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Phase changes of ultrasonic surface and bulk waves through focusing measured using non-contact ultrasonic methods

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Abstract

Focusing an ultrasonic surface or bulk wave to a point can maximise the amount of ultrasonic energy at a point and increase the sensitivity of a measurement. Using non-contact ultrasonic methods we focus an ultrasonic wave pulse on or in a sample. Focusing can be achieved by using a shaped source or by the surface profile of the sample itself. Experiments and modelling confirm the known result that once the wave pulse passes through the focal point, it will undergo a phase shift. Using non-contact ultrasonic methods on a sample with spherical or cylindrical geometry, one can exploit the surface profile of the sample to focus an ultrasonic wave, as there is no refraction to consider at the sample surface under the transducer.

Keywords: Ultrasound, focus

Ultrasound is focused to a point or region in many different applications, usually to increase the amount of energy at that location and to increase the sensitivity of a measurement such as the detection of a defect from a reflected signal. One can focus surface waves to a point on a sample, or bulk waves to a point within a sample, such that focusing can be effectively to be considered in two or three dimensions. Such ultrasonic measurements typically employ a pulse of ultrasound rather than a continuous wave. In addition to trying to simply detect a signal that may have reflected or scattered from a defect, one may wish to try and obtain more information from the detected pulse such as frequency dependent velocity. Therefore it is extremely important that one should understand the effects of focusing on the pulse as a reflecting object may lie either side of the focus point of the ultrasonic wave pulse.

For a cylindrically focused wave or a two dimensional geometry using simple modelling based on Huygens principle, one can explain the nature of a $\pi/2$ phase shift of a wave after it has passed through a focal point. The underlying physics that leads to a phase shift after focusing has been tackled by several workers over the past century[1-3] and is well documented, although it is often neglected or not considered in practical measurements using focused ultrasound.

In our first experiments we generate Rayleigh surface waves on a thick block of aluminium using a pulsed laser beam from a Nd:YAG laser, focused to a ring shape on the sample surface. The out-of-plane displacement is measured using a modified Michelson interferometer, with a bandwidth of 80MHz with pico-meter sensitivity. Focusing the surface waves to a point on a sample in this way can maximise the sensitivity to surface defects. This type of experiment has been reported qualitatively by earlier workers

using a less sensitive detector with a lower bandwidth.[4-5] What has not been reported previously is that one is also able to measure the elastic properties of the material in one measurement, without any diffraction losses, by comparing the inward travelling wave pulse to the outward travelling wave pulse, provided that the radial displacement of the detector is known. Frequency dependent velocity and attenuation can be calculated using a fast Fourier Transform approach.[6] Usually, where a generation laser line or point source is used, one would need to move either the generator or detector a known distance and record the data in two separate measurements. In this paper, the detection point is located a known distance from the centre of the focal point of the ring source, but within the ring source. This is shown schematically in figure 1. As expected, the ultrasonic surface wave pulse heading inwards towards the focal point increases in amplitude through constructive interference, and the measured peak to peak amplitude of this wave pulse is shown in figure 2 as a function of distance from the centre of the ring.

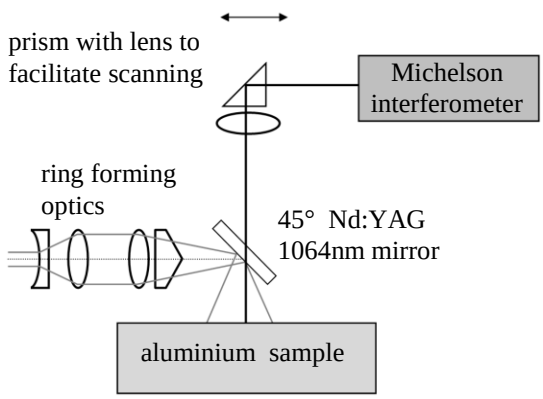

FIG. 1. Schematic diagram of experimental set-up used to measure the ultrasonic displacement generated by a pulsed Nd:YAG laser beam ring source.

