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Fast beating null strip during the reflection of pulsed Gaussian beams incident at the Rayleigh angle

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Abstract

It is well known that harmonic bounded Gaussian beams undergo a transformation into two bounded beams upon reflection on a solid immersed in a liquid. The effect is known as the Schoch effect and can be found at the Rayleigh angle for thick plates and at the different Lamb angles for thin plates. Here, a study is made on the effect of pulsed Gaussian beams reflected on solids. It is found experimentally that the Rayleigh wave phenomenon still generates two reflected bounded beams, whereas Lamb wave phenomena do not generate this effect. This fact may be explained intuitively by realizing that the Rayleigh phenomenon is a coincidental phenomenon that is generated in situ, whereas the Lamb wave phenomenon is a non-coincidental phenomenon that is generated only after incident sound is influenced by both sides of a thin plate. Another explanation is the fact that Rayleigh waves are not dispersive, whereas stimulation and propagation of Lamb waves is frequency dependent. A pulse contains many frequencies and therefore only a fraction of the incident pulse is transformed into a Lamb wave. In this paper, numerical simulations are performed that show that actually the Schoch effect does occur neither for Rayleigh waves, nor for Lamb waves. As a matter of fact, a pulse, incident at the Rayleigh angle, generates two reflected lobes with a null zone of a different kind. The null zone is beating several times during the passage of each pulse. This results in a 'null zone' having a lower mean intensity than any of the two lobes, still less outspoken than for the case of harmonic incident bounded beams. This effect does only occur for Rayleigh wave generation and is much less outspoken for Lamb wave generation.

Keywords: Scattering; Pulsed sound; Gaussian beams; Schoch effect; Null strip

1. Introduction

The Goos–Hänchen theory [1] about the reflection of light on a dielectric interface, was experimentally studied by Tamir and Bertoni [2] and its acoustic counterpart was later encountered by Schoch [3–5]. The effect, which is now called the Schoch effect, consists of the reflection of two reflected beams for one incident beam, due to the generation of surface waves. The low amplitude strip in between the two reflected lobes, is called the null strip [6]. The Schoch effect, occurs when harmonic ultrasonic bounded beams are incident on a smooth liquid–solid interface. The purpose of this paper is to study the effect of using a pulse instead of a harmonic incident beam and to see whether an effect like the Schoch effect happens as well.

2. Experimental setup and numerical simulations

All the experiments were performed by means of a 5 MHz transducer (a Krautkrämer H5M shock wave probe) immersed in water. The sound velocity in water is 1480 m/s whereas the density of water is 1000 kg/m^3. The sound beam produced by the transducer is Gaussian and has a profile given by

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$$G(x) = \exp\left(-\left(\frac{x}{W}\right)^2\right), \tag{1}$$

with Gaussian beam width W equal to 2.5 mm.

Experiments are performed in a harmonic regime and also in a pulse regime. For the harmonic regime, we connected a function generator to the transducer, whereas pulse generation has been achieved by means of a Krautkrämer USIP 20 ultrasonic apparatus. The generated pulse has a nominal frequency of 5 MHz and is given by

$$\frac{ft}{M}\cos(2\pi ft)\exp\left(-\left(\frac{ft}{p}\right)^2\right), \tag{2}$$

with $f = 5$ MHz and $p = 1.08$ with M a normalization constant.

The pulse repetition frequency in the experiments is 20 kHz. This is the maximum pulse rate available in the Krautkrämer USIP 20 ultrasonic apparatus.

In the numerical simulations, the period of each pulse (2) was set at 2.4 μs, which corresponds to a propagation length in water of 3.5 mm and a pulse repetition frequency of 416 kHz. The pulse (2) was simulated by means of a fast Fourier transform (FFT) applying 128 frequencies. The beam itself was simulated by the FFT as well. This is done by a decomposition of the bounded beam into 1024 plane waves, for an FFT taken on the interval $[-6W, 6W]$. Then, for each plane wave within the decomposition, the reflection is calculated by considering continuity of normal stress and strain on the liquid/solid interface(s). In the case of a thick plate, the system was simulated by assuming that the solid is a half space and taking into account an incident longitudinal plane wave, a reflected longitudinal plane wave and two transmitted plane waves (i.e., one shear and one longitudinal). In the case of a thin plate, the same principles hold, except that there are now four plane waves inside the plate, i.e., two downward propagating waves (one shear and one longitudinal) and two upward propagating waves (again one shear and one longitudinal).

