Measurement of Angle of Ultrasound Propagation from Phase

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Abstract. Acoustic field calibrations often use Fast Fourier Transforms (FFT) to quantify the spectral amplitude components of detected acoustic waveforms. The ability of FFTs to provide phase information is often overlooked. This phase data may be useful in determining the angle of propagation of the ultrasound beam. The angle of propagation at the focal peak (and any other point in the field) can be calculated easily and quickly without additional measurement, and may be the quickest and most accurate method of aligning the sound axis with respect to the beamplotting system’s co-ordinates.

Acoustic fields have been measured experimentally using a system capable of waveform acquisition. Measurements were made using a fibre-optic hydrophone (Precision Acoustics, UK) which provided spatial resolution of <100 µm. Two operating configurations of a 10 strip array HIFU (high intensity focused ultrasound) transducer were tested, as was a single element HIFU device. Theoretical pressure and phase distributions for these transducers were predicted using a linear acoustic field model. Results show that for the single element, radially symmetric device, beam alignment measurements using phase data at the focal peak are in agreement with the more conventional method based on finding the on-axis peak positions. In the case of a transducer with a number of elements de-activated to produce an asymmetric ultrasound source, the angle of propagation at the focal peak was altered, indicating a change in performance of the transducer which otherwise might not have been detected using the “on-axis peaks” method. Simulations agreed with the experimental data.

1. Introduction

Detailed acoustic field measurements are made using beam plotting systems to quantify the pressure distributions generated by both therapeutic and imaging ultrasound transducers. Such systems usually characterize properties such as peak acoustic pressure using calibrated hydrophones. If a system allows waveform acquisition, the use of a Fast Fourier Transform (FFT) allows spectral characterization of the detected signal. The phase information also provided at each frequency is usually ignored. However this data can provide useful information regarding the nature of the ultrasound beam.

In this paper, we show how the phase data can be used to calculate the direction of propagation of the ultrasound beam. Perhaps more importantly than allowing visualization of the way the ultrasound beam may be converging or diverging across the acoustic field, it could provide rapid evaluation of the correct alignment of the sound axis with the measurement system. Alternatively, a measurement of the angle of propagation at the focal peak may provide a quantity to be routinely measured when
monitoring transducer operation over time. This may be particularly useful for phased array devices with many elements, which allow electronic focal steering.

In the case of High Intensity Focused Ultrasound (HIFU) transducers the focal peak is the obvious position at which to measure beam alignment. In this paper, the measured angle of propagation at the focal peak is compared to the more standard technique of identifying, and then aligning, the on-axis pre- and post-focal peak positions to determine the 3D alignment of the sound beam with respect to the beam plotting coordinate system. Firstly, a single element HIFU transducer is tested, and secondly a 10 strip array transducer is used to illustrate how both techniques deal with an asymmetric ultrasound source. A linear ultrasound propagation model is used to predict the pressure and phase distributions for comparison with the experimental results.

2. Methods

2.1. Transducers and drive system: The HIFU transducers were driven using a pulse generator (HP33120A Agilent) set to burst mode, and an ENI A300 amplifier providing a gain of 55 dB. The tone burst length was set to between 40 and 80 cycles, depending on transducer and scan parameters, at a pulse repetition frequency of 100 Hz. The synchronisation signal from the pulse generator was used to trigger the oscilloscope used for measurement purposes. Transducers were connected to the drive system via their respective impedance matching circuits. A single element transducer and a 10 strip array transducer were tested. Details of transducer parameters are given in Table 1 along with the resolution for large area beam plots in the $X-Z$ plane. Two cases were tested for the single element transducer: 1) visual (by eye) alignment of the transducer sound axis with the $Z$ axis of the positioning system, 2) deliberate misalignment by a few degrees in the $X-Z$ plane (azimuthal angle). The 10 strip transducer was tested using two configurations: 1) all ten segments active and working in phase, 2) segments numbers 1, 2, 3 and 4 deactivated resulting in a non axisymmetric ultrasound source (as shown in Figure 1). The propagation angle calculation based on phase measurements was performed in the $X$ axis direction. The transducers were driven at relatively low powers (<30 W acoustic power).

