a Siemens Antares scanner. Concurrently, in an IRB-approved pathology study, ARFI imaging has been performed on fresh, surgically-excised gastrointestinal lesions. These experiments were implemented using a 75L40, 7 MHz linear array on a modified Siemens Elegra scanner. Data processing was accomplished off-line. **RESULTS:** The transesophageal probe has successfully created ARFI images to a depth of 4 cm in tissue-mimicking phantoms, with maximum displacements of 6 microns. The transesophageal probe does not heat appreciably during ARFI imaging. This demonstrates that the small size of this probe does not present a limitation for ARFI imaging. ARFI images of an adenocarcinoma of the gastroesophageal (GE) junction, status-post chemo and radiation treatment, demonstrate better contrast between healthy and fibrotic/malignant tissue than standard B-mode images. Gross and histologic evaluation of the lesion revealed fibrotic tissue, secondary to treatment, extending 3.0 cm laterally and invading to a depth of 0.5 cm. The ARFI images reveal a corresponding region of decreased displacement (i.e. stiffer tissue) also measuring 3.0 x 0.5 cm. ARFI images of healthy sections of gastric and esophageal tissue differentiate normal anatomic tissue planes (i.e. submucosal and muscularis layers), as confirmed by histologic evaluation. **CONCLUSIONS:** The smaller size of the transesophageal probe will not present a limitation for performing *in vivo* ARFI imaging of the gastrointestinal tract. In addition, ARFI images accurately portray the normal anatomic layers in *ex vivo* samples of stomach and esophagus. ARFI images of an *ex vivo* fibrotic/malignant lesion at the gastroesophageal junction correlate well with histologic and gross pathology images. These findings support the clinical feasibility of transesophageal ARFI imaging to help diagnosis and staging of disease processes in the gastrointestinal tract.
This work was supported by NIH grant 8 R01 EB002132 and the Whitaker Foundation. The authors would also like to thank Dr. Gregg Trahey for his valuable insight, and Siemens Medical Solutions USA, Inc. Ultrasound Division for their technical assistance.

Session: U2-G

HIGH FREQUENCY AND MICE
Chair: S. Foster
University of Toronto

U2-G-1 510BD 3:30 p.m.

COMPARISON OF 3D DEFORMABLE MODELS FOR IN VIVO MEASUREMENTS OF MOUSE EMBRYO FROM 3D ULTRASOUND IMAGES

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In the context of this paper, we are interested in the analysis of the 3D shape of mouse embryo from 3D ultrasound (US) images acquired using an experimental ultrasonic system. Automatic extraction (segmentation) of structures from images is a difficult and still opened problem in the image processing field. Among the existing segmentation methods, the deformable model based techniques rely on a a priori shape model of the structure. However, the methods have to be adapted according to specific properties of ultrasound images (low signal to noise ratio, presence of speckle, not well defined structure boundaries). From the anatomical point of view, at least two structures (the embryonic vesicle and the embryo) can be separately or even simultaneously extracted by iteratively deforming the a priori 3D anatomical model.

In this paper, we evaluate two deformable model techniques for the extraction of embryo in 3D US images. The first one is the simplex mesh based deformable surface model of Montagnat and Delingette (MD method). Surface simplex meshes are only representing anatomic structure boundaries in this model. The interior of the object is not modeled. Forces, computed from the images, are applied onto the mesh nodes to deform the model towards salient edges. The model deformation operates within an iterative minimization process of a global energy composed of an external and an internal term. The internal energy enforces the shape smoothness and keeps the memory of the reference shape. Attraction to image boundaries is controlled through the external term. The second model relies on the same energy minimization concept. The difference resides in that both the boundary and the interior of the object are modeled by an elastic material defined by a Young Modulus and a Poisson coefficient. Minimization is performed using specific numerical schemes and the Finite Element Method (FEM). This method, developed in our group, is named the Deformable Elastic Template (DET method).

Evaluation is conducted on simulated data, images acquired on a gelatin ultrasound phantom and on in vivo OF1 pregnant mice. 3D experimental images were acquired with a 20MHz ultrasound system equipped with a probe designed for a 2D displacement of a single transducer. Embryo volumes and dimensions are estimated from the geometric object produced by the segmentation algorithms. Computing time and influence upon the initial positioning of the a priori model are also considered in the study. With the physical phantom and the DET method, the comparison between measured and estimated dimensions of the inclusion inside the gelatin phantom leads to 33/32.1mm, 26/28.6mm, 26/26.3mm, along the X, Y and Z axis, respectively. On one in vivo dataset, the estimated volumes are 496 mm3 and 485 mm3 with the MD and DET methods, respectively. This tends to show that similar results are obtained with both methods. Computing time on a standard PC is however greater with DET (4-5 minutes) than with MD (<1 minute). These preliminary results have to be confirmed on a larger data set within this study.

U2-G-2 510BD 3:45 p.m.

ULTRASOUND B-MODE 360 DEGREE TOMOGRAPHY IN MICE

P. HOSKINS*, T. ANDERSON, S. MEAGHER, T. MCGILLIVRAY, S. HAMMER, and N. MCDICKEN, University of Edinburgh.
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Background. The mouse has become a powerful experimental model for investigation of human disease. Assessment of phenotype in mice may be achieved using micro imaging systems. MRI systems are expensive (US$2 million), and require long scan times (0.5-12 hours) hence have low throughput. X-ray CT is less expensive ($300k), is capable of high throughput (5-10 minute scan time), however high resolution studies may require delivery of a lethal radiation dose. Ultrasound techniques are based on real time 2D imaging, from which 3D information may be acquired. However current techniques are not based on whole body cross sectional imaging. This study demonstrates the potential of a whole body ultrasound approach to imaging mice. Methodology. The basis of the method is acquisition of cross sectional B-mode images taken at angles over 360o around the mouse. For the purposes of this demonstration study, dead mice were imaged. These were shaved, and embedded within tissue mimicking material to maintain structural stability and to provide a regular cylindrical geometry for imaging. The cylinder was mounted horizontally, with rotation provided by a motor connected at one end. Free wheels supported the mouse at intervals beneath the cylinder. Images were taken using a 12MHz probe from an ATL HDI 5000 scanner, and the 16 MHz probe from a Dynamic Imaging Diasus scanner. At each cross section, 150-160 images were taken for 1 full rotation of the mouse. The data was analysed off-line. Each image was rotated about the isocentre, to provide a set of aligned images. Ensemble averaging was performed to produce a single image at each cross section. Results. Images were produced showing full penetration through the body. Speckle was reduced from 18% from each B-mode image to 2% in the compound image. Individual B-mode images suffered from loss of data due to shadowing from skeleton and bowel gas. The compound images demonstrated substantial improvement in the appearance of structure at all levels, including thoracic, abdominal and pelvis, with no shadowing evident. Internal organs such as kidney and stomach were clearly visible. The skeleton was also clearly visible in the cross sectional images, including ribs and spine. Discussion. In the human the skeleton is heavily calcified, which prohibits the collection of whole body tomographic images using ultrasound. The success of this study is probably due to the cartilaginous nature of the mouse skeleton. It is known that cartilage is not as heavily calcified as bone, hence has an attenuation coefficient and speed of sound closer to that of tissue. A full 3D study of the mouse, assuming 100 frames per slice, 0.5 mm slice width, and 100 slices over 5 cm, would generate 5 Gbytes of data. The acquisition time at 30 frames/second could be as low as 5.5 minutes. Conclusion. This study has shown the feasibility of collecting whole body cross sectional data in the mouse. Further developments are necessary for longitudinal (serial) imaging of live mice, and for improvement of spatial and contrast resolution.

U2-G-3 510BD 4:00 p.m.

COMPARISON AND VALIDATION OF HIGH FREQUENCY ULTRASOUND DETECTION TECHNIQUES IN A MOUSE MODEL FOR RENAL TUMORS

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This study aims to compare and validate high frequency (20 50 MHz) ultrasound imaging techniques for early detection and follow-up of renal tumors in a murine model of Wilms tumor. This model is induced by renal sub-capsulary injection of malignant cells (from human Wilms tumors) in nude mice and is currently used in preclinical trials of new therapies for this cancer of the infant (frequency of 1/10000). Although, ultrasound is often used to detect Wilms tumors in infants, in murine studies, evaluation techniques remain limited to in vivo palpation and histologic studies following the sacrifice of the animal. To non invasively monitor and validate ultrasonic tumor detection, the following protocol was followed on 7 mice. Three days after cell injection, images of the control and injected kidneys were acquired in vivo using an imaging system with a hand-held probe containing a 25 MHz center-frequency mechanically-scanned transducer (3.2 mm diam. 7.4 mm focus). Imaging sessions were repeated (under anesthesia) every 4 days. Each tumor was followed from earliest detection until a different stage of development. The mouse was then sacrificed and kidneys were imaged post-mortem, in situ with an ultrasound biomicroscopy system (50MHz PVDF; 6.0mm diam. 12.3mm focus or 40MHz Lithium Niobate; 6.0mm diam. 12.3mm focus). Finally, histologic study independently characterized the tumor position, nature and dimensions. In vivo detection of small tumors (diameter $<$ 1mm) was confirmed as early as day 11, which is very early relative to first detection by palpation (typically $\geq$ 3 weeks and diameter $>$ 5 mm). Tumor size (width length 0.5) as assessed in vivo followed similar growth-curves for all detected tumors as a function of time after first detection. Tumor size assessed in vivo agreed with post-sacrifice estimation (caliper measurements) within 20 %. Early stage tumors (histology: anaplastic cells with large nuclei characteristic of tumor) appeared hypoechoic in vivo with respect to normal cortex. Comparison of site-matched ultrasound images (40MHz, 50MHz) and histologic sections suggests that necrotic and viable tumor present different echogenicity. Feasibility of non invasive detection and characterization of renal tumor development for monitoring of the same animal during longitudinal evaluations of therapy was demonstrated at 25 MHz. Modifications in echogenicity observed at different stages of tumor development (anaplastic cells, viable, necrotic) should be investigated as a means of further probing tumor nature by ultrasound.

U2-G-4 510BD 4:15 p.m.

