AN APPLICATION OF CAUSTICS TO ULTRASONIC DEFECT LOCATION

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INTRODUCTION

In this paper we describe a use of ultrasonic caustics to detect and locate defects in immersed rods and pipes.

In the short wavelength limit a wavefield can be approximated to rays directed along the direction of energy propagation [1]. A caustic is the envelope of a smoothly varying bundle or family of such rays, that is a surface to which all the rays are tangential. Figure 1 shows a simple 2-dimensional caustic line; note that it forms a boundary between the area that the rays illuminate and a zone which is in shadow.

Perhaps the most familiar optical caustic is formed when a parallel beam of light is reflected on the inside of a drinking glass or cup to form a bright cusped curve on the surface of the liquid, which is where the 3 dimensional caustic surface is intersected by the liquid [2].

A caustic is a generalised focus; the point focus is an idealised special case, nearly a caustic line of infinite curvature.

The potential of caustics in non-destructive evaluation stems from the fact that they form a well defined structure in the wave field in and around the specimen under test, allowing the location of a scattering defect to be deduced from the location of points on the caustic.

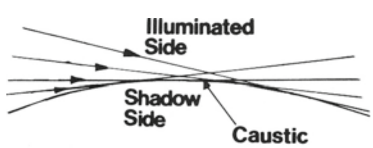

Figure 1. A line caustic.

THEORY

Consider a defect, or part of a defect, behaving as a point source of ultrasonic shear waves inside an aluminum cylinder immersed in water. Initially, let the sound wavelength be small relative to the sample dimensions so that the sound field can be described in terms of rays and geometrical laws of reflection and refraction applied at each interface. Figure 2 shows a cross-sectional view of rays produced by a point source at a distance from the axis of 75% of the sample radius. If we allow these rays to be reflected from the inner sample wall, remaining in shear mode, the triple cusped caustic shown in figure 3 is formed inside the sample. If these rays are now transmitted out of the sample, the caustic continues into the surrounding water as the pair of nearly straight lines seen in figure 4. It is this caustic formation outside the sample that we exploit here for the purpose of defect location.

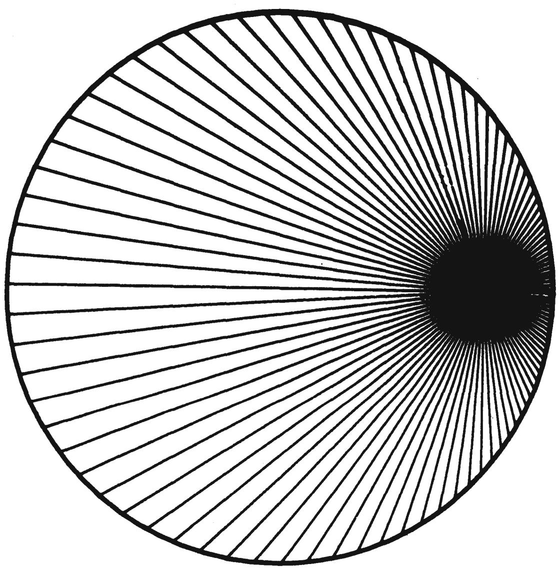

Figure 2. A point source of shear waves 75% of the radius from the center

Figures 5 and 6 show how strongly the caustic orientation varies with defect position. For the case shown in figure 4 a 1% change in the radial position of the defect results in a 2° angular diplacement of the caustics, permitting sensitive measurement of the position of the defect. We have obtained an analytic expression for the dependence of the caustic orientation on source location, plotted as the solid line on the graph of figure 7.

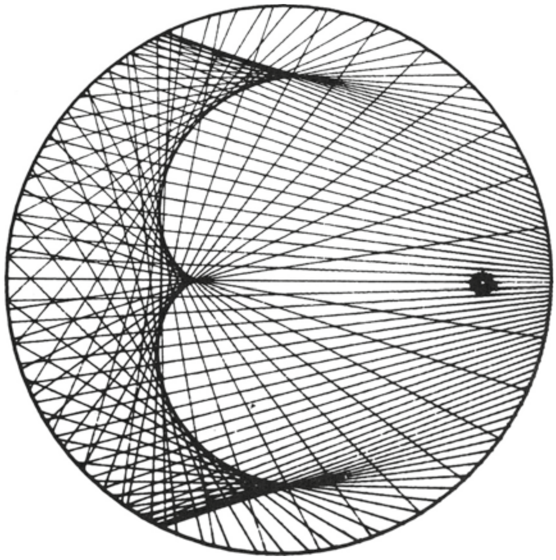

Figure 3. Rays reflected from the cylinder wall, remaining in shear mode.