2.2. Beam plotting system: A fibreoptic hydrophone [1] (Precision Acoustics, UK) was used to measure the acoustic field. The fibreoptic sensor is of the Fabry-Perot interferometer type and was chosen for its excellent spatial resolution (sensor diameter of 10 µm; fibre thickness ~ 100 µm) whilst maintaining sufficient sensitivity (>100 mV/MPa). The sensor was mounted on a motorised 3D positioning system under PC control (Labview). Measurements were performed in deionised, degassed water. The sensor signal output was connected to an oscilloscope (Lecroy Waverunner 64Xi) and the signal windowed to display a short number of cycles (<10) to give an apparent CW representation of the signal. The oscilloscope signal was averaged over several repeats (>100) to improve the signal to noise ratio. One average waveform per position was stored on the PC hard drive.
Table 1. Transducer specifications, including diameter, imaging aperture diameter, working frequency and scan resolution for the large area X-Z plane beamplots.

| Type            | Diameter (cm) | Hole (cm) | Focal length (cm) | Frequency (MHz) | Resolution (mm – X/Z) |
|-----------------|---------------|-----------|-------------------|-----------------|-----------------------|
| (1) Single element | 6.5          | 2         | 6.3               | 1.7             | 0.5 / 1               |
| (2) Segmented    | 11.5          | 5.5       | 15                | 1.7             | 0.5 / 2               |

2.3. Phase measurement: Phase was measured from the stored average waveforms. The timebase and time delay of the oscilloscope were fixed during measurements so that any changes in the position of the sensor in the acoustic field were seen as apparent changes in phase of the measured waveform. To obtain a measurement of phase, the measured waveform data set was trimmed to provide an integer number of cycles to serve as input to the FFT. The real and imaginary components from the FFT output at the fundamental frequency were used to calculate the phase angle.

\[
\sin(\theta) = \frac{\lambda \Delta \phi_X}{2\pi r} \quad (1) \quad \cos(\theta) = \frac{\lambda \Delta \phi_Z}{2\pi r} \quad (2) \quad \tan(\theta) = \frac{\Delta \phi_Z}{\Delta \phi_X} \quad (3)
\]

2.4. Ultrasound propagation direction calculation: The direction of ultrasound propagation with respect to the beam plotting system Z axis (nominal sound axis direction) can be computed by moving the sensor small distances \(r\) (typically less than a wavelength) in either the X or Z directions. Plane wave propagation was assumed over these small distances. The phase difference measured between the two points are used to estimate the angle of propagation \(\theta\) (see Figure 2). There are two possibilities: a one dimensional approach in which the calculation is performed using phase differences in either X or Z directions only (equations 1 and 2), or a two dimensional approach in which phase differences in two orthogonal directions are used (equation 3). The advantage of the two dimensional approach lies in the fact that it can be used to measure angles over the entire 360° range.
accurately, and the wavelength does not have to be known precisely. However, the distance $r$ must be kept smaller than half the wavelength for the calculation to produce the correct result. The one dimensional approach can only yield measurements over a 180° range and it is preferable to perform the calculation in the direction lying most orthogonally to the expected principal propagation direction component, in order to avoid ambiguity when solving the inverse sine and cosine functions in equations 1 and 2. The one dimensional approach also requires the wavelength to be accurately known, however for 2D mapping of the acoustic field the condition imposed on the step size $r$ need only apply in the measurement direction (e.g. $X$) meaning that the step size in the orthogonal direction (ie. $Z$) can be increased, leading to faster scan times. The results shown in this paper for large area beamplots were calculated using the one dimensional approach in $X$, with the wavelength based on an assumed speed of sound of 1500 m/s. For more detailed orthogonal linear scans across the focal peak, the above two dimensional description was extended to three dimensions. The phase differences in the three orthogonal directions were used to describe a unit vector, in a spherical coordinate system these produced estimates of the elevational ($\theta$) and azimuthal ($\phi$) angles describing the direction of ultrasound propagation.

2.5. Beam alignment: It was assumed that the angle of propagation at the focal peak would lie parallel with the sound axis for radially symmetric transducers. Plane wave conditions were assumed to be valid in the volume close to the focal peak. Measurements were performed in the three orthogonal directions across the focal peak using an $r$ value of 100 µm. A total of 6 repeat measurements were made in each direction for each transducer, alternating between scanning in the positive and negative directions to reduce any bias or systematic error due to temperature (sound speed) instability of the water, or backlash in the positioning system. Sound axis alignment was computed by identifying the 3D co-ordinates of 6 on-axis peaks (including the main focal peak). A linear regression was performed on $X-Z$ and $Y-Z$ data points, allowing computation of the elevational and azimuthal angles by determination of the gradients of the linear fits, together with their uncertainties.

2.6. Ultrasound field model. A linear ultrasound acoustic field model based on Raleigh-Sommerfeld diffraction theory [2] was used to predict acoustic field distributions, including amplitude and phase. The program was used to model acoustic fields at the fundamental frequency, assuming a speed of sound in water of 1500 m/s.

