Super-Resolution Mapping of Wave Field Using a Receiver from a Far Distance

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Abstract **– Recently, a PSF-modulation super-resolution imaging method was developed by the author (IEEE TUFFC, January 2024). In this paper, the method was used to obtain super-resolution images of pulse ultrasound wave field (super-resolution means higher than diffraction-limited resolution or a higher resolution than that limited by the highest spatial frequency component of the point spread function (PSF) of the imaging system). This method can not only be used to map ultrasound field, but also be applied to map any other wave fields such as electromagnetic and optical fields. In principle, this method can work well with any linear shift-invariant (LSI) system. Even if the ultrasound wave field is disturbed or scattered by objects such as biological soft tissues, this method is still applicable. Compared to the conventional method where a small hydrophone or a small scatterer was used to map ultrasound wave fields, this method has the advantages of the small scatterer method that is simple and can withstand a higher ultrasound intensity while being flexible in terms of receiver positioning and the existence of other scattering objects in the ultrasound field.**

In the study, a 2.25-MHz center frequency, 61.3% -6-dB pulse-echo relative bandwidth, and 25.4-mm diameter PZT (lead zirconate titanate) transducer (transmitter) focused at about 33.5 mm was used to produce a short ultrasound pulse in water (the transducer was driven by a one-cycle electrical pulse signal). The produced pulse ultrasound field was then mapped by another PZT transducer that was used as a receiver and had the same center frequency, bandwidth, and diameter as the transmitter except that the receiver had a focal length of about 50 mm (an *f*-number of about 2). The axis of the receiver was in parallel with that of the transmitter and the receiver was scanned mechanically in the direction that was perpendicular to the wave propagation to map the pulse ultrasound field at the focal distance of the transmitter (33.5 mm). Because the receiver was placed at a far distance from the ultrasound field measured, the spatial resolution of the image of the pulse ultrasound field was low. However, when a small modulator that was a glass bead of about 0.7-mm diameter was placed at the focal point of the receiver to map the ultrasound field together with the receiver, high spatial frequency components were introduced to the image of the ultrasound field. Subtracting the images of the ultrasound fields mapped with and without the modulator, a super-resolution image of the wave field was produced.

To evaluate the quality of image of the ultrasound field mapped with the PSF-modulation super-resolution imaging method, a broadband (1-20 MHz) needle hydrophone of 0.6-mm diameter was used to map the same ultrasound field. The results show that the super-resolution image obtained with the PSF-modulation super-resolution imaging method was very close to those obtained by the hydrophone.

Finally, to demonstrate the flexibility of the super-resolution imaging method in mapping the ultrasound field, the receiver was rotated 90^{o} from the axis of the transmitter to obtain the super-resolution image of the pulse ultrasound field. The results show that the ultrasound field mapped after the rotation of the receiver was very close to that mapped before the rotation.

Keywords – ***Point Spread Function (PSF); super-resolution imaging; modulation; modulator; linear shift-invarian (LSI) system; ultrasound field mapping; wave field mapping; electromagnetic wave; optical wave.***

I. INTRODUCTION

Mapping wave fields such as ultrasound and other types of waves in space and time has various applications. For example, mapping ultrasound wave field distributions in space and time will help transducer design and improvement [1] and help focusing high intensity ultrasound on targeted tumors in ultrasound therapy [2].

Many methods have been developed to map and characterize ultrasound wave fields. A sensor of a small size is usually used to map the wave fields in space to avoid spatial averaging effects to achieve a high spatial resolution [3]. However, sensors of a small size are delicate and may be damaged in some cases. For example, although ultrasound field can be mapped with a small Polyvinylidene fluoride (PVDF) hydrophone in a liquid [4], such hydrophone can be damaged by high ultrasound intensity, high temperature, or corrosive media, and it is difficult to drive a long cable due to its high output impedance. Although a small scatterer can be used in place of a small hydrophone to map or characterize ultrasound field and address the issue of hydrophone damage [5]-[13], such methods cannot be used when there are other scattering media such as biological soft tissues in the ultrasound field or the ultrasound field can reach the receiver directly. To measure high-intensity ultrasound field, some alternative methods that use a more robust transducer or sensor such as a small lead zirconate titanate (PZT) transducer and fiber optic transducer were introduced. However, these transducers or sensors may be expensive and/or have other limitations [5].