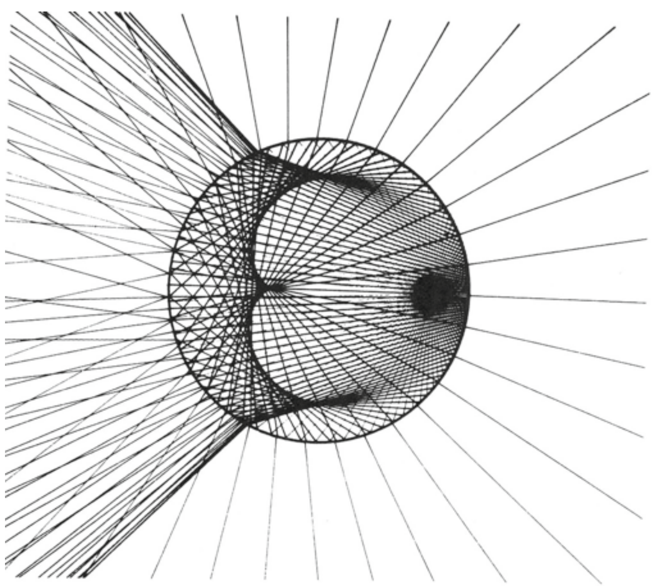

Figure 4. Rays refracted out into the surrounding water

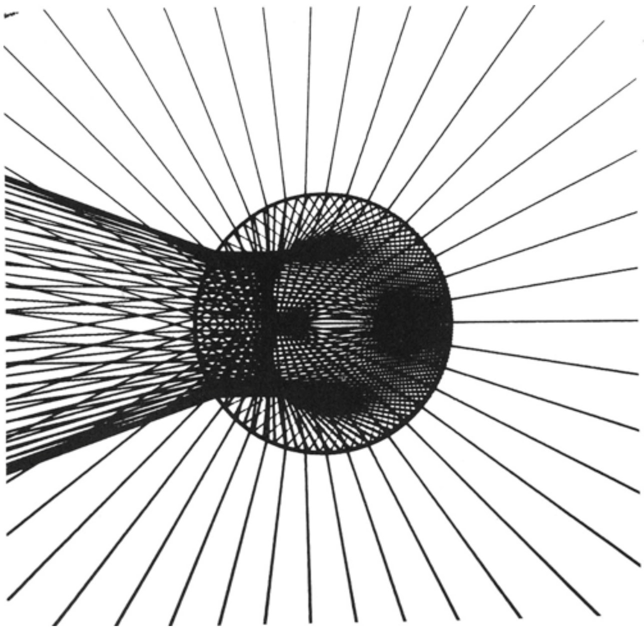

Figure 5. Rays from a source 60% of the radius from the center.

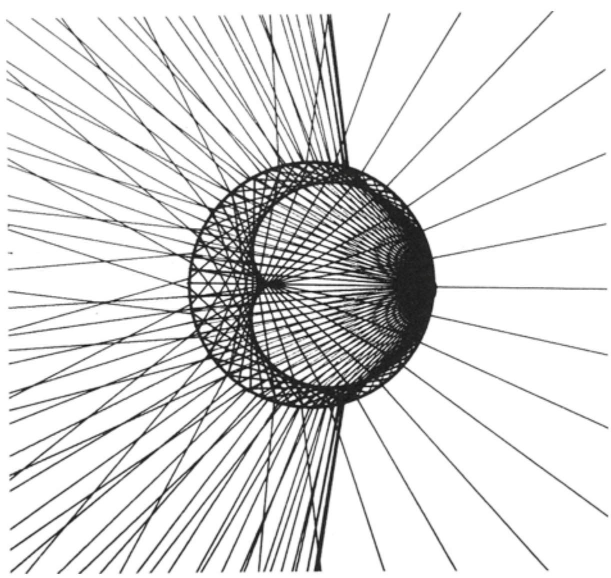

Figure 6. Rays from a source 90% of the radius from the center.

