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Experimental study of ultrasonic beam sectors for energy conversion into Lamb waves and Rayleigh waves

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ABSTRACT

When a bounded beam is incident on an immersed plate Lamb waves or Rayleigh waves can be generated. Because the amplitude of a bounded beam is not constant along its wave front, a specific beam profile is formed that influences the local efficiency of energy conversion of incident sound into Lamb waves or Rayleigh waves. Understanding this phenomenon is important for ultrasonic immersion experiments of objects because the quality of such experiments highly depends on the amount of energy transmitted into the object. This paper shows by means of experiments based on monochromatic Schlieren photography that the area within the bounded beam responsible for Lamb wave generation differs from that responsible for Rayleigh wave generation. Furthermore it provides experimental verification of an earlier numerical study concerning Rayleigh wave generation.

1. Introduction

In this report an (thick or thin) immersed plate is considered and bounded beams of ultrasound propagating in water are taken incident on the immersed plate at known angles. To shorten the explanation the word ‘leaky’ is omitted whenever the notions ‘leaky Lamb waves’ or ‘leaky Rayleigh waves’ appear further in this paper.

From experience with Lamb waves and Rayleigh waves it is known [1] that a higher efficiency is achieved when a wide beam is used for Lamb wave generation and a narrow beam for Rayleigh wave generation. The current paper investigates which sectors of a Gaussian type bounded beam are primarily responsible for conversion of incident sound waves to Rayleigh waves or to Lamb waves. If it is indeed true that narrow beams are better capable of stimulating Rayleigh waves than wide beams, then probably the edges of the beam play a more imminent role in the stimulation than the central part. If on the other hand wide beams are better in generating Lamb waves, then it is likely that in this case the center of the beam is more important than the edges.

The outline of this paper is as follows. The experimental setup and procedure are briefly discussed, followed by the case of sound incident on a plate at an angle that generates Lamb waves and subsequently the case of the same bounded beam incident on a very thick plate at the Rayleigh angle is tackled. Wherever appropriate the results are compared with earlier reported statements and numerical studies.

2. Experimental setup

A monochromatic Schlieren experimental setup is used very similar to that described in Refs. [2–4]. A Schlieren setup is essentially based on the acousto-optic effect. A wide parallel (He–Ne) laser beam passes through a water tank where the acoustic experiment is done. This wide laser beam is then focused onto a black ink dot on glass. When the wide optical beam in the water tank is not disturbed by sound it is stopped on its path by the ink dot. Whenever a portion of the light is disturbed through diffraction by sound waves, its path deviates from the ink dot and reaches a camera. Hence the method allows visualization of sound in the water tank. From a practical point of view there are some specific problems one should cope with in order to obtain clear pictures. The wide laser beam must be perfectly parallel and must be incident perfectly perpendicular to every involved sound beam. For this reason perfect alignment must be accomplished for the sound emitter as well as for the surface on which sound is scattered. Once those conditions are met, high quality Schlieren pictures are possible as are shown below. The acoustic part of the experiment consists of a harmonic incident bounded sound beam reflected on a surface. This surface can be a thin plate or a thick plate depending, respectively, on whether Lamb wave generation or Rayleigh wave generation is intended. We are particularly interested in effects caused by the edge of the plate to allow a study of different

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interaction sectors of the ultrasonic bounded beam. Therefore once the incident beam is fixed and the plate is aligned, the plate can be moved horizontally, maintaining alignment, in order to position the edge of the plate at a certain distance from the central spot of sound incidence. A schematic of the acoustic part of the experiments is shown in Fig. 1. The thick black lines and arrows denote the direction of propagation of sound waves. Hence comparison is possible with the Schlieren pictures given below. More explanation is given whenever necessary.

The angle of incidence is either a Lamb angle or a Rayleigh angle. This is achieved by changing the angle, while the incident beam is incident far away from the edge of the plate, until the Schoch effect [5–10] occurs. The Schoch effect is a beam displacement effect that is most often accompanied by a parallel separation of a specular beam and a non-specular beam with a null strip in between. The creation of a specular beam, a non-specular beam and a null strip is caused by the combination of a direct reflected sound beam and a leakage field caused by the Rayleigh or Lamb wave. Both fields can phase-cancel each other and hence show destructive interference in some areas (the null strip) or show constructive interference in other areas such as the specular beam and (depending on the situation dominated by beam width, frequency and material properties) a portion of the non-specular beam, or elsewhere (the remaining part of the non-specular beam) the leakage field is predominant. The characteristics of the Schoch effect may for instance reveal properties of the solid or any coating on it [11] and is therefore sometimes used for NDT purposes.