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II. METHOD AND EXPERIMENT

In this paper, a newly developed super-resolution imaging method (January 2024, IEEE TUFFC [14]) was used to experimentally map a wave field using a large (25.4-mm diameter) receiver from a far distance (see the experiment setup in Fig. 1). This super-resolution imaging method can work in any linear shift-invariant (LSI) systems to overcome the degradation of image resolution due to a limited spatial bandwidth of the point spread function (PSF) of the system [14][15].

In the method, a PZT ultrasound transducer of a broad bandwidth (61.3% -6dB pulse-echo bandwidth) and 2.25-MHz center frequency was used as a receiver that had about 50-mm focal distance (*f*-number of about 2). This receiver was used to map a short focused ultrasound pulse field produced by another PZT ultrasound transducer that had the same bandwidth, center frequency, and diameter as the receiver. The focal distance of the transducer was about 33.5 mm (*f*-number of about 1.318) and the transducer was driven by a one-cycle electrical pulse signal.

Because of the large *f*-number and the long wavelength, the diffraction effect of the receiver is significant and thus the image spatial resolution of the pulse ultrasound field mapped by the receiver is low. To increase the spatial resolution (achieve a super image resolution), the PSF-modulation super-resolution imaging method [14] was used, where two pulse ultrasound fields mapped with and without a modulator were subtracted to obtain a super-resolution image. The modulator was a small glass bead of about 0.7-mm diameter and was placed at the focal point of the receiver.

For comparison, the same ultrasound pulse field also was mapped by a broadband (1-20 MHz) PVDF hydrophone of 0.6-mm diameter (see the experiment setup in Fig. 2).

To map the pulse ultrasound field using the modulator, the modulator was scanned mechanically with the receiver through the center of the ultrasound field in the direction that was perpendicular to the axis of the transmitter at a step size of 0.125 mm for 200 steps. To map the pulse ultrasound field without the modulator, the experiment setup was the same as that in Fig. 1 except that the modulator was removed. To map the pulse ultrasound filed using the hydrophone, the receiver was replaced with the hydrophone as in Fig. 2. The pulse field was measured at the focal distance (about 33.5 mm) from the transmitter and each signal was digitized at 50 MS/s sampling rate for 512 samples at 12-bit resolution.

To demonstrate the flexibility of the PSF-modulation super-resolution imaging method [14][15] in mapping the pulse ultrasound filed, the receiver was rotated 90^{o} relative to the transmitter (see Fig. 3) (in fact, the receiver can be rotated by any angle). This configuration is similar to those used by other researchers, where a single scatterer was used in water and there were no other scattering objects such as biological soft tissues in the ultrasound field or the ultrasound field did not reach the receiver directly [5]-[13]. If there were other scattering materials in the ultrasound field or part of the ultrasound field can reach the receiver directly, those methods cannot be used and the PSF modulation super-resolution imaging method must be used to obtain super-resolution images of the ultrasound field.

III. RESULTS

Results of the experiments show that without using the super-resolution imaging method (see Fig. 1 but with the modulator removed), the spatial resolution of the image of the pulse ultrasound field in the direction that is perpendicular to the wave propagation is low (see the vertical direction in Fig. 4(a) and 4(d) that are the radio frequency (RF) image and its analytic envelope respectively, or see Fig. 5(a) and 5(d) that are the same as Figs. 4(a) and 4(d) respectively). However, with the PSF-modulation super-resolution imaging method (subtracting the images obtained with and without the modulator) [14], the spatial resolution of the pulse ultrasound field (see Fig. 4(b) and 4(e)) mapped was close to that mapped with the 0.6-mm diameter hydrophone (Fig. 4(c) and 4(f)). As the diameter of the modulator is reduced, the method can be used to map ultrasound field at a higher spatial resolution, which is desirable for mapping the field of transducers of a higher frequency, at the expense of a lower sign-to-noise ration (SNR) and a larger required dynamic range of the measuring system. In addition, the field that is disturbed or scattered by objects such as biological soft tissues also can be mapped using the method. If the bandwidth of the receiver is increased, the length (time duration) of the measured ultrasound pulse will be reduced and will be closer to that measured by the broadband hydrophone (compare Fig. 4(b) and 4(e) with Fig. 4(c) and 4(f) respectively). As is illustrated in the PSF-modulation super-resolution method, a modulator can be a small object that changes the amplitude of the field, such as the small glass bead in this case, or changing the phase of the field, or changing both the amplitude and the phase of the field (see Section III "Examples" on Page 153 of [14]). This means that mapping ultrasound field using the PSF-modulation super-resolution imaging method is flexible.