PERFORMANCE OF A 50 MHZ ANNULAR ARRAY BASED IMAGING SYSTEM

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The difficulty in fabricating miniature transducer arrays for high frequency medical ultrasound imaging is currently limiting the development of this field. Most high frequency ($>$ 30 MHz) imaging systems are based on single element geometrically shaped transducers. Although these transducers are relatively easy to fabricate, their performance is restricted by the inherent compromise between the image resolution and depth of field. This compromise could be avoided by replacing the single element transducer with an annular array. In many ways an annular array is an ideal candidate for a high frequency imaging system. Although it is not possible to electronically steer the ultrasound beam, the depth of field of an annular array may be extended greatly over that of a geometrically focused transducer. Perhaps the biggest advantage of an annular array is that the axial symmetry of the array leads to the formation of a high quality radiation pattern using larger and far fewer elements than required by a linear/phased array. We previously described the design and fabrication of a 2 mm diameter 50 MHz, 7-element annular array and the associative beamformer. In this paper we will describe our recent work evaluating the performance of the combined system (annular array + beamformer) and present our first high frequency in-vivo images. The radiation pattern of the array was evaluated by imaging a point target immersed in a water bath. For comparison, a radiation pattern was also measured for a single element geometrically focused (f/2) transducer with an equal aperture. The lateral image resolution at a distance of 4 mm was 75 microns for the array transducer, and 65 microns for the single element transducer. The depth of field however, was much larger for the array. Wire targets separated by 1 mm intervals were also imaged using each transducer. When displayed with a dynamic range of 40 dB, only three targets were visible for the single element transducer whereas all 6 targets were clearly visible with the array. Preliminary images of mouse eyes (CD-1 mice) were also made. The images were made in-vivo and displayed with a dynamic range of 60 dB. The images show many identifiable features in the anterior segment including the cornea, lens, and ciliary muscles.
Financial support for this work was provided by NSERC and ORDCF.

U2-G-5 510BD 4:30 p.m.

HIGH-RESOLUTION ULTRASOUND IMAGING OF MUSCLE DYNAMICS AND EFFECTS OF FATIGUE

R. S. WITTE*, D. E. DOW, R. OLAFSSON, Y. SHI, and M. O'DONNELL, University of Michigan.
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Electrocardiomyography, magnetic resonance, optical tomography and birefringence have all been used to image skeletal muscle function during contraction. None of these conventional techniques, however, offers adequate spatial and temporal resolution to portray dynamics inside the muscle. We describe a real-time high-frequency ultrasound acquisition system that provides ample resolution (~30 μm and 200 μs) to depict coordination of individual muscle fibers during an isometric contraction; the resulting strain profile relates directly to muscle performance. We further examine the effects of muscle fatigue by imaging a cross section of an isolated muscle excised from an anesthetized mouse. The *extensor digitorum longus* (EDL) was removed from the hind limb of a mouse and immersed in Ringers solution. One end of the isolated muscle was fixed to a metal plate and the other to the lever of a force transducer, which measured the strength of each muscle contraction. Unstretched muscle thickness ranged from 3 mm in the middle and tapering to 1 mm at the ends. Muscle length was adjusted such that maximal twitch force was obtained. Isometric contractions were controlled by the pulse amplitude of electrical stimulation (square pulse, 0.4 ms duration) produced by electrodes placed in the Ringers solution. Muscle fatigue was caused by intervals of tetanic stimulation (supramaximal pulse trains, 0.4-2 ms pulse width, 150 Hz) until the force produced by a signal contraction was reduced by the desired fatigue level. A high-speed acquisition board (Signatec PDA500) and a spherically-focused high-frequency (85 MHz) ultrasound transducer were used to produce axial images of the muscle at 5 kHz frame rate for 200 ms following stimulation. A phase-sensitive speckle-tracking algorithm, capable of detecting displacements as small as 100 nm, was used for strain estimation. Axial strain during peak isometric contraction exceeded 2 % and was highly dependent on stimulation parameters and muscle performance. In one experiment, after the EDL muscle was fatigued to 25% of maximal force, we observed a corresponding reduction in peak strain (2.0 % to 0.5 %) and strain rate (3.2 Hz to 0.5 Hz) within the muscle cross section. Moreover, the spatial distribution of strain was not uniform and varied by as much as the peak value during contraction, corresponding to a gradient of 0.7 % per 100 μm. This study gives new insight related to the intricate coordination of muscle fibers during contraction and the effects of fatigue. We have also planned a fatigue experiment with humans using a clinical ultrasound scanner that will further investigate the impact of fatigue *in vivo* at high resolution. This potentially noninvasive technique may also be appropriate to assess severity of movement disorders, such as cerebral palsy, and track coordination during therapy and rehabilitation after muscle injury.
Research supported by DARPA #N66001-02-C-8059

U2-G-6 510BD 4:45 p.m.

HIGH FREQUENCY ULTRASOUND SIGNAL STATISTICS FROM MOUSE MAMMARY TISSUE DURING INVOLUTION

A. S. TUNIS*[1,2], A. GILES[2], D. SPURRELL[2], D. MCALDUFF[2], M. HARIRI[1,2], R. KHOKHA[1,2], G. J. CZARNOTA[2,3], M. D. SHERAR[1,2], J. W. HUNT[1,2], and M. C. KOLIOS[1,3], [1]Department of Medical Biophysics, University of Toronto, [2]Ontario Cancer Institute/Princess Margaret Hospital, University Health Network, [3]Department of Math, Physics & Computer Science, Ryerson University. Corresponding e-mail: adam.tunis@utoronto.ca

Our lab has previously shown that high frequency ultrasound (HFUS) backscatter is sensitive to the structural changes that occur during necrotic and apoptotic cell death. There is a marked increase in HFUS integrated backscatter (IB) in cells that have undergone apoptosis and necrosis; forms of cell death thought to play a role in the response of tumours to cancer therapy. While HFUS IB has been used successfully to monitor structural changes in cells in vitro, monitoring changes in vivo has proven more difficult due to the changes that can occur in both cell and tissue structure. As a complementary technique, we are investigating the use of signal envelope statistics to monitor structural changes occurring in cells. This technique has previously been applied at lower frequencies to ultrasound tissue characterization in the skin, breast and heart. To evaluate the application of this technique to monitoring cell death, we use a well-characterized model of apoptosis: the tissue restructuring during mouse mammary involution.

We examined the mammary tissue of four mice studied for 6 days during mammary involution. The pellets were 1mm thick and formed with concentrations of treated cells from 0a heated water bath as a coupling medium. Images were collected along with radio frequency (RF) data from 100 independent locations within the mammary tissue using a HFUS imaging device (VisualSonics VS-40B) with a 20MHz f #2.35 transducer. The envelope of the RF data was computed using the Hilbert transform method and the maximum likelihood method was implemented in Matlab to fit theoretical probability density functions (PDFs) to the data. The goodness of fit of the PDFs was evaluated using the Kolmogorov-Smirnov (KS) goodness of fit statistic.

For the mammary tissue, the GG PDF yielded KS values one order of magnitude less than the Rayleigh PDF. The KS values indicate that at day 2 of involution the signal tends towards Rayleigh statistics, while at a later time the statistics become increasingly non-Rayleigh. The parameters of the GG PDF show good sensitivity to changes in tissue structure. There is a trend in the GG parameters where at day 2 of involution the GG PDF becomes closer to a Rayleigh PDF.

Results demonstrate that signal statistics are affected by cellular changes during cell death. Data collected from the mouse mammary tissue show a trend toward Rayleigh statistics at day 2 of involution. The results of the study indicate that HFUS signal statistics can be used to monitor tissue changes in this model.

This work was funded by the Natural Sciences and Engineering Research Council of Canada, the Canadian Institutes of Health Research, the Canada Foundation for Innovation and the Whitaker Foundation.

Session: U3-G

MEDICAL TRANSDUCERS
Chair: M. Schafer
Sonic Tech Inc.

U3-G-1 511AB 3:30 p.m.
(Invited)

CLINICAL APPLICATION AND TECHNICAL CHALLENGES FOR INTRACARDIAC ULTRASOUND IMAGING

S. BOLORFOROSH*, J. BARTLETT-ROBERTO, D. TASKER, and T. PROULX, Siemens Medical Solutions USA Inc., Ultrasound Division.
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Increasingly, advanced catheter-based interventional cardiac procedures require accurate anatomic imaging tools. Conventional transthoracic and transesophageal ultrasound imaging can not provide the imaging requirements of many advanced procedures due to restricted access to the anatomy. Intracardiac echocardiography (ICE) can provide unrestricted access and has been shown to be very effective in accurately guiding interventional cardiac procedures through high quality visualization of anatomy. ICE is steadily replacing transesophageal ultrasound as the preferred imaging tool to guide devices for atrial fibrillation treatment and closure of both atrial septal defects and patent foramen ovale.

In the first part of this paper we will review the clinical application for ICE such as electrophysiology and minimally invasive surgical procedures. The requirements for an intracardiac ultrasound imaging system and catheter transducer will be reviewed with respect to the clinical applications. We will also compare the performance of ICE to fluoroscopy.

In the second part of this paper we will discuss the recent advances in transducer technologies such as miniature interconnects, micro coaxial cables, miniature acoustic transducers and 2D arrays. Critical performance requirements such as image quality, catheter size and catheter maneuverability will be discussed.

In the third part of this paper we will briefly discuss the ICE regulatory requirements to ensure patient safety.

In the final section of this paper we will discuss future trends in ICE and emerging applications for catheterbased ultrasound imaging systems.

U3-G-2 511AB 4:00 p.m.

REAL-TIME 3-D TRANSESOPHAGEAL ECHOCARDIOGRAPHY

E. C. PUA* and S. W. SMITH, Duke University.
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Transesophageal echocardiography (TEE) is established as an essential diagnostic tool for patients that are obese or that exhibit signs of pulmonary disease. However, current techniques in transesophageal scanning of the heart are limited by the maneuverability of the esophageal probe as well as by incomplete visualization in close proximity to the transducer. In order to improve on these shortcomings, multiplane TEE probes have been made commercially available. These devices incorporate a rotating linear array; by processing multiple B-scans after image acquisition from these arrays, 3D images can be attained. These off-line rendered TEE images have been shown to provide information previously unavailable in standard diagnostic or intra-operative procedures; however, multiplane probes cannot acquire 3D ultrasound images in real-time, and they rely on an additional mechanical rotation system within the endoscope. A real-time 3D TEE probe has been fabricated in our laboratory in order to increase the amount of information available during a transesophageal procedure. The 6mm diameter endoscope probe utilizes a 2-dimensional, 5MHz array at its tip with a 6.3mm diameter aperture, including 508 transmit and 256 receive channels. The array has a periodic vernier geometry with an element pitch of 0.18mm, and it was built on a multilayer flexible interconnect circuit (MLF). Simulations performed in Field II show a theoretical -6dB beamwidth of 3.2 degrees, yielding a lateral resolution of 3.4mm at 6cm depth. In order to accommodate 508 channels within the endoscope, 1m long Gore Microflat cable was utilized for wiring the MLF to the corresponding system handle connectors. The prototype array was built without a matching layer in order to simplify fabrication, and pulse-echo tests in a water tank have yielded a -6dB bandwidth of 28%. Fully connected to the system through 3m of cable, the probe shows an average insertion loss of -85dB with a standard deviation of 3.3dB, as determined through pitch-catch measurements for 10 elements. Using the completed 3D TEE probe with the Volumetrics Medical Imaging 3D scanner, real-time volumetric images of hyperechoic and hypoechoic lesions in tissue phantoms have been acquired using phased array scanning in both azimuth and elevation for a total 65 degree pyramidal volume. In addition, volumetric scans of excised sheep hearts have been obtained in real-time.