We have performed experiments and simulations on a 1.45 mm thick aluminum plate immersed in water. The sonic velocity in water is 1480 m/s, whereas the density of water is 1000 kg/m^3. The longitudinal wave velocity in aluminum is 6370 m/s, the shear wave velocity is 3160 m/s, whereas the density of aluminum is 2770 kg/m^3. We have found several Lamb angles and considered the one at 25.3°. Consideration of other Lamb angles delivered qualitatively the same results.

Simulations and experiments are also performed on a thick (>1 cm) stainless steel plate immersed in water. The longitudinal wave velocity in stainless steel is 5790 m/s, the shear wave velocity is 3200 m/s, whereas the density of stainless steel is 7900 kg/m^3. The Rayleigh angle of stainless steel immersed in water is 30.1°.

The experimental results have been obtained by application of Schlieren imaging [7–9]. Schlieren images are made by means of the acousto-optic effect. A wide parallel laser beam (generated by a He/Ne laser source) traverses the water tank in which the experiments are done. The presence of ultrasound generates diffraction phenomena of the laser light. Behind the water tank, the traversed laser light is focused onto a spatial filter. Only undisturbed laser light is blocked by the filter. Diffracted laser light is not influenced by the spatial filter and reaches a projection screen. Therefore, an image of the ultrasonic wave field inside the water tank is formed on the projection screen. This image is captured by a digital camera and is discussed in the current paper.

3. Results

3.1. Lamb waves

Fig. 1a shows a Schlieren picture of a harmonic 5 MHz bounded Gaussian beam ($W = 2.5$ mm) incident on a 2.4 mm thick aluminum plate at a Lamb angle of 25.3°. Dark areas correspond to areas in the water tank where no ultrasound is present. Light areas represent ultrasound. The sound is generated by a transducer (upper right) that is connected to a function generator. The reflected sound consists of two beams instead of one. This effect is called the Schoch effect. At angles other than Lamb angles, the Schoch effect is not visible. For this continuous regime, exact simulations have been performed that are left out of the report because such simulations are well known.

In order to simulate the effect of a pulse, the pulse is decomposed into harmonic waves and for each harmonic wave, a reflection pattern is calculated, taking into account the elapsed time that is considered after impact on $(x,z) = (0,0)$. The result is then a summation of each of the calculated patterns for the different frequencies and for the chosen elapsed time. The effect of a pulse is seen on the Schlieren picture of Fig. 1b. This picture corresponds to Fig. 1a, except that pulsed sound is used here, generated by the same transducer as in Fig. 1a, though connected to the USIP 20 ultrasonic apparatus. The Schlieren picture is taken, just as the previous one, by a camera exposure time of two seconds. Therefore, what is seen on the image is not a snapshot of one single ultrasonic pulse in time, but the mean effect of many pulses passing along the path of propagation during the exposure time of two seconds. Because of the limited pulse rate, the image of the present beams is very fade. Therefore, a rectangular area is artificially contrast enhanced. Note that a fade incident beam is visible and also one fade reflected beam. The Schoch effect is not visible here. There are different ways to understand this fact intuitively. For a harmonic wave, the Schoch effect is due to re-radiation of sound by generated Lamb waves. The Lamb waves are generated through the influence of both sides of the plate – therefore we may speak about non-coincidental generation. If a pulse is used instead of a harmonic wave, upon impact, the sound field is only influenced by the upper side of the plate and not yet by the lower side of the plate. It