Fig. 5 is the same as Fig. 4 except that Figs. 5(b) and 5(e) were obtained with the experiment setup in Fig. 3, where the receiver was rotated 90^{o} from the axis of the transmitter. Figs. 5(a), 5(c), 5(d), and 5(f) are the same as Figs. 4(a), 4(c), 4(d), and 4(f), respectively, and are there for convenience and for an easy side-by-side comparison.

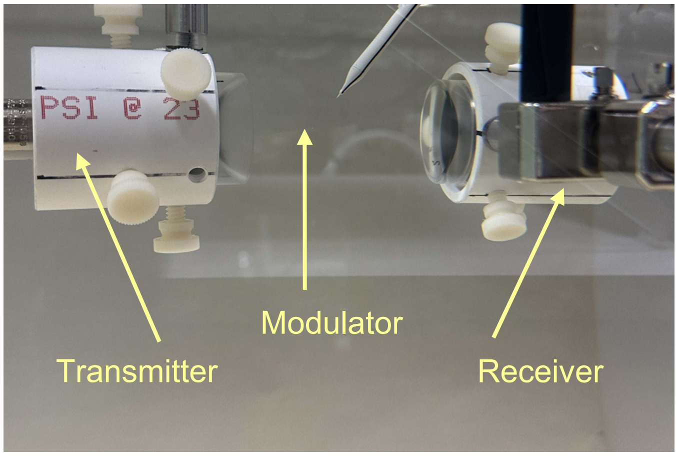

Figure 1. Experiment setup for mapping a pulse ultrasound field. A modulator was located between two transducers. The transducer on the left was a transmitter that produced the pulse ultrasound field and the one on the right was a receiver used to map the field. The transmitter was fixed in space and the receiver along with the modulator (0.7-mm diameter glass bead) scanned mecahnically though the center of the pulse ultrasound field in the direction that was perpendicular to the axis of the transmitter. Both transducers were identical (25.4-mm diameter, 61.3% fractional pulse-echo bandwidth, and 2.25-MHz center frequency) except that the focal lengths of the transmitter and receiver were about 33.5 mm and 50 mm respectively. To map the ultrasound field without a modulator, only the modulator was removed and everything else was unchanged.

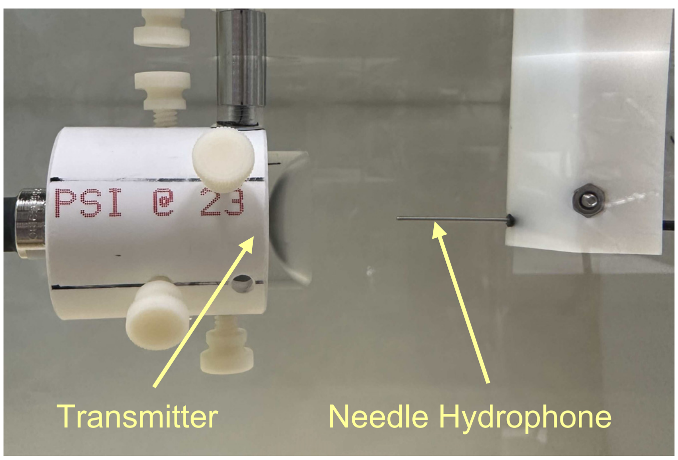

Figure 2. A broadband PVDF needle hydrophone was used in place of the receiver and the modulator in Fig. 1 to measure the same pulse ultrasound field.