U3-G-3 511AB 4:15 p.m.

3D ULTRASOUND IMAGING SYSTEM USING FRESNEL RING ARRAY & HIGH VOLTAGE MULTIPLEXER IC

S. TAMANO*[1], T. KOBAYASHI[2], S. SANO[2], K. HARA[3], J. SAKANO[3], and T. AZUMA[4], [1]Research & Development Center, Hitachi Medical Corporation, [2]Ultrasound Department, Hitachi Medical Corporation, [3]Hitachi Research Laboratory, Hitachi, Ltd., [4]Central Research Laboratory, Hitachi, Ltd.
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In the previous report [IEEE 2003 Ultrasonics Symposium P1H-5], the prototype two-dimensional convex-convex shaped array probe and a real-time three-dimensional ultrasound imaging prototype system have been reported. In that probe, a few thousands of elements are electrically bundled into dozens of Fresnel rings shape using high voltage multiplex custom ICs. And we presented (1) a transmit beam form was measured by a convex-convex shaped two-dimensional array probe having 4,096 elements, (2) a principle of 3D imaging system using this array and an 8:1 high-voltage multiplexer custom IC with 8 channels, and (3) the result of three-dimensional imaging with 8-channels ultrasound transmission and reception. At this time, our convex-convex (40mmR-40mmR, 3.5MHz center frequency) shaped 2D array probe has been changed to include approximately eight-thousand of elements and has been modified into more packed fashion. Moreover, signal handling capability of our custom multiplexer IC is scaled up to 32:1 with 32 channels from 8:1 with 8 channels. This high voltage multiplexer ICs are COB(Chip On Board) mounted on PCB(Printed Circuit Board) inside the 2D array probe to decrease thickness of scan-head. With these improved array and multiplexer ICs, we can realize that more than three-thousand active elements are bundled into 32 Fresnel rings, and these rings are connected to the probe connector of conventional system via cables, and scanning is sequentially performed with an ring-diameter of 20mm or larger. Using this newly developed configuration, we expect to improve our previous system to more practical real-time 3D imaging system in order to achieve further improvement of sensitivity of ultrasound transmission and reception, improvement of spatial resolution, and enlargement of Field of View angle (FOV angle). In this presentation, we demonstrate our real-time 3D imaging system with 70° x 35° FOV angle and report preliminary feature of this system. Especially, transmission-reception sensitivity is dramatically improved and it may reach up to conventional systems. We believe that feature of our system, (1) axially uniform beam profile of Fresnel-Ring aperture and (2) huge number of active elements is reduced to only 32-64 channels (easily employing conventional mid-range beamformer) is promising in the point of view of image resolution and cost-effectiveness.

U3-G-4 B11 4:30 p.m.

REAL-TIME 3D ULTRASOUND WITH MULTIPLE TRANSDUCER ARRAYS

M. P. FRONHEISER*, E. D. LIGHT, and S. W. SMITH, Deptartment of Biomedical Engineering, Duke University.
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We modified our real time 3D ultrasound system (Duke U./Volumetrics Medical Imaging) for near simultaneous 3D scanning with multiple 2-D array transducers. The 3D scanner uses 512 transmit channels and 256 receive channels for arrays operating from 2-10 MHz. The real time system scans a 650-1200 pyramid with 16:1 receive mode parallel processing producing up to 60 volumetric scans per second and features up to five image planes as well as 3D rendering, 3D pulsed wave and 3D Color Doppler. To incorporate multiple near simultaneous arrays, we divided the phase delay memory into multiple segments, each segment corresponding to a separate array transducer with unique array geometry. This allows multiple combinations of transthoracic, transabdominal, endoscopic, catheter and ultrasound therapy probes of annular, linear and 2-D arrays limited only by the total number of 512 transmitters, 256 receivers. As a first illustration we modified the transducer cable assembly to incorporate two independent 3D intra-cardiac echo catheters, a 7 Fr (2.3 mm O.D.) side scanning catheter and a 14 Fr forward viewing catheter with tool port each of 85 channels operating at 5 MHz. For applications in treatment of atrial fibrillation, the goal is to implant the side-viewing catheter within the coronary sinus to view the whole left atrium including left pulmonary veins. Meanwhile the forward viewing catheter inserted within the left atrium is directed toward the os of a pulmonary vein for therapy using the integrated tool port. With pre-loaded phasing data, the scanner switches between catheters automatically at the push of a button with a delay of only a few seconds so that the clinician can view the therapy catheter with the coronary sinus catheter and vice versa. At present the automatic switching system has been tested in tissue phantoms. Ultimately, the system will switch between 3D probes on a frame-by-frame basis, line-by-line basis, or on the basis of frequency separation for true simultaneity and enable image fusion of multiple 3D scans.

U3-G-5 511AB 4:45 p.m.

ADVANCES IN TWO DIMENSIONAL ARRAYS FOR REAL TIME 3D INTRAVASCULAR ULTRASOUND

E. D. LIGHT* and S. W. SMITH, Duke University.
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Real time 3D IVUS may require imaging depths of a few centimeters to look down the axis of a coronary vessel to view vulnerable atherosclerotic plaque. We have previously described 2D array transducers for forward looking real time

3D intravascular ultrasound (IVUS). We used a non-coaxial based cable that allowed 100 signal wires to be placed inside a 4.8 French IVUS lumen with an inner diameter of 1.3 mm. In order to obtain the desired penetration depth, we constructed an 10.0 MHz transducer array which includes $11 \times 11 = 121$ elements for real time 3D intravascular imaging. The transducer was constructed in the forward viewing configuration to allow simultaneous real time B-scans, C-scans and volumetric rendering of vessels and vascular stents. In order to conform to the round aperture of the IVUS lumen, the corners were cut off resulting in a total of 97 signal channels. The 50 Ohm insertion loss is 83 dB and the 6 dB bandwidth is 25%. Average cross talk on nearest neighbor elements is 27.6 dB when loaded by the Volumetrics Medical Imaging scanner, and 31.6 dB when loaded by 50 Ohms. However, our earlier processes led to poor yield and image quality. A new process, based on a custom fixture, improved the flatness of the wireguide. This improved our bonding and dicing techniques and increased our yield by 50%. Real time 3D images include tissue vascular phantoms with a 4.0 mm diameter lumen, a vascular stent before after deployment in a tissue mimic phantom, and images of the aorta of an excised sheep heart. We have also pursued the fabrication of another 2D array transducer for IVUS that was constructed with non-rectilinear element placement. Using the same cabling, 61 elements were diced out with a laser. Preliminary impedance plots show a resonance at 10.0 MHz.

Session: U4-G

PHYSICAL ACOUSTICS III

Chair: J. Brown
JB Consulting

U4-G-1 513AB 3:30 p.m.

A VARIATIONAL PRINCIPLE FOR THE EQUATIONS OF VISCOPIEZOELECTRICITY

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In a previous paper (Lee, Liu, and Ballato, IEEE Trans. UFFC, Vol.5, No.1, pp.52-62,2004), the 3D equations of linear piezoelectricity was extended to include losses attributed to the acoustic viscocity and electrical conductivity. These equations were employed to investigate effects of dissipation on the propagation of plane waves in an infinite solid, and thickness vibrations and plane waves in an infinite viscopiezoelectric plate of general symmetry. In the present paper, the internal energy, kinetic energy, and electic enthalpy densities are defined for a viscopiezoelectric crystal of volume V and bounding surface S. By introducing these density functions into a variational principle, it is shown that the equations of viscopiezoelectricity as well as the natural boundary conditions

are obtained. The resulting variational governing equations and boundary conditions will be employed to derive, systematically, a system of 2D approximate equations for high- frequency vibrations of viscopiezoelectric plates.

U4-G-2 513AB 3:45 p.m.

PIEZOELECTRIC DEVICES FOR EXTREME-TEMPERATURE APPLICATIONS

H. J. WHITEHOUSE*, A. M. LEESE DE ESCOBAR, and M. PEREIRA DA CUNHA, [1]Linear Measurements, Inc, [2]SPAWAR Systems Center, [3]Dept. of Electrical and Computer Engineering, University of Maine.
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Piezoelectric devices have recently been developed for extreme-temperature applications. Extreme temperature is used here to mean low or high temperatures outside of the "traditional" range of -55 to +125 degrees Celsius. At the low-temperature extreme, there is a need for filters that operate from room temperature, ~300 Kelvin, to cryogenic temperatures of less than ~77 K. Y-cut, Z propagating Lithium Niobate Surface Acoustic Wave (SAW) delay lines have been investigated for temperatures between 5 K and 300K. The temperature coefficient of delay becomes small at temperatures less than 77 K and goes to zero at ~20 K. Thus thermally stable SAW filters can be constructed at cryogenic temperatures using high temperature superconductor, YBCO, electrodes. Since these filters are based on piezoelectric properties they should continue to operate above the superconducting transition temperature.

At the high-temperature extreme, there is a need for crystal controlled oscillators that operate from room temperature to 315 degrees Celsius. Both Bulk Acoustic Wave (BAW) and SAW materials have been found that have turnover temperatures in this range. Generally, these materials outperform quartz at temperatures above 150 degrees Celsius. The most promising of these materials is Gallium Ortho-Phosphate. A 5MHz BAW oscillator for geothermal wells has been designed and tested that had a total frequency variation of 300 ppm over the temperature range from 0 to 300 degrees Celsius. Similar results are expected from Gallium Ortho-Phosphate SAW oscillators at higher frequencies.
This work was supported in part under a Department of Energy (DoE) SBIR Grant No. DE-FG03-99ER82812 and by the SPAWAR Systems Center - San Diego

U4-G-3 513AB 4:00 p.m.