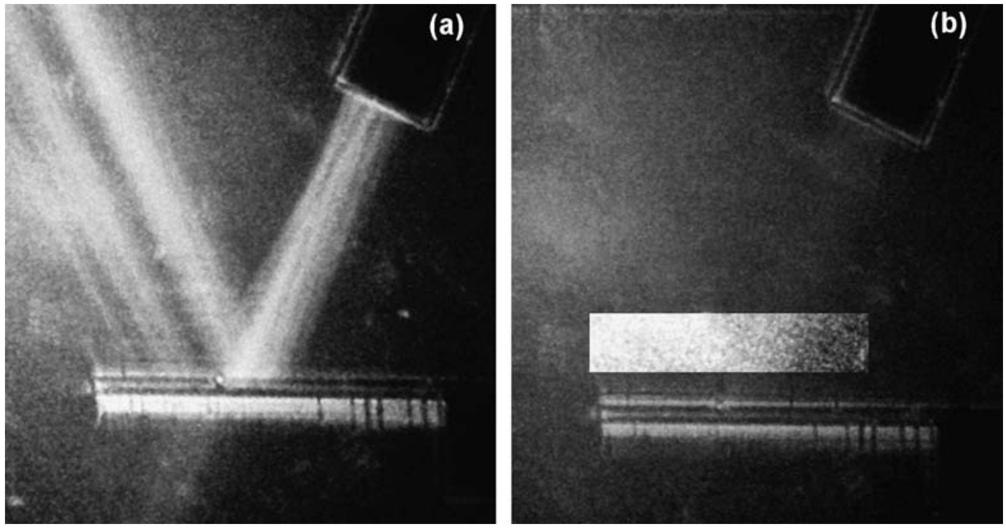

Fig. 1. Schlieren pictures of a 5 MHz bounded Gaussian beam ($W = 2.5$ mm) incident on a 2.4 mm thick aluminum plate at a Lamb angle of 25.3°. The sound is generated by a transducer (upper right) that is connected to a function generator (a) or connected to the USIP 20 ultrasonic apparatus (b). In (a) the reflected sound consists of two beams. This effect is called the Schoch effect. In (b), because of the limited pulse rate, the image of the present beams is very fade. Therefore, a rectangular area is artificially contrast enhanced. Note that a fade incident beam is visible and one fade reflected beam. The Schoch effect is not visible here.

takes a while before Lamb waves are truly generated. Then, because of the dispersive nature of Lamb waves, only a fraction of the incident energy of the pulse is really transformed into a Lamb wave. The rest is just reflected/transmitted. In other words, a Lamb wave pattern is only realized after some time and it is not really outspoken. This is the reason why a pulse does not show any Schoch effect.

In Fig. 2, a simulation is presented of the reflected pulse, 0.00184 ms after impact at the same Lamb angle of 25.3°. Note that there is a strong reflected pulse, accompanied by a second pulse on the left hand side that is actually attached to it. Therefore, no 'null' zone is created. This corresponds to the experiment of Fig. 1b.

3.2. Rayleigh waves

Contrary to Lamb waves, Rayleigh waves are coincidental phenomena, because they are generated right on the upper surface of a thick plate on the area where sound is incident. It is therefore expected that the Schoch effect must be visible for both harmonic waves and pulses.

In Fig. 3a, a Schlieren picture is shown of a harmonic 5 MHz bounded Gaussian beam ($W = 2.5$ mm) incident