3. Generation of Lamb waves

It is well known that sound incident at certain angles produces Lamb waves in a thin plate. The velocity of the possible Lamb modes depends on the frequency times the thickness. Fig. 2 shows the different calculated dispersion curves for an aluminum plate immersed in water. The calculations are based on a longitudinal wave velocity of 6370 m/s, a shear wave velocity of 3160 m/s and a density of 2770 kg/m^3 for aluminum whereas a longitudinal wave velocity of 1480 m/s and a density of 1000 kg/m^3 for water. Each of the curves corresponds to a particular Lamb mode. The experiments are performed on a 1.45 mm thick aluminum plate using a 3 MHz bounded beam of 1 cm physical width. The horizontal line in Fig. 2 corresponds to the experimental configuration. It is seen that 5 Lamb modes can originate each at a specific angle of incidence. Experiments have revealed the Schoch effect up to a certain extent for each of these modes, however the clearest effect was found at 19°. For this reason the reported experiments are performed at a fixed angle of 19°. It is seen in Fig. 2 that this angle generates the A_1 Lamb wave which is an anti-symmetrical Lamb mode. In order to ensure correct conclusions, experiments at 14.5° have been undertaken and resulted in equivalent results as the ones reported here. The first question is how we can detect the generation of Lamb waves at this angle of 19°. Of course there is the Schoch effect, but when the incident beam reaches the edge of the plate, this effect can be corrupted, so it would not be possible anymore to verify the presence of Lamb waves. Therefore it is interesting to know that when Lamb waves reach the edge of the plate, complicated mode conversions occur [12–21], similar to the case of a Scholte–Stoneley wave reaching the edge of a solid [22,23]. Going into the details would deem beyond the scope of this paper. Nevertheless one effect is very important for the cause of the current paper: Lamb waves are partly retro-reflected, which means that a standing wave pattern is formed in the plate as a result of forward and backward propagating identical Lamb modes. Hence whenever the A_1 mode reaches the edge, a standing wave pattern is formed with an inter notch distance d given by

$$2d = \frac{v}{3\ \mathrm{MHz}} \tag{1}$$

with v the velocity of A_1 Lamb waves. Fig. 2 shows that $v = 4546$ m/s and therefore $d = 0.76$ mm. Indeed if we take a look at the Schlieren picture given in Fig. 3, when the considered bounded beam is incident at 19° with the furthest part of the right reflected lobe reaching the edge of the plate without surpassing it, a fringed pattern of vertical lines of thickness 0.76 mm appears superposed on the other sound patterns. The reason why these lines are vertical is because Snell's law involves that standing wave patterns in a plate can only emit energy along the direction normal to the interface. Backward propagating A_1 waves can be generated not only by means of incident A_1 waves, but also by interaction of the bounded beam with the edge whenever part of it surpasses the edge. Nevertheless the standing wave pattern and hence the vertical lines pattern can only exist if those backward propagating A_1 waves are accompanied by forward propagating A_1 waves. Therefore the pattern is a direct indication for forward propagating A_1 waves and is hence proof of the generation of A_1 waves by means of the incident beam. Actually a weak pattern corresponds to weakly generated A_1 waves, while a strong pattern corresponds to strongly stimulated A_1 waves. Fig. 4 reveals what occurs if the incident beam surpasses the edge of the plate. Besides the patterns seen in Fig. 3, there is also sound

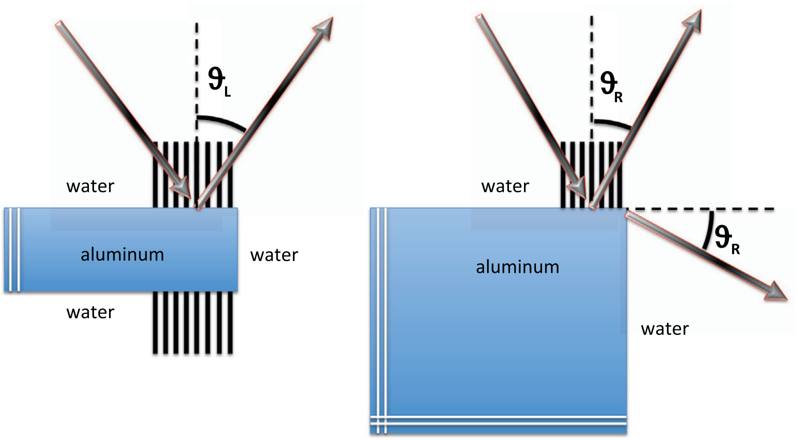

Fig. 1. Schematic of experimental setup. Left: sound incident on plate at Lamb angle. A characteristic vertical line pattern is generated because of retro reflected Lamb waves. Right: sound incident at Rayleigh angle. The generated Rayleigh wave propagates around the corner and generates a ray of sound at the Rayleigh angle for the vertical edge face. There is also a vertical line pattern due to retro reflected Rayleigh waves.