REVISITING THE STOKES RELATIONS IN A TIME REVERSAL CAVITY: SUPPRESSION OF INTRA-PLATE ECHOES INDUCED BY AN ULTRASONIC FABRY PEROT

F. VIGNON*, J.-F. AUBRY, M. TANTER, G. MONTALDO, and M. FINK, Laboratoire Ondes et Acoustique, ESPCI, Université Paris VII,U.M.R. C.N.R.S. 7587, 10 rue Vauquelin, 75005 Paris, France.
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When focusing through plates or tubes the presence of multiple interfaces induces reflected wave fronts that follow the main wave front. Adaptive focusing techniques can be used to cancel the echoes. For that purpose, two linear arrays of transducers have been placed on each side of a titanium plate. Three propagation operators have been acquired: transmission from one array to the other and two reflection operators acquired by each array. In this work, two adaptative focusing methods have been used to cancel the echoes: firstly, they have been suppressed with a time reversal mirror, using the two arrays cavity surrounding the plate. Secondly, the echoes have been cancelled by using the inverse filter technique, inverting the transmission operator. Thus, the inverse filter achieves echoes cancellation (up to 40dB decrease) by using only the transmitted fields, whereas time reversal also requires the reflected fields. It is shown how transmission and reflection operators are related by the Stokes relations in a matrix formalism. These relations clearly exhibits how the inverse filter takes advantage of the reflections towards the emitting array: the emission vector is composed of the sum of two signals corresponding respectively to the time reversed signals of the reflected wave front and the inverse of the filter of the transmitted wave front. An iterative mathematical resolution yields to a new way to invert the transmission operator thanks to first order and second order series derived from a matrix formulation of the Stokes relations between the transducers of the cavity.
This work was supported by grant QLG1-CT-2002-01518 (UMEDS: Ultrasonographic Monitoring and Early Diagnosis of Stroke) from the European Commission.

U4-G-4 513AB 4:15 p.m.

2D PSEUDO-ARRAY USING AN ULTRASONIC ONE CHANNEL TIME-REVERSAL MIRROR

N. QUIEFFIN*, S. CATHELINE, R. K. ING, and M. FINK, laboratoire ondes et acoustique.
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Focusing and beam forming is achieved using a time-reversal process and a unique transducer coupled to a solid cavity. This technique allows one to focus acoustic energy anywhere on a 3-D domain with a spatio-temporal resolution comparable to multiple transducers array. We first record the signal emitted by the transducer and detected by an hydrophone needle at a reference point. The signal received is then time-reversed and remitted using the same transducer. At the reference point one can observe a spatio-temporal recompression. More over, it is shown how the experimental Greens functions at the surface of the cavity can be used to control the emitting ultrasonic field. The solid cavity becomes a 2D pseudo-array. A careful study of this phenomenon leads us to better understand the resolution of the focusing system: according to the diffraction theory, the focal width is no more dependent on the transducer aperture but on the dimensions of the solid cavity. The signal-to-noise ratio of such a system is then explained by a modal theory and leads to define four influencing parameters: the frequency bandwidth, the number of transducers, the geometry of the cavity

and the time reversed signal duration. At last, a one channel Inverse Filter based on the frequency analyze is defined: its efficiency is compared to the time reversal one and linked to the modal theory.

U4-G-5 513AB 4:30 p.m.
(Invited)
WHAT ARE THE LIMITS OF ENERGY FOCUSING IN SONOLUMINESCENCE?

S. PUTTERMAN*, C. CAMARA, B. KAPPUS, C.-K. SU, and E. KIRILOV, University of California.
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Sonoluminescence ['SL'] is an amazing marker for the extraordinary degree by which ultrasonic energy can be focused by a cavitating bubble of gas. Local energy dissipation exceeds Kirkhoffs law by 15 orders of magnitude and the ambient acoustic energy density concentrates by 12 orders of magnitude to create picosecond flashes of broadband ultraviolet light. At the minimum bubble radius where the contents have been compressed to their van der Waals hard core the acceleration exceeds a trillion 'g' and a Mega-Bar level shock wave is emitted into the surrounding fluid. For single bubbles driven at 30KHz SL is nature's smallest blackbody. This implies that the bubble's interior is such a dense plasma that the photon-matter mean free path is shorter than the wavelength of light, and suggests that SL originates in an unusual state of matter. Excitation of a vertical column of fluid [$\sim$10Hz] so as to create a water hammer leads to the upscaling of SL so as to generate flashes of light with 3x10^8 photons and peak powers approaching 1W. At 1MHz the spectrum resembles Bremstrahlung from a transparant plasma with a temperature $\sim$1MK. At 10MHz the collapsed size of the SL bubble approaches 10nm, which raises the possibility that the SL parameter space may extend to the domain of quantum mechanics. At 30MHz experiments are under way to excite sonoluminescence with sound fields in excess of 3,000atm. The strongest cavitation collapses may be realized with M. Greenspan's ultrasonic resonators which can reach sound fields in excess of 20 atm without cavitating. When bubbles are seeded with an external laser a massive cavitation event ensues. Although the SL mechanism and its robust parameter space remain a mystery it has already been put to use as a surgical device. At 30KHz it is used for internal lipectomy and at 1MHz it is used for externally assisted lipectomy.
Supported by Darpa and the DOE (BES)

Session: U5-G

SAW SENSORS
Chair: M. Da Cunha
University of Maine

U5-G-1 512C-H 3:30 p.m.

GLOBAL SAW TAG RFID SYSTEMS

C. HARTMANN*, P. BROWN, P. HARTMANN*, J. BELLAMY, L. CLAIBORNE, and W. BONNER, RF SAW, Inc.
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The Global SAW Tag [1] is projected to be a large-volume SAW device application because it solves the restricted code range problem that characterized prior SAW ID tags. This system has global usefulness because it has the large code range needed for international trade and because it operates legally world wide using the 2.45 GHz ISM frequency band. SAW RFID has recently gained market acceptance for numerous applications that can only be implemented by using this technology. It is the only approach that achieves relatively long read range with a passive (i.e. no battery) tag. The Global SAW Tag fills various market needs and compliments the capabilities of IC chip based RFID systems that have relatively short read range.

Recent improvements in the modulation method and overall tag data structure are reviewed for a family of SAW RFID devices. Current implementations use a basic group structure that encodes 16 information bits using 4 reflectors chosen from 75 reflector slots. Several groups are placed in-line on a single acoustic track to achieve ID tag devices with capacities up to 256 bits.

RFID system requirements for anti-collision, low tag loss and high tag accuracy are presented and their impact on required SAW device performance will be presented. Performance characteristics of Global SAW Tag systems will be shown

[1] C. S. Hartmann, A Global SAW ID Tag with Large Data Capacity, Proc. 2002 IEEE Ultrasonics Symposium, pp. 63-67.

U5-G-2 512C-H 3:45 p.m.

DUAL CONFIGURATION HIGH TEMPERATURE HYDROGEN SENSOR ON LGS SAW DEVICES

J. A. THIELE* and M. PEREIRA DA CUNHA, Dept. of Electrical and Computer Eng., University of Maine.
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In the past few years there has been an increasing interest in the langasite family of crystals (LGX) for surface acoustic wave (SAW) applications in communications, frequency control, and sensors. LGX has several interesting properties including: up to about six times higher electromechanical coupling than quartz ST-X; existence of temperature compensated cuts with zero power flow angle

and minimal diffraction; up to 26% reduction in phase velocities with respect to quartz ST-X, which allows the fabrication of smaller devices; and the absence of a crystal phase transition up to the crystal melting point (around 1177K). Since this crystal has no phase transition, bulk acoustic wave (BAW) and SAW devices have been explored as temperature and pressure sensors at temperatures up to several hundred °C. In addition to temperature and pressure sensors, a need exists for high temperature sensors capable of detecting target gases. Hydrogen (H_2) detection, in particular, is of paramount importance in applications such as hydrogen fuel cells, fuel leakage from jet engines, and power plants. This paper reports on a dual LGS SAW device configuration for the detection of H_2 gas at 250°C using original all palladium (Pd) electrodes. The Pd electrodes are used for the SAW transduction and reflection functions and to detect H_2. The phase differences between two identical all Pd SAW resonators have been tracked. The dual configuration scheme has been used to minimize temperature cross interference, since the LGS (0°, 138.5°, 26.6°) orientation is not temperature compensated at 250°C. The detection of H_2 gas concentrations produces a three degree differential phase shift with respect to the reference for a 1000ppm H_2 gas concentration, and a one and a half degree phase shift for 500ppm H_2 gas. The SAW resonators respond to the presence of H_2 in a matter of seconds and become stable between 25 to 75 minutes later. The devices have been continuously operated at 250°C for a period of six weeks, with no degradation in the device response. The dual configuration high temperature LGS SAW devices and experiments reported in this work prove the capability of these crystals to withstand prolonged exposure to high temperatures (250°C) and to perform as appropriate high temperature H_2 gas sensors.
Funding for this project was provided by the Maine Space Grant Consortium (MSGC EP-02-08 and MSGC SG-03-15) and the National Science Foundation (NSF ECS-0134335 and NSF EEC-9820332).

U5-G-3 512C-H 4:00 p.m.

A THEORETICAL STUDY OF LOVE WAVE SENSORS MASS LOADING AND VISCOELASTICITY SENSITIVITY IN GAS AND LIQUID ENVIRONMENTS

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The sensitivity of Love wave (also known as guided shear horizontal surface acoustic wave (SH-SAW)) sensors to mass loading and/or to viscoelasticity change, in gas and liquid environments, is theoretically investigated. The objective is to present effective design parameters for Love wave sensors. The investigated sensor platform consists of a number of orientations of rotated Y-cut quartz substrate, a guiding layer, and a thin polymethylmetacrylate (PMMA) coating used to simulate the chemically sensitive layer. The platform sensitivity is determined by calculating the relative change in velocity, DV/V, for a small change in PMMA density and/or viscoelasticity. The investigation process consists of computing optimal guiding layer thickness (resulting in the largest perturbation, hence the highest sensitivity), for increasing layer density and shear modulus. The calculated highest sensitivity is reported on a 3D plot as a function of guiding layer density and shear modulus for a given substrate orientation. While the results are obtained for arbitrarily large ranges of density and shear modulus, optimum sensitivity for practical materials such as SiO2, PMMA, SU8, Si3N4, is indicated on the plot. It is observed that optimum thickness values ranging from 0.1 to 10 μm are needed depending on the waveguiding material. It is seen that the device sensitivity, in general, increases as the difference in bulk shear wave velocities between the substrate and the guiding layer. For a given mass sensitivity, the viscoelasticity sensitivity is analyzed and vice versa. The relative importance of mass loading and viscoelasticity are discussed, in terms of chemical sensors and biosensors implementation. In liquid-phase operation, the influence of the liquid viscosity on the sensor response is also studied. Various experiments are conducted to confirm the above results.

U5-G-4 512C-H 4:15 p.m.

