The Radiation Mode Theory in Ultrasonics

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***Abstract*—This paper describes the history and the state of the art in radiation mode theory (RMT) in ultrasonics. The RMT originates from electromagnetism in which it has proved to be very efficient in the field of wave guides and discontinuities. In ultrasonics, the RMT made its entrance only a decade ago and has already proved to be very efficient in describing the interaction of sound with discontinuities such as a step on a plate, a liquid wedge, the extremity of a plate and much more. It is likely that the development of the RMT for two-dimensional (2-D) isotropic media has come almost to an end. This paper lists the results obtained so far. Further extensions to more complicated media are to be expected in the coming decade.**

I. Introduction

The general rule in acoustics is to describe sound in the same symmetrical system as the scatterer or as the sound source. For example sound emitted by a cylinder is described in cylindrical coordinates, and sound emitted by a sphere is described in spherical coordinates.

When the interaction of sound needs to be described in a system with only discontinuities in one dimension (e.g., an infinite plate swamped in water), the theory of plane waves is very suitable. That is because plane waves extend to infinity and so does the considered system. However, if the interaction of sound is to be described in a system containing discontinuities in more than one dimension [1] (e.g., a cube swamped in water [2]), then the plane wave theory becomes unsuitable because it does not reflect the symmetry of the system under consideration. In such systems, a description by means of modes becomes very suitable. Furthermore, whenever an incident bounded beam is considered, most scientists decompose this bounded beam into plane waves. However, from a mathematical point of view, this is only correct if normal incidence is taken under consideration. The reason is that, if a decomposition into plane waves is considered, the Fourier method is applied. This method consists of an integration of the beam profile along the z'-axis (see Fig. 1) and thus implicitly imposes that there are no discontinuities along that direction. If the profile is considered far away from the interface, the mentioned problem is avoided by the fact that the profile becomes almost zero at large distances away from the beam center; but, if the profile is considered closer to the interface, it is clear that the Fourier method actually should not be applied. Moreover, whenever the Fourier method is applied, it is always assumed that the reflected sound depends on the incident sound and not vice versa. In other words, the incident sound is not disturbed by the reflected sound. This again follows from the incorrectly assumed fact that the incident sound pattern would depend solely on its amplitude distribution along an infinite line (z' in Fig. 1) and cannot depend on the fact that there is an interface present along the integration path in the Fourier analysis. In addition to the Fourier method, there are also other techniques to describe bounded beams. One of these techniques is developed by Bertoni and Tamir [3] and is later extended by Marston [4]. But, even though it is a sophisticated mathematical method, it does only work in the vicinity of the Rayleigh angle and for infinite plane surfaces [3] and curved surfaces [4]. Another technique is developed by Bertoni [5] and is only an approximation, not an exact method. In addition, there is also the inhomogeneous wave method [6], which is accompanied by severe numerical problems. The radiation mode theory (RMT), first created and applied in electromagnetism [7], [8] and later developed in acoustics [9]–[19], provides a physical and mathematical solution to such problems. In the RMT,

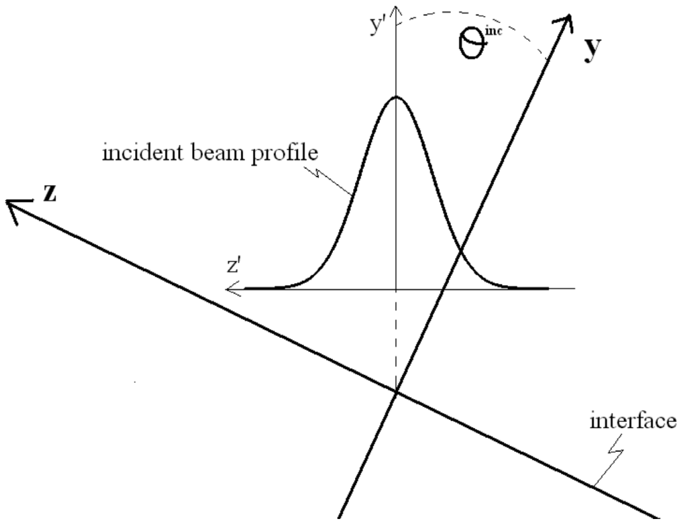

Fig. 1. A bounded beam incident on the interface at an angle θ^{inc}.