3. Results

![Figure 3. Normalised pressure distributions at the focal peak (top) and angle of propagation plots (bottom) in the X-Z plane for HIFU single element transducer (#1). The plots represent the parallel alignment “by eye” (left) and deliberately misaligned (right) arrangements. The white rectangles on the pressure plots indicate the alignment of the on-axis peaks.](image)
Figure 3 shows the pressure and propagation angle plots in the $X$-$Z$ plane for the second single element HIFU transducer which had been initially aligned by eye with the $Z$ axis, and subsequently for the condition in which the transducer was rotated azimuthally in the $X$-$Z$ plane. In the resulting angular plot there is an overall increase in all the angular values including at the focal peak position. In the pressure plots, the on-axis peak positions can also be identified, illustrating the ability to measure the amount of rotation using this method. Table 2 shows the measurement of the elevational and azimuthal angles as measured using both the 3D linear scan phase data and the on-axis peaks method. The measurement of the angle of the sound axis using the on-axis peaks method agrees, within errors, with the mean angle of propagation measured at the focal peak for both the aligned and mis-aligned arrangements.

| Method   | Elevational angle $\theta$ | Azimuthal angle $\Phi$ |
|----------|-----------------------------|------------------------|
|          | Phase                      | Peaks                  | Phase             | Peaks                  |
| “Straight” | -0.24±0.32                 | -0.07±0.05             | 0.23±0.16         | 0.38±0.03              |
| “Angled”  | 0.95±0.33                  | 1.18±0.40              | 6.25±0.24         | 6.06±0.30              |

Table 2. Sound axis elevational and azimuthal angles (in degrees) as calculated using the propagation angle at the focal peak and the on-axis-peaks method for single element HIFU transducer. The uncertainties represent the standard deviation for the phase method, and the standard error of the linear fit for the on-axis-peaks method respectively.

Figure 4 shows the pressure and angular plots obtained using the 10 strip HIFU transducer for both configurations tested. A clear pressure field asymmetry arises with the four elements switched off. The on-axis peaks appear in approximately the same positions for both configurations, giving similar results. If the user was unaware of the malfunction of some of the device’s elements, the angle of...
propagation measurement at the focal peak would produce a result which might alert the user to the problem, whereas the on-axis peak method would not. However, it could be argued that the on-axis-peak method is a robust way of determining the geometric sound axis of the transducer, irrespective of how the transducer may be responding, while the propagation angle method gives a better indication of from where the energy in the ultrasound beam as a whole is originating. Experimental data agreed with the simulation data for both methods. Results are summarised in Table 3.

| Configuration     | Elevational angle θ | Azimuthal angle Φ |
|-------------------|---------------------|-------------------|
|                   | Phase | Peaks | Model phase | Model peaks | Phase | Peaks | Model phase | Model peaks |
| All elements on   | -0.39±0.62 | 0.09±0.04 | 0 | 0 | -0.99±1.10 | -0.27±0.03 | 0 | 0 |
| Elements #1-4 off | 0.92±0.30 | -0.03±0.04 | 0 | 0 | -8.21±0.81 | -0.17±0.05 | -8.37 | 0 |

Table 3. Sound axis elevational and azimuthal angles (in degrees) calculated using the propagation angle, and on-axis peaks method for the segmented HIFU transducer. The uncertainties represent the standard deviation for the phase method, and the standard error of the linear fit for the on-axis peaks method respectively. Results from the simulation data are included.

4. Discussion and Conclusion

Phase data measured from acoustic field measurements can be used to derive estimates of the ultrasound beam propagation angle at any point in an ultrasound field. The method relies on measuring changes in phase with position as a hydrophone is scanned through the acoustic field. The data presented shows it is possible to visualise the convergence and divergence of focused ultrasound beams, but measurements around the focal peak may also help in aligning the transducer sound axis to be parallel to the beam plotting coordinate system. The advantage of the phase method lies in the relative ease and speed with which an estimate of the angle can be measured directly from the waveform data acquired during the acoustic field acquisition. The phase method has, therefore, a major advantage over the more traditional method which consists of identifying on-axis peak positions using a number of trans-axial scans. This can be time consuming when performed carefully, or lead to errors if done in an approximate manner. The principal sources of error in the phase measurement method are due to the stability and accuracy of the measurement system. If water temperature is not stable, changes in sound speed introduce apparent changes in phase over the course of a scan which will bias the result. The accuracy of the positioning gantry is also important, particularly for measurements at the focus of a HIFU field where small phase differences are measured over limited distances. Steps must therefore be taken to eliminate positioning errors (arising, for example, from backlash). The data reported in this paper shows good agreement between the phase and on-axis peaks methods in determining the relative alignment of the sound axis and beam plotting system. In the case of the 10 strip transducer, measurement of the propagation angle at the focal peak may indicate mis-functioning of the device. More rigorous analysis of the sources of errors in the phase method is now needed, together with further study of the technique when applied to the acoustic fields from a variety of transducers.

References
[1] Morris P, Hurrell A, Shaw A 2009 *J. Acoust. Soc. Am.* 125 3611
[2] Clarke R L 1995 *Ultrasound in Medicine and Biology.* 21 353