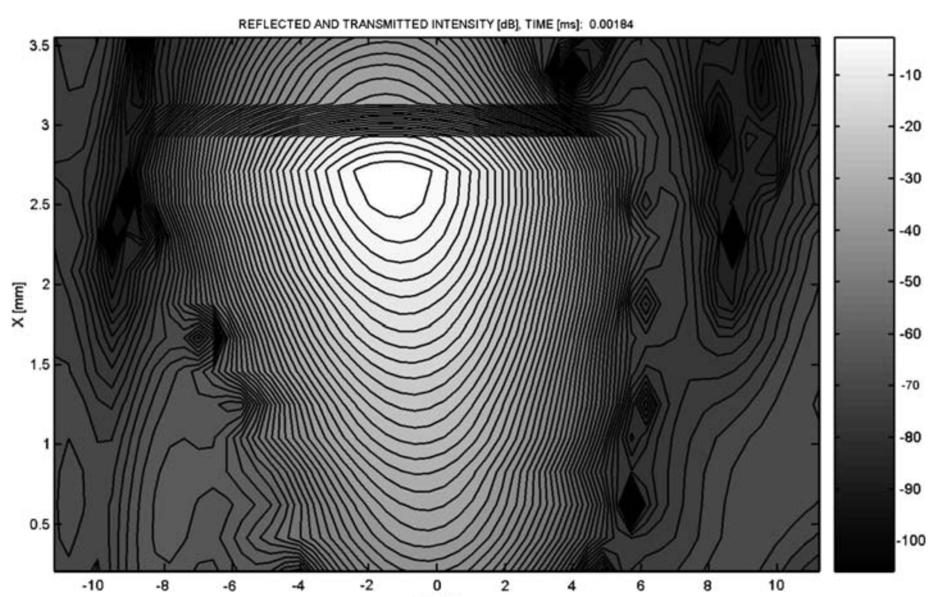

Fig. 2. This is the simulation of a reflected pulse, 0.00184 ms after impact at the Lamb angle of 25.3°. Note that there is a strong reflected pulse, accompanied by a second pulse on the left hand side that is actually attached to it. Therefore, no 'null' zone is created. This corresponds to the experiment of Fig. 1b.

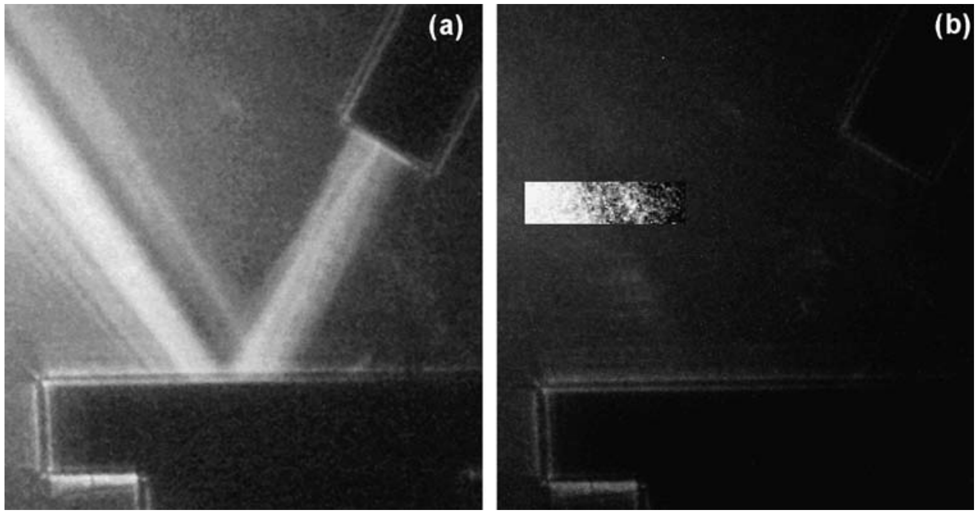

Fig. 3. This figure corresponds to Fig 1, except that here sound is incident on a thick stainless steel plate at the Rayleigh angle (30.1°). In both situations, i.e., harmonic in Fig. 1a and pulsed in Fig. 1b, the 'Schoch effect' is visible.

on a thick stainless steel plate at the Rayleigh angle (30.1°). The sound is generated by a transducer (upper right) that is connected to a function generator. The reflected sound consists of two beams. This effect is again called the Schoch effect. Again, we have been able to simulate this effect perfectly and the result is left out because such simulations are well known.

Now let us take a look at the result for incident pulses. The Schlieren picture of Fig. 3b corresponds to the one of Fig. 3a, except that pulsed sound is used here, generated by the same transducer as in Fig. 3a, though connected to the USIP 20 ultrasonic apparatus. The same pulse rate was set as in the section of Lamb waves. Because of the limited pulse rate, the image of the present beams is, once gain, very fade. Therefore, a rectangular area is artificially contrast enhanced. Note that a fade incident beam is visible and two fade reflected beams, with a null zone in between. The latter is similar to the Schoch effect for harmonic beams – though not perfectly equal to it, as we will outline in what follows.