SAW SENSOR FOR ANTI-HUMAN-IMMUNO-GLOBULIN G MOLECULE DETECTION

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We developed surface acoustic wave (SAW) sensors to detect human-immunoglobulin G molecule applying a particular antibody thin film on the delay line of transverse SAW devices. The mass loading effect was given by the antibody-antigen bonding of the target molecules on the delay line. The sensor consists of twin SAW delay lines operating at 110 MHz fabricated on 36 degrees rotated Y-cut X-propagation LiTaO3 piezoelectric single crystals. The sensor structure was optimized to achieve the highest signal to noise ratio with the least energy leakage to the protein solution. In addition, the input IDT of the sensor was configured as a single-phase-unidirectional-transducer (SPUDT) for more stable operation. The sensitive channel of the SAW sensor was coated with a gold film on which an antibody layer was immobilized. The antibody investigated was human-immuno-globulin G (HigG) and protein A molecules were coupled with the HigG molecules to work as an immobilizer layer to hold the antigens (anti-HigG). For proper immobilization of the detection molecules, Bovine Serum Albumine layer worked as a blocking layer to prevent the adhesion of any other molecules different from the anti-HigG to the SAW delay line. The relative change in the frequency of the two oscillators was monitored to measure the anti-HigG concentration in the protein solution. Sensor properties investigated include selectivity, sensitivity, response time and stability in response to the antigen concentration as well as the viscosity and electrical conductivity of the protein solution. The sensor showed linear response to the mass loading effects

of the anti-HigG molecules with the sensitivity up to 5 ng/ml. The SAW sensor in this work can be applied to the detection of various molecules with different antibody immobilization layers while maintaining all the beauties of general SAW sensors.

U5-G-5 512C-H 4:30 p.m.

BALL SAW HYDROGEN SENSOR WITH AMPLITUDE AND DELAY TIME RESPONSE

A. MIZUKAMI*[1], D. Y. SIM[3], I. SATOH[4], T. MIYAGISHI[4], H. TANAKA[4], T. K. FUKIURA[4], H. KAZATO[4], S. AKAO[2], T. OHGI[2], N. NAKASO[2], H. WATANABE[1], T. MIHARA[1], and K. YAMANAKA[1], [1]Tohoku University, [2]Toppan Printing Co., Ltd., [3]Ball Semiconductor Inc., [4]Yamatake Corp.
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Although hydrogen (H_2) is the most promising energy source for the new generation, it is necessary to develop H_2 sensors since it is explosive. The H_2 sensor using surface acoustic wave (SAW) on a plane has been developed which detects the change of SAW velocity due to absorption of H_2 to Pd sensing film, but the response time was not short enough (more than 100s). We then proposed a unique H_2 sensor using SAW on a ball, the ball SAW sensor [1]. We successfully improved the sensitivity using multiple roundtrips of 45 MHz SAW of as many as 51 turns on a Φ10mm quartz ball, realizing surprisingly long propagation length of 1.6 m. Since we could use much thinner Pd film (20nm) than in the planer SAW sensor, response time was considerably shortened (20s). In addition, although the Pd film was degraded due to the phase transformation from α to β phase at above 1.8% H_2 (23°C), and delay time response in α phase was lost, amplitude response due to absorption of H into Pd lattice [1] was hardly influenced. In this study, for the purpose of downsizing sensors, we used Φ1mm quartz ball SAW device on which a 40nm Pd film was deposited by aligning a mask with a Φ0.8mm pinhole, covering about 25% of the ball. As a result, delay time and amplitude responses were obtained at 0.1% H_2 . Also, we confirmed that the amplitude response in α phase linearly increases with H_2 concentration although that in β phase saturates with no noticeable change. On the other hand, although the delay time response linearly increases in both phases, the sensitivity is especially remarkable in β phase. In addition, delay time response in β phase is hardly influenced by the degradation of Pd film. Therefore, we can enhance the reliability of sensor for less than 3% H_2 adopting amplitude response in α phase and delay time response in β phase. However, in case sensors are used under more severe conditions, it is necessary to further improve the durability of sensors. Therefore, we added Ni in Pd films since it is reported that the addition of Ni in Pd suppresses the phase transition. As a result, although there was no noticeable change either in the delay time or the amplitude response in addition of 5%Ni, significant change was observed when 37%Ni was added. The threshold for rapid increase of delay time response was shifted to a higher concentration range, improving durability of delay time response in α phase. In conclusion, it is confirmed that compact and practical

1 mm ball SAW H_2 sensor can be developed. [1] K. Yamanaka, S. Ishikawa, N. Nakaso, N. Takeda, T. Mihara and Y. Tsukahara, Proc. 2003 IEEE Ultrason. Symp. 299 (2004).

U5-G-6 512C-H 4:45 p.m.

ULTRASONIC MEASUREMENT OF MOLAR FRACTIONS IN GAS MIXTURES BY ORTHOGONAL SIGNAL CORRECTION

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Natural gas and biogas consist of mixtures of several gases. The combustion properties, and thus the monetary value, of the mixture depend on its composition. It is therefore important for producers, distributors, and customers to have a simple, fast, and reliable method for measuring gas mixture composition and energy content.

In this paper we present a method based on pulse-echo ultrasound, to quantify the volume or molar fraction of Ethane in an Ethane/Oxygen mixture. The molar fractions of the gases can then be used to determine the energy content. We use *Principal Component Analysis* (PCA) to quantify changes in the shape of the ultrasound pulse caused by changes in experimental conditions for the pure gases. The measurements in mixtures of gases are then processed using a principle called *Orthogonal Signal Correction* (OSC) to extract inter-gas interaction effects. The PCA is used to determine a set of components that describe the experimental variation in the ultrasound pulse, for individual gas components by themselves. This can be seen as a calibration step. In a gas mixture, the sound will not only be affected by the individual gases by themselves, but also by inter-gas interaction effects. By removing the experimental variation already described by the individual components, it is possible to quantify the variation caused by the interaction alone. Hence, it is possible to determine the gas composition by studying these interaction effects.

The method is evaluated with experiments on mixtures of Ethane and Oxygen, for molar fractions in the range of 20%-80%. The results show that the parameters extracted using PCA and OSC correlates well with the molar fraction of the gas mixture, for different static pressures and for different temperatures.

The authors wish to express their gratitude towards Prof. Rolf Carlson at Troms University in Norway for valuable discussions and to Prof. Jerker Delsing at Lule University of Technology for supporting this work.

Session: U6-G

TISSUE CHARACTERIZATION

Chair: P. Laugier
LIP

U6-G-1 512A-F 3:30 p.m.

HIGH RESOLUTION ULTRASONOGRAPHY OF RETINAL DEGENERATION IN RAT

C. JOLLY[1], J.-C. JEANNY[2], F. BEHAR-COHEN[2], P. LAUGIER*[1], and A. SAIED[1], [1]Laboratoire d'Imagerie Parametrique CNRSParis VI UMR 7623, [2]Physiologie des maladies oculaires, Innovations theapeutiques INSERM U598.
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Purpose: Hereditary retinal dystrophy is associated with a progressive loss of the photoreceptors (light sensitive cells) layer leading ultimately to blindness. The assessment of the morphological retinal status which is crucial for the understanding of the pathology disorders and evaluation of new treatment strategies mainly relies on histologic analysis on animal models. The purpose of the current study was to evaluate the potential of 80 MHz ultrasound for the imaging of the intra-retinal structure and follow up of the photoreceptors layer. **Methods:** The study included Royal College of Surgeons control and dystrophic rats with retinal dystrophy. In this animal model, the retina degeneration is characterized by the thinning of the photoreceptors nuclei layer (PNL). The animals were sacrificed at different post-natal (PN) stages (25, 35, 45 and 55 days). The dystrophic eyes (n=20) and the non-dystrophic controls (n=20) were enucleated and immediately examined using an 80 MHz three-dimensional ultrasound bio-microscope (20 μm axial resolution at transducer focus). A series of parallel B-scan-images of a region close to the optic nerve was acquired, through the sclera from outside the intact globe. Identification of sub-retinal layers on US images was performed using correlation with histology. The degree of retinal degeneration was quantified by measuring the PNL mean thickness over time on 5 adjacent B-scan images (500 μm long, spaced at 50 μm interval). **Results:** Ultrasound images of control and dystrophic eyes showed the entire retina thickness and allowed the visualization of intra-retinal layers. In particular, the PNL boundaries were identified as two hyperechoic bands separated by an hypoechoic layer. There was an excellent correlation ($R=0.93$, $p<10-6$) between PNL thickness measured by ultrasound and PNL histology. At the beginning of the degeneration (PN25), the PNL thickness of control group (56 ± 1 μm) was not different ($p>0.05$) from that of the dystrophic group (55 ± 5 μm). The first evidence of retinal degeneration started at day 35. The difference between PNL thickness of control and dystrophic retina progressively increased from PN35 (50 ± 1 μm in controls and 42 ± 3 μm in dystrophic group) to PN55 (49 ± 3 μm in controls and 24 ± 6 μm in dystrophic group). All differences between ultrasound PNL thickness of controls and dystrophic retinas were significant (PN35 to PN55, $p<0.05$). Histologic thickness measurements confirmed US

measurements in all groups and at all times. **Conclusions:** In this study, first ultrasound images of sub-retinal rat structure were obtained. Features of high resolution US images were well correlated to morphological subtle and progressive changes during the time course of the degenerative retinal disease. 80 MHz ultrasonography has potential to monitor non-invasively, through longitudinal studies retina degeneration, and quantitatively evaluate the effects of genic and pharmacologic therapies in small animals.

U6-G-2 512A-F 3:45 p.m.

HIGH FREQUENCY ULTRASOUND IN MONITORING LIVER SUITABILITY FOR TRANSPLANTATION

R. VLAD*[1], M. C. KOLIOS[1,3], G. J. CZARNOTA[1,2], A. GILES[1,2], M. D. SHERAR[1,2], and J. W. HUNT[1,2], [1]Department of Medical Biophysics, University of Toronto, [2]Ontario Cancer Institute, [3]Department of Mathematics, Physics and Computer Science, Ryerson University.
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INTRODUCTION High frequency ultrasound(HFU) imaging can be used to assess cell structural changes, as well as damage during liver preservation, prior to transplant. During the preservation period, liver cells undergo progressive changes and after 8-24h of cold storage, irreversible injury occurs, leading to liver transplant failure. We hypothesize that the changes in the ultrasound signal intensity in liver ischemia are related to the changes in the cell size and viscoelastic properties of the cell cytoskeleton induced by osmotic stress, following ATP depletion. The objective of the project is to investigate the potential of HFU to assess liver damage during preservation. METHODS Organs from Wistar rats(n=10) are surgically excised, immersed in phosphate buffer saline(PBS) and stored at 4C for 24h or left to decay at room temperature, for the same period of time. In preservation experiments, organs from Wistar rats(n=4), are surgically excised, flushed with preservation solution, specifically University of Wisconsin(UW) solution, and stored at 4C for 24h. Preservation injury is simulated by either not flushing the livers(n=2) with UW solution or by allowing the livers(n=2) to reach the room temperature before imaging. Ultrasonic images and the corresponding radio frequency(RF) data are collected over the ischemia period from a region located within the transducer focal zone. At the end of the experiment samples are fixed for Hematoxylin & Eosin(H&E) and Electron Microscopy(EM) staining. The HFU scanner employs an f/3 transducer operating at 40MHz. Special care is taken to use the proper normalization pulse in calculating the normalized backscatter power. RESULTS For livers stored in PBS at 20°C and 4°C, the ultrasound backscatter (UB) increases exhibiting similar kinetics but different magnitudes. The UB increase for the livers stored in cold PBS ($\sim$9 dBr) is higher than the UB increase for the livers stored in PBS at 20°C ($\sim$6 dBr). This can be attributed to the greater cell swelling and higher stress induced to cell membrane cytoskeleton for cold stored livers. For organs prepared using standard preservation conditions there is a slight increase in UB ($\sim$2.5 dBr). The UB increases by 4-10 dBr for livers in which preservation injury

is simulated demonstrating similar kinetics but different magnitudes. CONCLUSIONS UB variations in liver preservation injury seem to correlate well with cell swelling which consequently induces changes in mechanical properties of the cell cytoskeleton. Cell swelling and ionic imbalance could be important factors leading directly to cell death if ischemia is maintained beyond 8-24h. On the other hand, cell swelling could cause microvascular compression and perfusion defects which could further exacerbate anoxia or prevent reperfusion of ischemic areas and thereby potentate parenchymal cell injury. Since the UB variation seems to correlate well with ischemic damage, it is conceivable that HFU can be used to monitor liver injury during the preservation period.
The authors would like to acknowledge the financial support of the Whitaker Foundation.