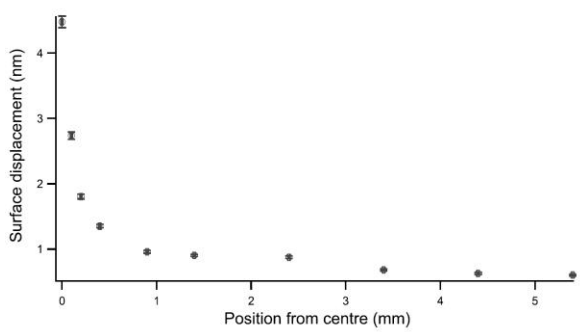

FIG. 2. Peak-to-peak amplitude of the Rayleigh surface wave generated by a pulsed ring shaped laser beam.

In addition to the inward travelling surface wave, the outward travelling surface wave that has been through the focal point can also be detected. However, it is clear that the shape of the inward and outward travelling wave pulses are very different, as is shown in figure 3. The experimental inward travelling wave pulse is low pass filtered and a Hann window is applied to the result to bring the ends smoothly down to zero. This processed pulse is then used in a numerical simulation of the effect of focusing by applying Huygens principle to the ring, using a finite number of points on the ring. For the purpose of this simulation, 720 points, as the method showed convergence for much fewer points than this. The experimentally observed waveform, together with the simulated waveform are shown in figure 3.

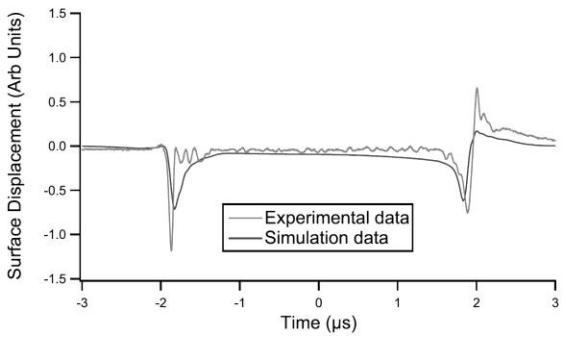

FIG. 3. Simulated and experimental surface wave forms fora pulsed laser beam ring source.

Fourier analysis of the simulated outward travelling shear wave pulse in figure 3, shows that it is equivalent to applying a phase shift of $\pi/2$ to the inward travelling pulse. This extra phase shift must be factored in when using this method to measure the elastic properties of the sample. This has been shown qualitatively by previous workers,[5] by performing the forward problem of phase shifting the initial pulse by $\pi/2$ and visually comparing it to experimental data.

A further experiment was conducted using focused bulk shear waves in a cylindrical aluminium sample. An electromagnetic acoustic transducer (EMAT)[7-8], designed to generate linearly polarised shear waves[9] is used to generate shear waves on the curved surface of a 50.7 mm diameter aluminium cylinder as is shown schematically in figure 4. Many technologically important samples are cylindrical in shape, and one can exploit the geometry of the sample to focus ultrasonic energy through the centre of the sample. The coupling between the sample and the transducer is electromagnetic, and so the Lorentz force that generates the acoustic wave at the surface of the sample follows the surface profile of the cylinder, which focuses the shear wave through the centre of the cylinder. As the ultrasonic pulse passes through the focal point in the centre of the cylinder, it will impinge on the opposite side of the cylinder and this surface will also act so as to focus the wave pulse back through the focal point to the other side of the cylinder. There will be some wave energy that lies outside the focused region of the beam, due to side lobes from the generation source.

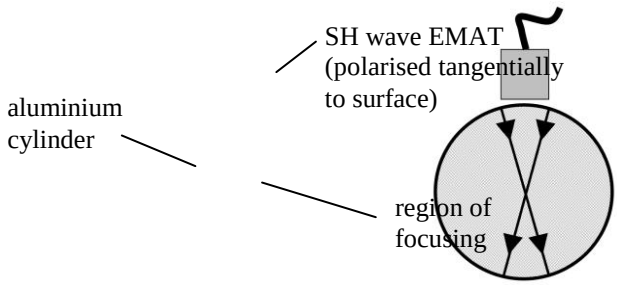

FIG. 4. Schematic diagram of set-up used to focus linearly polarised (SH) shear waves in a 50.7 mm diameter aluminium cylinder.

The same transducer that generates the shear waves shown in figure 4, also detects the ultrasonic waves that reverberate through the sample thickness as a series of echoes. If one examines both the odd and even echoes it becomes clear that the odd echoes are phase shifted by π, when compared to the even echoes. This is evident by examining the windowed and time shifted even and odd echoes as shown in figure 5 and 6.