Because we are dealing with a finite sonic wavelength, the region of highest sound intensity is not on the caustic formed by the rays but is slightly inside the illuminated zone. This diffraction effect was modeled by G.B.Airy [1] who, by assuming that the ray approximation applies well away from the caustic, arrived at the result:

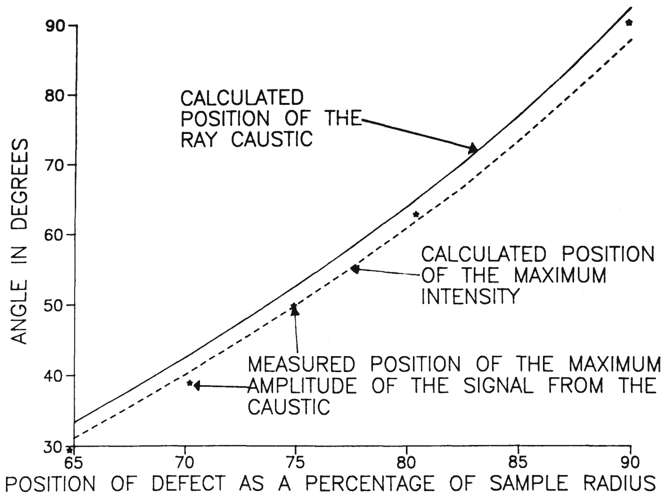

Fig. 7. Caustic position as a function of defect location.

$$x = 1.02X(\rho/(2k^2))^{1/3} \qquad 1$$

where x = distance from the amplitude maximum to the caustic
ρ = radius of curvature of the caustic at that point
k = wave number of the sound

The curvature of the caustic has been determined numericaly and the expected positions of the maxima in amplitude thereby calculated. These are shown as the broken line on figure 7.

EXPERIMENTAL

A 76mm diameter aluminum rod, containing an off-center 1mm diameter hole drilled perpendicular to the axis, was immersed in water and illuminated with 5MHz pulsed ultrasound. The experimental configuration is shown in figure 8. Two tranducers were used with a standard ultrasonic pulser/receiver operating in pitch-catch mode The received pulses were observed on an oscilloscope. In order to achieve the maximum compression wave intensity at the defect, the sound was sent in normal to the part of the cylinder closest to the hole. The sound field outside the cylinder was received using a tranducer mounted so that it can more in a arc centered on the cylinder axis and oriented to face down the line of the expected caustic.

RESULTS

The signal from the caustic was easily identified on the oscilloscope screen as a peak which rose very quickly as the receiving transducer was moved from the shadow side to the illuminated side of the caustic. The signal grows from non-existence to the largest peak on the screen within a twelve degree movement of the receiving probe. Figure 9 shows the amplitudes of the signal of interest, and the largest other signals,as functions of transducer location using a sample with a hole drilled at a radial distance from the center of 75% of the radius. The ray paths visible were identifed by measuring their times of flight; in this case the two other signals correspond one, to sound which travels

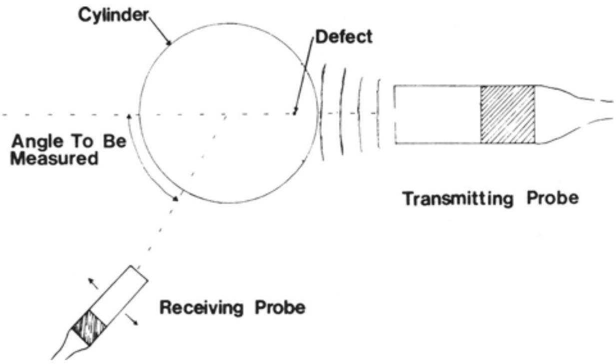

Fig. 8. Schematic diagram of the experimental set up.