U6-G-3 512A-F 4:00 p.m.

NEW DEVELOPMENTS IN TISSUE-TYPE IMAGING (TTI) FOR GUIDING PROSTATE BIOPSIES AND FOR PLANNING AND MONITORING TREATMENT OF PROSTATE CANCER

E. J. FELEPPA*[1], J. KETTERLING[1], P. LEE[1], S. URBAN[1], A. KALISZ[1], C. R. PORTER[2], G. KUTCHER[3], and F. ARIAS-MENDOZA[3], [1]Riverside Research Institute, [2]Virginia Mason Medical Center, [3]Columbia University.
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OBJECTIVE: Our research seeks to develop imaging methods for identifying and characterizing cancerous prostate tissue and thereby for improving the effectiveness of biopsy guidance, therapy targeting, and treatment monitoring. METHODS: We acquired radio-frequency (RF) echo-signal data and clinical variables, e.g., prostate-specific antigen (PSA), during biopsy examinations. We computed the spectra of RF signals in each biopsied region, and we trained artificial neural networks with over 3,500 sets of data acquired since the inception of the study in collaboration with several medical centers; biopsy histology results served as the gold standard for training and evaluating classifiers. Our classification studies utilized standard and custom software for implementing multi-layer perceptrons and radial-basis functions. Our baseline for evaluating the improved classification provided by our methods was the level of suspicion (LOS) for cancer using the B-mode appearance of the biopsy site combined with other available clinical information such as PSA level. We compared the neural-network classification performance to conventional classification using ROC analyses. The optimal classifier produced a lookup table for translating spectral parameter and clinical variables to a likelihood for cancer. We then generated issue-type images (TTIs) by using the lookup table to obtain scores for cancer likelihood on a pixel-by-pixel basis from local spectral parameter values and global PSA values. TTIs were compared to prostatectomy histology to further assess classification performance. Preliminary comparisons were made with magnetic resonance spectroscopy (MRS) methods, and studies of combining MRS and ultrasound parameters were initiated. RESULTS: ROC-curve areas for the analysis of our

most-recent data set were significantly greater for neural-network-based classification than for the B-mode-based LOS classification by more than 20%, e.g., for our most-recent data set of 93 patients with 705 biopsy specimens, our radial-basis function ROC curve area was 0.8100 $\pm$ 0.0249 with a 95% confidence from 0.7574 to 0.8549; our multi-layer-perceptron area was 0.7986 $\pm$ 0.0248 with a 95% confidence from 0.7465 to 0.8437. In this data set, 28% (26/93) patients had positive biopsies, and 17% (119/705) biopsy specimens were cancerous. The LOS-based curve area was only 0.6473 $\pm$ 0.0290 with a 95% confidence from 0.5891 to 0.7022. TTIs derived from the LUTs showed tumors that were entirely unrecognized in conventional images and undetected during surgery. Registration of ultrasonic and MRS parameter images and multi-feature analyses based on both methods proved feasible. CONCLUSIONS: TTIs based on neural-network classification of ultrasonic and clinical parameters, and possibly also incorporating MRS parameters, show promise for improving the detection and management of prostate cancer, e.g., for biopsy guidance, planning dose-escalation and tissue-sparing options for radiation therapy, and assessing the effects of treatment.

Supported in part by NIH/NCI grant CA53561 awarded to Riverside Research Institute.

U6-G-4 512A-F 4:15 p.m.

THE INTENSITY REFLECTION COEFFICIENT: A NEW METHOD FOR BLOOD TISSUE CHARACTERIZATION

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Objectives: Ultrasound (US) backscattering by blood has been an active field of research for more than 25 years. However, the measurement of the backscattering coefficient (BSC) is complex and most of its experimental data do not compensate for attenuation or use estimated values. Despite these drawbacks, less attention has been devoted to other US parameters. In this work, we propose a new method for blood investigation. It is based on the measurement of the intensity reflection coefficient (IRC). **Methods**: A Couette viscometer was used to measure the IRC versus hematocrit (volume fraction of red blood cells) from 0 to 50% for porcine blood. The 2 mm space between the two coaxial cylinders of the Couette was filled with blood experiencing a shear rate of 500 s^{-1}. A narrow band 10 MHz center frequency transducer with a focal length of 12 mm was used. The cavity between the transducer and the blood contained agar-gel to which glycerol (8%) was added to increase the acoustic impedance mismatch. The relative IRC was computed as the squared amplitude of the pulse reflected at the interface agar-blood and then normalized to a reference medium (reflected echo for a hematocrit of 0%). Sound velocity was also measured as well as the attenuation which was determined relatively to the reference medium. **Results**: The relative IRC variation versus hematocrit exhibited a bimodal shape with a minimum value at 23%. On a logarithmic scale, the IRC dropped by a magnitude of 8 dB (between volume fractions of 0 and 23%) and

then increased by 15 dB (between volume fractions of 23 and 50%). The attenuation increased with the volume fraction. Two slopes of attenuation could be distinguished with a frontier occurring around a volume fraction of 20%. Sound velocity also increased with the hematocrit. **Conclusion**: Among the studied US parameters, the relative IRC clearly established a behavior well documented in blood investigation by the BSC. There was a good agreement with our data. This could be explained by considering the energy conservation. The reflected energy at the interface agar-blood is a mirror function of the backscattered energy (i.e. the IRC is equivalent to 1-BSC). The IRC is not affected by the attenuation since it is calculated on the first interface before propagation in the blood. Its determination is less complex than the BSC and could be a powerful complementary tool to the classical US tissue characterization parameters.
This work was supported by an operating grant from the Canadian Institutes of Health Research (# MOP - 36467), and by a research scholarship award from the Fonds de la Recherche en Sante du Quebec.

U6-G-5 512A-F 4:30 p.m.

ATTENUATION COMPENSATED SPECTRAL SLOPES DURING THE KINETICS OF ROULEAU FORMATION FOR PORCINE BLOOD BACKSCATTERING IN COUETTE FLOW AT 25-60 MHZ

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The characterization of red blood cell (RBC) aggregation using ultrasound is a promising technique allowing in vivo and in situ assessment of its level in the human body. It is known that pathological levels of RBC aggregation are correlated with diseases involving hemorheological disorders. Important efforts have been invested in theoretical and empirical studies of ultrasonic absolute RBC backscatter. In this study, we present (1) the spectral slope dependence of RBC ultrasonic backscatter (BSC) with temporal shear rate variation, and (2) absolute backscatter values. Porcine anti-coagulated blood at 40% hematocrit (H) was placed in a modified Couette flow system. Radiofrequency data were digitized and analyzed, using two wide-band focussed transducers of 35 MHz and 55 MHz. Linear regression was then used to measure the spectral slopes for both frequency bands. An attenuation coefficient of 1.5 dB/mm/MHz was assumed for compensation. As previous results in our lab showed minimal variation of attenuation with RBC aggregation, this variation was neglected. Relative integrated BSC values were referenced to the echo of a planar metallic reflector. The reference medium used for absolute BSC values was a H=6% suspension of RBCs in Ringer solution, as suggested by Wang and Shung (Trans. Biomed. Eng., 1997). Frequency dependent beam variations were taken into account using a correction factor introduced by Ueda and Ozawa (JASA,1984). (1) With the 35 MHz transducer, for whole porcine blood sheared at 500 s-1, integrated relative BSC was minimal (-38.8 dB) and the frequency dependence showed a

spectral slope of 3.7. The shear rate was then abruptly changed to 2 s-1: the integrated BSC followed a sigmoid shape to reach a value of -29.6 dB (increase of 9.2 dB). The spectral slope showed the inverse symmetrical behavior: the slope sigmoidally decreased from 3.7 to 2 (err=0.32). When the shear rate was abruptly raised to 10 s-1, the BSC decreased and the spectral slope increased. When abruptly changed back to 2 s-1, both parameters returned to previous values in a predictable way. At 55 MHz, similar patterns were observed: BSC sigmoidally varied from 33.4 dB at 500 s-1 to 29.8 dB at 2 s-1, for a relative variation of 3.6 dB. Spectral slopes symmetrically changed from 3.5 to 1 (err=0.20). (2) The reference BSC values for the H=6% reference medium were coherent with reported values in the literature, as well as with the Rayleigh theory, showing a F3.9 frequency dependence. Absolute BSC for whole blood at 35 MHz was of 1.2x10-3 cm-1sr-1 at 500 s-1, and 7x10-3 cm-1sr-1 at 2 s-1 for a relative variation of 7.3 dB. At 55 MHz, the BSCs were respectively 3x10-2 cm-1sr-1 at 500 s-1 and 6x10-2 cm-1sr-1 at 2 s-1 for a relative variation of 3 dB. According to these results, it is expected that spectral slope at higher frequencies between 25-60 MHz could be of clinical relevance for in vivo detection of red cell aggregation.

This work was supported by an operating grant from the Canadian Institutes of Health Research (# MOP - 36467), and by a research scholarship award from the Fonds de la Recherche en Santé du Québec.

We would also like to gratefully thank Jean Brochu for his cooperation and abundant porcine blood supply.

U6-G-6 512A-F 4:45 p.m.