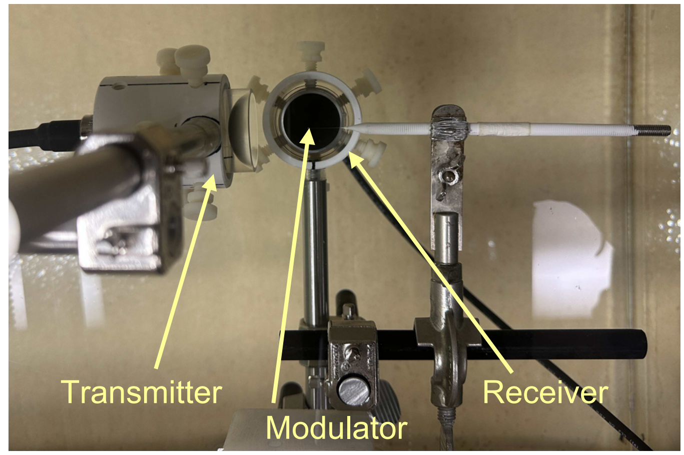

Figure 3. This figure is the same as Fig. 1 except that the receiver was rotated 90° from the axis of the transmitter and the modulator was in parallel with the axis of the transmitter. The setup was used to demonstrate the flexibility of mapping the pulse ultrasound field using the PSF-modulation super-resolution imaging method. With the method developed in this paper, the setup above can be used to measure the pulse ultrasound filed with and without a disturbance to the field by objects such as biological soft tissues.

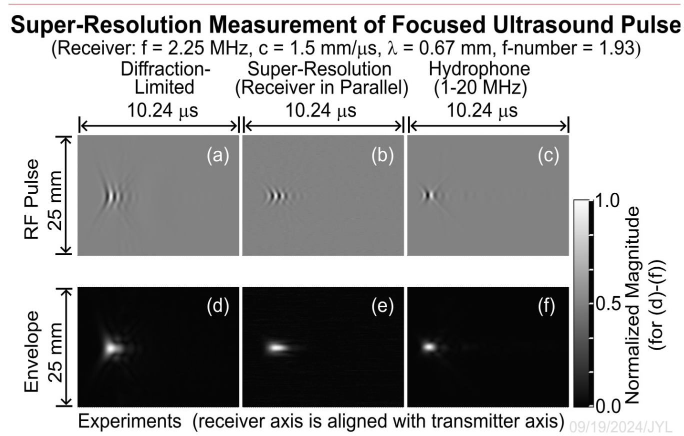

Figure 4. The measured ultrasound pulse field using the setup in Figs. 1 and 2. The top and bottom rows are mapped radio-frequency (RF) pulse ultrasound field and its analytic envelope respectively. The first, second, and third columns are the fields mapped without using the super-resolution imaging method, with the super-resolution imaging method, and directly with a broadband needle hydrophone. The vertical direction is perpendicular to the transmitter axis and the horizontal direction is the time duration of the received signals. The parameters used in the experiment are shown in the figure.

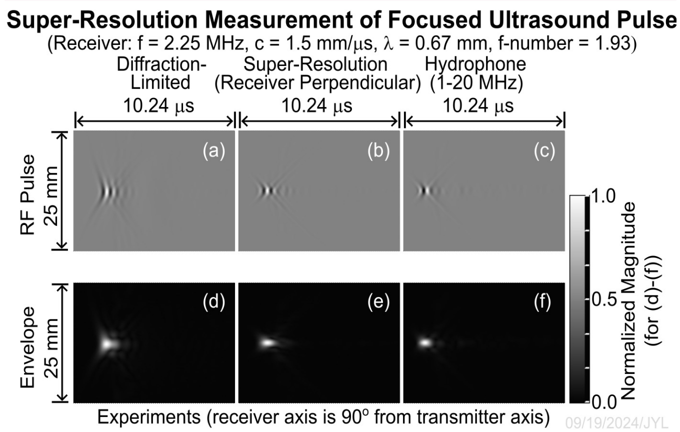

Figure 5. This figure is the same as Fig. 4 except that the measured pulse ultrasound field was mapped using the setup in Figs. 2 and 3. In Fig. 3 the receiver was rotated 90o from the axis of the transmitter. Panels (a), (c), (d), and (e) are the same as the corresponding panels in Fig. 4.

IV. Conclusion

The newly developed PSF-modulation super-resolution imaging method (IEEE TUFFC, January 2024 [14]) was used to map a pulse ultrasound field. This method is flexible and can be applied to various receiver configurations. The method can also be applied when the ultrasound field is disturbed or scattered by objects such as biological soft tissues. Thus, the developed method can be a new tool to map ultrasound or other wave fields in areas such as optics and electromagnetics at a high image resolution. Because super-resolution can be achieved, the receiver or detector used to map the wave fields can be large in size and be placed at a large distance from the wave field to avoid damage or other physical limitations.

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