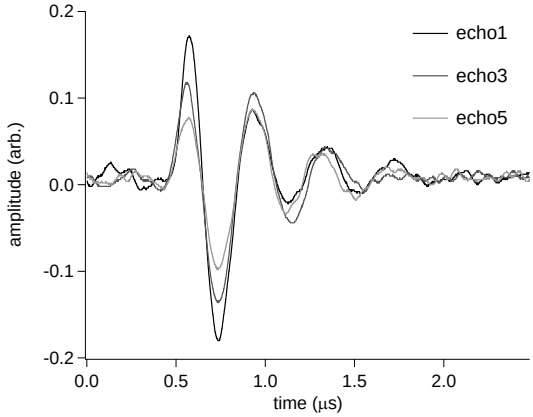

FIG. 5. The odd echo numbers have slight changes is shape, but are essentially the same shape with a smaller amplitude for higher order echoes due to attenuation.

This inversion in the amplitude of alternate echoes arises because each time the wave pulse passes through the focal point, all the frequency components that are contained within the pulse, experience a phase shift of $\pi/2$. When the pulse is subsequently reflected from the far side of the cylindrical sample, it passes through the focal point again and thus experiences a total phase shift of π relative to the initial pulse. Thus, alternate echoes in time will appear inverted relative to each other as they will have a relative phase shift of π to the previously detected echo.

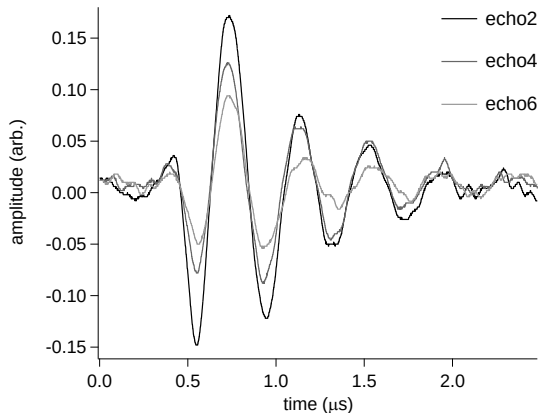

FIG. 6. The even echo numbers have slight changes is shape, but are essentially the same shape with a smaller amplitude for higher order echoes due to attenuation. Note that the even echo numbers appear inverted relative to the odd echo numbers.

Whilst there is evidence for some limited amount of dispersion or frequency dependent attenuation changing the temporal profile of the echoes, there is a clear inversion of successive echoes. The experiment shown in figure 4 is repeated on a steel sphere of 50.7 mm diameter. In this case, the phase change on going through the focal point should be π. Again the opposite side of the sample to where the wave is generated will act to focus the wave back through the centre of the sphere. In this case however, the total phase shift on passing through the focus should be 2π and successive echoes do not appear inverted relative to each other as is shown in figure 7. Once again, successive echoes have been shifted in time to aid comparison.

Using non-contact ultrasonic methods, this paper has demonstrated clearly, that one can exploit the curvature of the surface of a sample or a shaped source to focus bulk and surface waves. The importance of taking into account the phase shift after passing through a focal point has been explained. This phase shift effect is not unique to non-contact ultrasonic and must be taken into consideration when performing any measurements using focused waves.

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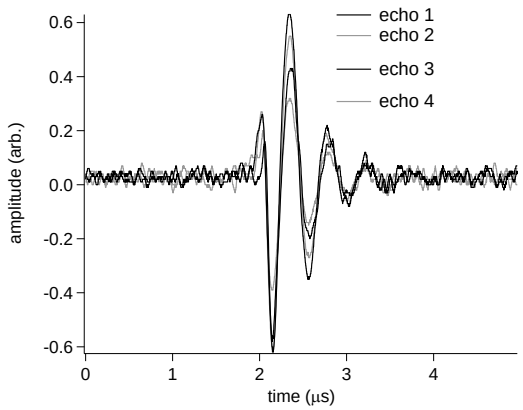

FIG. 7. The first four shear wave echoes in the spherical steel sample exhibit some slight change in pulse shape caused by frequency dependent attenuation or dispersion, but successive echoes clearly are not inverted relative to each other.

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