HIGH FREQUENCY ULTRASOUND CHARACTERIZATION OF THE COAGULATION PROCESS OF WHOLE BLOOD

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We present the results of a study designed to characterize the blood clotting process in vitro by following changes in its acoustic properties. These acoustic properties are described on the basis of evaluation of high frequency ultrasound parameters both in double transmission (pulse echo) and backscattering mode. In transmission mode, we used a 45 MHz single element transducer to assess sound velocity and the attenuation coefficient. In backscattering mode, the backscatter coefficient (from which the integrated backscatter coefficient (IBC) and the effective scatterer size (ESS) can be estimated) and the attenuation coefficient were assessed. The latter parameters were measured from RF-signals by using a real time high frequency echographic device (Dermcup 2020) allowing spectral analysis of signals in the frequency range 10 - 30 MHz. Whole blood samples were collected from healthy volunteers in 3.5 ml sodium citrate tubes. The samples were then placed in a 3 ml temperature controlled acoustic measurement cell (37°C ± 0.1). The coagulation process was initiated by adding calcium chloride (100 μl with concentration of 0.5M), and the hematocrit and fibrin concentration were determined for each whole blood sample. During the blood clotting process (two hours' observation), the entire set of acoustic parameters was measured with 15 seconds time resolution for the transmission parameters and 30 seconds for the backscattering parameters. The results clearly showed that changes in several acoustic parameters are able to identify stages in the blood clotting process. Rayleigh scattering in the blood can be measured during the first few minutes due to individual red cells, and the IBC values compared to hematocrit are in accordance with reference articles. At the end of the first few minutes, scattering was dramatically affected by the formation of red cell aggregates (non-Rayleigh scattering) leading to an increase in ESS with typical final values between 25 and 35 μm. These modifications of the scattered signal seemed to be linked to the biochemical reactions before the real coagulation process (i.e. transition from liquid to "solid" state of the biological medium). The transmission parameters were very little affected during these first minutes, but after about 20 minutes, typically, the sound velocity parameter increased strongly (typically from 1590 to 1620 m/s) reaching a plateau at a time corresponding to the end of the coagulation process. Histological analysis of the clots was performed and several acoustic parameter values were analyzed in relation to clot structures. Finally, the assessment of high frequency ultrasound parameters in both double transmission and backscattering modes offers very good potential for fine description of the blood clotting process.

Session: FE1-G
MODELING, THEORY, AND DOMAINS
Chair: D. Damjanovic
EPFL

FE1-G-1 513CD 3:30 p.m.

FEM MODELING OF ELECTRO-ELASTIC FIELD IN FERROELECTRIC CRYSTAL WITH DOMAIN BOUNDARIES

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The parameters of ferroelectric thin layers are closely related to properties of materials from which they are made. Electric and elastic fields have large influence on important properties of discused materials. The paper describes an application of the finite element method (FEM) in modelling of electric and elastic fields in ferroelectric crystals and their influence on the shifts of domain boundaries. The boundary in ferroelectrics is idealized as two-dimensional defect in an electro-elastic continuum, which represents the source of inhomogenity and internal distortion in both elastic and dielectric fields. The presented approach contains a derivation of the numerical model of the problem, based on

the physical description of piezoelectric continuum - piezoelectric equations of state, Newton's Law, quasistatic approximation of Maxwell equations. Solving of this problem by FEM leads to the set of linear equations with large and sparse matrices. Computed quantities - electric potentials, electric field, mechanical displacements, stress - are necessary for computing energies, which directly determine the boundary shift.
This project was supplied with the subvention from Ministry of Education of the Czech Republic under Contract Code MSM 242200002.

FE1-G-2 513CD 3:45 p.m.

PIEZOELECTRIC ANISOTROPY-PHASE TRANSITION RELATIONS IN PEROVSKITE SINGLE CRYSTALS

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The orientation dependence of the longitudinal piezoelectric coefficient, d_{33}^{42}, is investigated as a function of temperature in $BaTiO_3$ and $PbTiO_3$ crystals using the Landau-Ginzburg-Devonshire theory. We show that a presence of the ferroelectric-ferroelectric phase transition in $BaTiO_3$ leads to enhanced d_{33}^{42} along nonpolar directions. The reason for this is that in the vicinity of a phase transition temperature at which a polarization vector changes its direction (tetragonal-orthorhombic/monoclinic, orthorhombic/monoclinic-rhombohedral), the shear piezoelectric coefficients become high. It is shown for all ferroelectric phases of $BaTiO_3$ that the shear stress deforms the crystal cell and changes the polarization direction in a similar way as the corresponding temperature-induced phase transition. The influence of the piezoelectric shear effect on the anisotropy of d_{33}^{42} is particularly pronounced in the orthorhombic/monoclinic phase where the piezoelectric shear coefficients are determined by the presence of both the high-temperature tetragonal and the low-temperature rhombohedral phases. In $PbTiO_3$, which does not exhibit ferroelectric-ferroelectric phase transitions, the shear piezoelectric effect is weak and d_{33}^{42} has its maximum along the polar axis at all temperatures.These results can be generalized to include phase transitions induced by electric-field and composition variations and are valid for all perovskite materials, including complex relaxor- ferroelectric perovskites that have recently attracted attention for their exceptionally large piezoelectric properties.
The authors acknowledge financial support of the Swiss National Science Foundation

FE1-G-3 513CD 4:00 p.m.

MODELING AND EXPERIMENTS OF LOCAL STRESSES, ELECTRIC FIELDS, AND FERROELECTRIC DOMAIN SWITCHING AT INDIVIDUAL GRAIN BOUNDARIES IN PZT

B. D. HUEY*[1,2], E. GARCIA[2], A. SCOTCH[2], M. VAUDIN[2], S. HONG[3], and J. BLENDELL[2], [1]University of Connecticut, Institute of Materials Science, [2]NIST Ceramics Division, [3]Samsung Advanced Institute of Technology.
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As ferroelectric devices continue to shrink, the importance of individual grain boundary effects correspondingly grows. In this work, we combine modeling and experiment to determine the influence of elastic and electrostatic fields on the ferroelectric properties of PZT at a variety of interfaces. The ferroelectric properties are first determined by mapping the local inverse piezoelectric response for several grain and grain boundaries using an atomic force microscope (AFM). This includes quantitative measurements of the switching field as well as the effective inverse piezoelectric coefficient, d_{33}^*. The crystallographic orientation of the same grains is then mapped in a scanning electron microscope using electron backscattering diffraction. Finally, a two-dimensional, object oriented finite element calculation is performed based on the measured grain shapes and orientations. In these calculations the electromechanical energy is minimized, incorporating the following: stresses due to thermal expansion mismatch between the substrate and the film, specifically accounting for any orientation-dependent mismatches; stresses due to direction-dependent thermal expansion mismatches between individual grains in the film; and stresses resulting from the inverse piezoelectric effect where the requisite electric field arises due to the inhomogeneous strain in the sample. In this manner, the measured ferroelectric response at and near grain boundaries can be compared to realistic models of the same structure.
NRC

FE1-G-4 513CD 4:15 p.m.

COMPLEX LATTICE QUASICONTINUUM THEORY AND ITS APPLICATION TO FERROELECTRICS

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Complex lattice Quasicontinuum theory is being developed and applied to the description of ferroelectric phenomena.

Quasicontinuum theory is a multiscale theory that provides a unified description of materials by combining atomistic and continuum approaches. It provides a seamless transition between atomistics and continuum, but the description of the material is derived directly from the underlying atomic structure, using

the computationally expensive atomistics only where needed at the location of atomistic origin phenomena.

Complex Lattice Quasicontinuum theory can be applied to complex lattice crystals consisting of many kinds of atoms. One highlight of it is treatment of each component lattice as separately and independently as possible. The component Quasicontinua are coupled through the microscopic forces within nodal clusters, making the complex atomistics of the heterogeneous lattice the basis of the description.

Ferroelectrics are especially suited to the application of Quasicontinuum theory. The nature of defects in ferroelectric materials is atomistic, but their influence over the material is long ranged due to induced elastic fields. Many different ferroelectric phenomena involving Barium Titanate have been investigated and simulated. In particular the domain wall structure : 180 degree domain wall in tetragonal phase with simultaneous consideration of about eleven million atoms. The results show that even if the effect of the domain wall is long ranged due to long range of the columbic potential, the main switch of the polarization happens in the 4-6 cells adjacent to the wall. This is in accordance with most experiments.

Another example simulated is a crack in Barium Titanate. An originally pure tetragonal phase specimen is being subjected to many incremental loading steps. The results are important and noteworthy. One can see a polarization change around the crack tip which is reminiscent of the pattern building in 90 degree domain walls. More calculations are needed to make a final statement about the nature of polarization change but the calculations are very promising.

FE1-G-5 513CD 4:30 p.m.

MODELLING OF THE POLING PROCESS IN FUNCTIONALLY GRADED MATERIALS

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Materials with an one or more dimensional gradient of structural or chemical properties, corresponding with a changing of the material properties, are called Functionally Graded Materials (FGMs). They have a high potential in a wide range of applications, for instance to improve the interface between two different materials. Moreover new functions of materials can be created by them. Piezoelectric FGMs can be used in actuator or ultrasonic applications. It is known that FGM ultrasonic transducers show a broader frequency bandwidth. There are different ways and technologies to prepare ceramics with a functional gradient. One possibility is the preparation of ceramics with a gradient of the chemical composition along the thickness direction. The chemical gradient will be transformed into a gradient of the electromechanical properties by a poling process. Usually, there is a very inhomogenious distribution of the poling field inside the graded material due to a corresponding gradient of the dielectric coefficient. Or et al. [1] have shown that the electric field distribution is not constant in time and depends on the electric conductivity of the used materials. Their model describes the poling process of two layer system using a modified tanh function for the ferroelelectric hysteresis loop. We enhanced this model by implementation of the Preisach model, an established approach of hysteresis effects in ferromagnetics and ferroelectrics. This allows the modelling of the electric field distribution and the polarisation of each layer at arbitrary applied voltages for different poling regimes as well as the time-dependent modelling of switching processes. The numerical model can be used for multilayer structures of two or more materials and is therefore a good approximation of functionally graded materials. We compare the modelling with experimental results of the measurement of the electric field distribution in multilayers based on $BaTi_{1-x}O_3$-$BaSn_xO_3$ ceramics, where the Sn content changes from 7.5 to 15 mol%. Additionally, the maximum and remnant polarisation as well as the dielectric and piezoelectric coeffients were determined and compared with FGM ceramics with the same chemical composition.

[1] Or et al., J. Appl. Phys., 93 (7), 2003, 4112-4119

Financial support of the Deutsche Forschungsgemeinschaft is gratefully acknowledged.