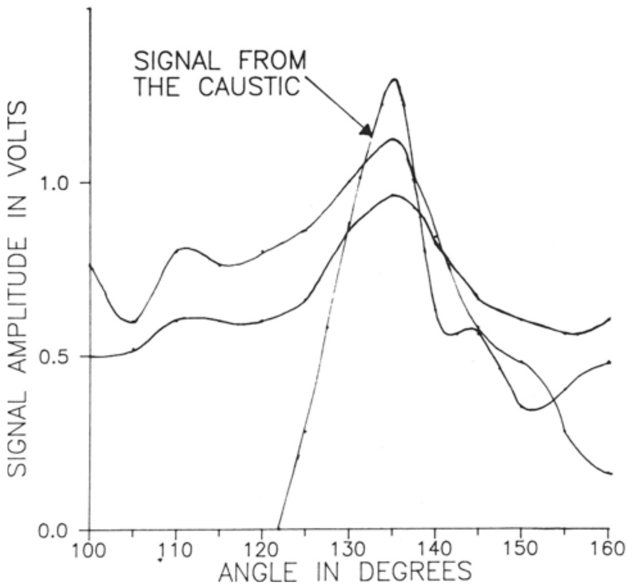

Fig. 9. Amplitudes of the three largest received signals as a function of receiving probe position.

through the sample in compression mode without interacting with the hole and the other to the shear wave scattered from the hole and refracted out into the water without being reflected. The fact that these two signals peak at about the same time as the caustic is a coincidece unique to a sample with this hole location. Note that the caustic appears as a signal which varies rapidly compared with those from sound arriving via other paths; it is this unique property that makes it a detectable marker in the wave field.

The probe position corresponding to the maximum signal amplitude due to the caustic was measured on both sides of the sample and the angle shown on figure 8 calculated. This was carried out for several positions of the hole,and the results are plotted on figure 7. At least to first order, the results match the Airy model of the caustic. The small discrepancy (less than 2°) is thought to be due to the fact that the scatterer has finite size and an attempt to account for this is in progess; the error is small enough not to affect any N.D.E. applications.

DISCUSSION -APPLICATION TO NDE

A prototype testing machine would use the configuration shown in figure 7 with the receiving probe linked to electronics capable of detecting the quickly appearing and disappearing signals from the caustics, and communicating to a computer the angles at which these events happen. For each pair of angles, the computer would calculate the defect location using the known relationship between the caustic separation and the radial source location, and the symmetry of the set-up. There is a problem in that two sources (for example the two ends of a crack) will create 4 caustics which means there are 6 pairs of caustics and therefore 6 calculated defect locations. This can be resolved by scanning the transducer in an arc of different radius, the 4 falsely calculated defect locations will be in different places whereas the positions of the two real results will be unchanged.

As stated above, caustics are markers in the wave field and as such they open up the possiblity of performing defect location with out knowledge of the sonic time of flight. This allows testing using continous wave or long tone burst sound and more accurate defect location in cases where the time of flight is too short to be easily measurable.

Freedom from the need to produce short sound pulses offers a substantial advantage in the testing of components (and here we include some high performance composites [3]) in which sound is highly dispersive both in amplitude and velocity. Using this technique the illuminating beam can have a very narrow frequency distribution and in which case it is affected much less by the material properties.

The absence of any need for time measurements will be useful in cases such as the very high frequency testing of small components where the time measurment needed in a conventional pulse-echo technique is either difficult or expensive.

CONCLUSION

We have demonstrated that when sound is scattered from a defect in a metal rod ultrasonic caustics are formed in the surrounding medium. The caustics can be accurately modeled using diffraction theory and promise to be useful for NDE. The most important feature is that they promise a testing technique that requires no accurate time information.

REFERENCES

1. L. D. Landau and E. M. Lifshiftz, The Classical Theory of Fields (revised second edition). (Addison-Wesley, Reading Ma., 1965).
2. T. Poston and I. N. Stewart, Catastrophe Theory and its Applications (Pitman, London, 1978).
3. W. J. Murri and B. W. Sermon, in this volume.