Fig. 4 shows the numerical simulation of the reflected pulse, 0.00176 ms after impact at the Rayleigh angle. In order to obtain the result, the same procedure was followed as in the previous section. Note that there is a strong reflected pulse, accompanied by a second pulse on the left hand side that is separated by a string of very low amplitudes. This string of low amplitudes results in a zone of low amplitude (a 'null zone') on the experimental Schlieren picture in

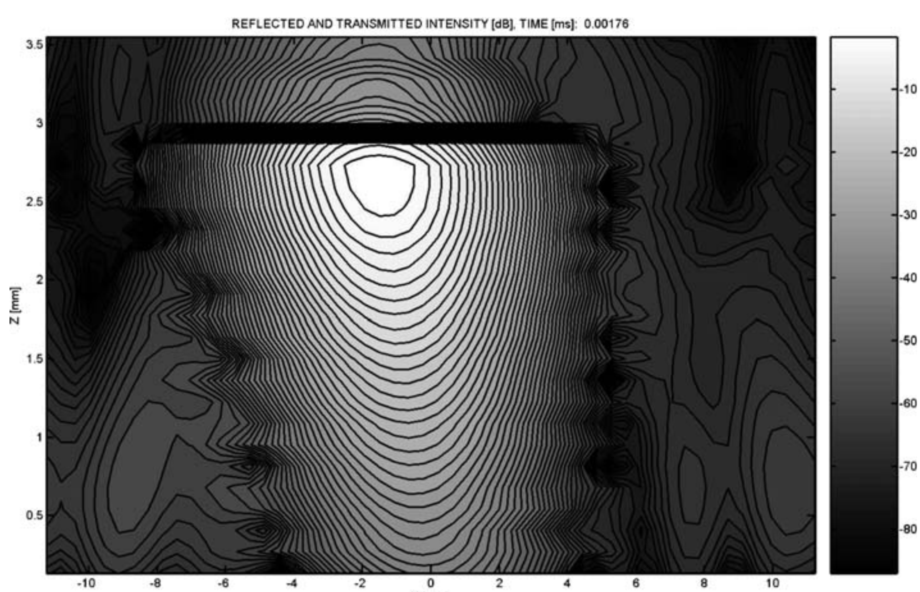

Fig. 4. This is the simulation of a reflected pulse, 0.00176 ms after impact at the Rayleigh angle. Note that there is a strong reflected pulse, accompanied by a second pulse on the left hand side that is separated by a string of very low amplitudes. This string of low amplitudes results in a zone of low amplitude (a 'null zone') on the experimental Schlieren picture in Fig. 3b. A similar outspoken string of low amplitudes is not visible in Fig. 2.

Fig. 3b. A similar outspoken string of low amplitudes is not visible in Fig. 2. In other words, what appears to be a null zone on the Schlieren image of Fig. 3b, is actually formed as a consequence of a string of low amplitude spots that result in a small mean intensity (after passage of the pulse) and is noticed as a strip of low intensity similar to the null strip when the Schoch effect occurs for harmonic sound.

The null zone, which is actually a string of low amplitude zones alternated by zones of a little higher amplitude, is therefore a dynamic zone, because it also vibrates in time if a fixed spot is considered along the propagation path of the reflected sound field. This beating effect occurs at a higher rate than the pulse rate and occurs several times during the passage of each pulse.

4. Conclusions

A study has been presented that shows the difference between Lamb wave generation and Rayleigh wave generation and the effect on the Schoch effect for harmonic and pulsed ultrasonic bounded beams. It has been shown experimentally and numerically that the Schoch effect disappears if a pulse is considered incident at the Lamb angle, whereas an effect, similar to the Schoch effect is visible if a pulse is considered incident at the Rayleigh angle. The difference with the real Schoch effect is the fact that the null zone is not a homogeneous area, but consists of a string of low amplitude areas that appear like a null zone if a large exposure time is applied to make the experimental Schlieren pictures. It has also been explained that the difference between the effect for Lamb waves and the effect for Rayleigh waves, is due to the fact that Lamb waves are generated non-coincidentally, whereas Rayleigh waves are generated coincidentally.

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