Session: FC1-G

MICROWAVE AND MEMS RESONATORS - THEORY AND FABRICATION

Chair: R. Eiller
US Army CECOM

FC1-G-1 511CF 3:30 p.m.
(Invited)

DESIGN OF DISTRIBUTED BRAGG RESONATORS WITH CYLINDRICAL SYMMETRY

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An analytical method is presented that allows the solution of all the dimensions of a multi-layered dielectric $TE_{0,1,n}$ mode cylindrical resonant cavity that constitutes a Distributed Bragg Reflection (DBR) resonator. The analysis considers an arbitrary number of alternating dielectric and free space layers in a cylindrical geometry enclosed by a metal cylinder. The layers may be arranged along the axial direction, the radial direction or both. Given only the aspect ratio of the cavity and the desired frequency, the relevant dimensions are determined from a set of simultaneous equations. The formulas are verified using Method of Lines (MoL) calculations and previous experimental work. The design is shown to give a more compact solution and higher Q-factor when compared to other reported DBR structures (~5 million). Also, we show how the properties of

this type of resonator may be influenced by spurious modes within the dielectric structure. We determine a methodology to tune these modes away from the operational mode if they occur close by in frequency, with minimal degradation of the Q-factor.
This work was supported by the Australian Research Council

FC1-G-2   511CF   4:00 p.m.

PIEZO-CONTROLLED FREQUENCY AGILE MICROWAVE DIELECTRIC DEVICES

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Compact size, low cost, fast operational components are required for telecommunication systems, car collision prevention radars, etc. The limiting property of existent tunable components based on ferrite and semiconductor materials is a high loss at centimeter and, especially, millimeter waves. On the other hand, mechanically tunable dielectric devices insert practically no loss. However, the known ways of mechanical control is slow because the size of the required displacement (Δ) in commonly used devices is rather big (a few millimeters).

A new operational component is proposed for tunable devices that are based on microwave low loss dielectrics. The key idea is to reduce the required displacement Δ by implanting a narrow piezo-tunable air gap into a high dielectric constant (ϵ) element perpendicularly to the direction of the RF electrical field. Under these conditions, a dielectric-air sandwich is developed with a highly tunable effective parameter ϵ_ef(Δ). This enables us to use cymbal or mooni type actuators for fast (10^{-4}s) electromechanical control of $\Delta(E)$ at small displacement $\Delta(E)<100\mu$m. Wide-band low loss waveguide and microstrip phase shifters (360°/1db), highly tunable dielectric resonators with high quality factor ($\delta f/f$ 30
realized experimentally.

What is new? - We use a design where the air gap crosses low loss microwave dielectric perpendicularly to the electric field lines, where the sensitivity in the air gap is maximal. - We use microwave dielectric with a high dielectric constant ϵ_D>30 to increase the difference between the ϵ_D and the air gap ϵ_A=1. That is why the sensitivity to change the size of air gap additionally increases. - As a result, we can realize large electromechanical tenability of microwave devices with very small displacement (less than 50 micrometers).

Why did we need to increase the sensitivity? - Piezo-electrically controlled filters and phase shifters need high operation speed. However, usual piezoelectric actuators and motors are relatively slow ($>10^{-2}$s) when they have to provide a displacement with the order of magnitude of 1 millimeter. - Recently elaborated small size and very fast actuators ($>10^{-4}$s) can provide relatively small displacement (3050 micrometers). Our sensitive microwave devices can work fast and with bigger tenability than the known ones.

FC1-G-3 511CF 4:15 p.m.

FREQUENCY TUNING OF VIBRATING MICRO-ELECTRO-MECHANICAL RESONATORS AND FILTERS VIA LASER TRIMMING

M. ABDELMONEUM*[1] and C. NGUYEN[2], [1]Radiation Laboratory, University of Michigan Ann Arbor, [2]DARPA.
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Location dependent laser trimming of the resonance frequencies of micro-scale clamped-clamped beam (CC-beam) and disk vibrating mechanical resonators has been demonstrated in steps ranging from 22 ppm to 28,400pm, with targeting measures that suppress the Q and motional resistance variations. In particular, geometrically symmetrical laser targeting is instrumental in preserving the resonator's high Q, where it is commonly a non-issue for macroscopic vibrating resonators. A semi-empirical model has also been developed that identifies the locations best targeted for laser trimming for a desired shift in frequency.

Among previous approaches to frequency tuning of MEMS resonators and filters, voltage tuning via DC-bias-dependent electrical stiffnesses [1] has been the most common method used to date. However, DC-bias tuning has several drawbacks, including the need for extra interconnect pads, as well as its impact on motional resistance entailing complex trimming process. Hence, a less intrusive tuning method is desirable, such as laser trimming. Although laser trimming has been previously used for precise tuning of macro scale (order of mm to cm) metal resonators [2], it is less useful for trimming their micro-scale renditions, since the stress distributions generated by laser trimming are more debilitating at the micro-scale.

This work solves this problem by strategically targeting laser trims to not only achieve a desired frequency shift, but to also cancel Q-limiting stress distributions. At the center of a CC-beam, negative frequency drift steps as low as -22 ppm are observed. By moving the location of the trimming point off center, the magnitude of the frequency shift increases gradually till a maximum drift of -28,400 ppm is achieved at topography lines above the sense electrode running under the beam. Beyond this point the frequency shift turns positive, meaning that either upward or downward frequency trims are achievable. Unfortunately, unlike larger mm size resonators [2], moving the trimming point off center of a micro-scale resonator reduces its Q by about 25%. Here, the off center laser pulse disturbs the stress distribution along the beam and so increases the beam internal losses, reducing its overall Q. To create a balanced stress distribution, the next trimming point is selected to be at a mirror symmetric location to that of the previous off center point. Doing so, the resonator restores its original Q value with minimum change in device motional resistance.

The model predicting the degree of frequency shift for a given trim location on a CC-beam resonator makes use of a location-dependent effective mass trimming coefficient. Using this model, a two-CC-beam resonator filter has been trimmed to a flat passband using only three laser pulses on the output resonator: one at the beam center, and two symmetric pulses at topography lines, to maximize the frequency shift with minimum Q loss.

Ref [1] F. A. Bannon, IEEE Journal of Solid State Circuits, April 2000, pp.512-526. [2] Mechanical Filters IN Electronics, R. Johnson, pp.245-249.

FC1-G-4 511CF 4:30 p.m.

BRIDGED MICROMECHANICAL FILTERS

S.-S. LI*, M. U. DEMIRCI, Y.-W. LIN, Z. REN, and C. T.-C. NGUYEN, University of Michigan.
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High-order micromechanical filters comprised of 3 to 4 mechanically coupled resonators, and employing for the first time bridging between nonadjacent resonators to affect loss poles for better filter shape factors, have been demonstrated with sharper passband-to-stopband roll-offs than achievable by equivalent non-bridged filters [1], with insertion losses less than 3 dB, and with 50 dB of stopband rejection, which is 15 dB better than a previous 2-resonator design [1]. Via this bridging design approach, 20dB shape factors down to 1.95 have been achieved for filters centered at 9 MHz using only 3 resonators. This work stands to greatly reduce the number of resonators needed in a micromechanical filter to achieve a given shape factor. The filters of this work consist of several clamped-clamped beam ("CC-beam") resonators coupled by soft mechanical links. In this way, coupled mechanical systems are achieved, each with several modes of vibration that combine to form the passband of an eventual filter. Previous micromechanical filters utilized only coupling between adjacent resonators, leading to frequency characteristics with monotonic stopbands. In contrast, the bridged filter of this work employs a more general coupling scheme, where non-adjacent resonators are now linked. This new linkage introduces a feedforward path in the filter structure that generates loss poles in the filter transfer function, leading to a faster roll-off from passband to stopband. To allow the use of identical resonators, each of the three bridged filter designs utilize quarter-wavelength ($\lambda/4$) couplers between adjacent resonators, and either $\lambda/4$ or $3\lambda/4$ (for longer distances) coupling beams to connect non-adjacent resonators. The design variations include (a) a 3 CC-beam filter using a $\lambda/4$ bridging beam (3CC $\lambda/4$); (b) a 3 CC-beam filter using a $3\lambda/4$ bridging beam (3CC $3\lambda/4$); and (c) a 4 CC-beam filter using a $3\lambda/4$ bridging beam (4CC $3\lambda/4$). The 3CC design has one loss pole, which occurs below the passband when a $\lambda/4$ bridging beam is used, and above when a $3\lambda/4$ is used. The 4CC design achieves two loss poles with a $3\lambda/4$ bridging beam. These filters were fabricated using a previously described small-vertical gap surface-micromachining technology [1]. The 3CC $\lambda/4$ design achieves an insertion loss of only 2.74 dB for a 0.2% bandwidth centered at 8.82 MHz, with a 50 dB stopband rejection, and a (notch) loss pole below the passband, as expected. The 3CC $3\lambda/4$ design centered at 9 MHz with a 0.25% bandwidth, achieves an insertion loss of 2.84 dB with 50 dB of stopband rejection, a loss pole above the passband, and a 20dB shape factor of only 1.95. The 4CC $3\lambda/4$ design achieves comparable characteristics, but with two loss poles, hence, even better shape factor in theory. (Duffing nonlinearity

in the filter transfer function prevents exact determination of the shape factor, but it is better than the 3CC versions.)

[1] F. D. Bannon, J. R. Clark, and C. T.-C. Nguyen, High-Q HF micromechanical filters, IEEE J. Solid-State Circuits, vol. 35, no. 4, pp. 512-526, April 2000.

This work was supported by DARPA and NSF ERC on Wireless Integrated Microsystems.

Session: FC2-G
PANEL DISCUSSION - MANUFACTURING TECHNOLOGY
Chair: G. Johnson
Sawyer Research Products

FC2-G-1 511DE 3:30 p.m.

NEW MATERIALS PANEL DISCUSSION

B. TYSINGER*[1] and G. R. JOHNSON[2], [1]Agilent Technologies, Inc., [2]Sawyer Research Products, Inc.
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Quartz, lithium niobate, and lithium tantalate are the dominant single crystal piezoelectric materials used in frequency control applications. These three materials are available widely from multiple suppliers in high volume at low cost and with predictable material properties. The most important physical characteristics of each for most frequency control applications are temperature stability and piezoelectric coupling coefficient. The search for a high coupling, high stability material is a major factor driving new materials development. Researchers also have sought materials with improved properties both to better address current applications and to expand the use of single crystal materials into new areas.

During the past two decades several new materials have attracted the interest of researchers. Among these are: aluminum orthophospate ("Berlinite"), gallium orthophosphate, lithium tetraborate, and the langasite family. In addition to the body of work on bulk single crystal materials considerable work has occurred on layered structures incorporating piezoelctric films.

The panel will review important developments and the current status of the technologies and commercial applications both of new single crystal materials and of layered structures.