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no integration path is needed in the Cartesian axes system (x, y, z) but only in the phase space (k_y). Furthermore, discontinuity conditions in two dimensions are dealt with by dividing the system into substructures that only contain discontinuities in one direction. A worthy counterpart of the RMT is the use of Fresnel patches, as can be found in [2] and [20].

In what follows, we will describe the basics of the RMT, followed by some of the main results that have been obtained in the first decade of its existence.

II. The Basics of the Radiation Mode Theory in Words

There are three ways to describe the basics of the RMT. The first is a description in words and may give the wrong impression that it is, in fact, a simple theory. The other two methods consist of giving the mathematics behind the theory with or without poetic explanations. The latter two methods can be found in the few papers [9]–[19] that already exist on the RMT and are automatically lengthy and cumbersome. For that reason we will deal with the first method, explaning the basics in words and running the risk of giving the misplaced impression that it is a simple theory.

A mode is the combination of all possible reflected and transmitted waves for a given incident plane wave on a system containing only discontinuities in one dimension, e.g., a plate swamped in water. Therefore, for each possible incident plane wave, coming from each possible direction above or below the system, there is a mode. For example, in a system consisting of a liquid half space and a solid half space, the radiation mode having a component of sound incident from the liquid, consists of that incident plane sound wave together with one reflected plane wave and two transmitted plane waves. Such modes that, in fact, consist of radiated energy are called radiation modes. However, in the RMT there also are also nonradiating modes available, called eigenmodes. These modes contain all possible transmitted and reflected waves given the fact that there is no radiation of sound. For example, on a solid/fluid interface, such eigenmodes are the Scholte-Stoneley modes [21]. Lambmodes are not eigenmodes in that sense because, in a system in which there are also radiation modes present (i.e., there is a coupling medium), Lamb modes become leaky and, hence, radiate sound. Furthermore, a Lamb wave can be written as a linear combination of radiation modes. The relative amplitude attributed to each component of a given mode is relatively simply calculated from continuity conditions along the one-dimensional (1-D) discontinuity system. For example, if a radiation mode is considered in a solid/liquid system with incident sound coming from the liquid side, the relative amplitudes of each component of the mode are calculated by considering the condition of normal stress and normal displacement and by building a continuity matrix from which each amplitude attributed to each component is calculated.

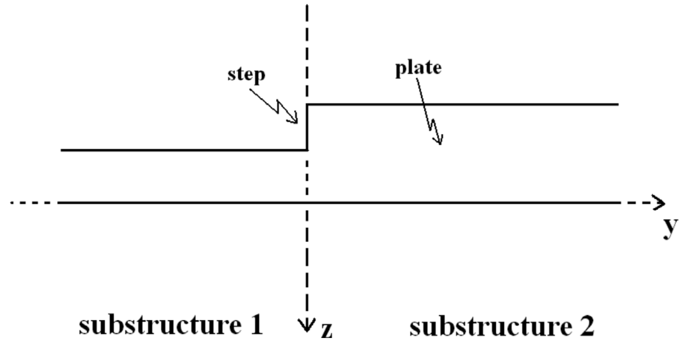

Fig. 2. Schematic of a step on a plate. This system having discontinuities in two dimensions is divided into two substructures, each having only discontinuities in one dimension.

Because one should actually deal with the system in which discontinuities are present in two dimensions instead of one, as in Fig. 2, one generates all possible modes for each subsystem that has only discontinuities in one dimension. For example, if a step is present on a solid plate swamped in water, then this system containing discontinuities in two directions is divided into two systems that have only discontinuities in one direction, i.e., two infinite plates are considered.

The complete sound field in each substructure is fully described by means of a linear combination of all possible radiation modes and all possible eigenmodes. This is done as follows: The particle displacement u(r) is written as

$$\mathbf{u}(\mathbf{r}) = \sum_j C_j \mathbf{u}^j(\mathbf{r}) + \int_0^{+\infty} \sum_m C_m(k_y)\mathbf{u}^m(k_y, \mathbf{r})dk_y, \tag{1}$$

whereas the stress tensor components are written as

$$T_{kl}(\mathbf{r}) = \sum_j C_j T_{kl}^j(\mathbf{r}) + \int_0^{+\infty} \sum_m C_m(k_y)T_{kl}^m(k_y, \mathbf{r})dk_y. \tag{2}$$

The index j is attributed to eigenmodes, whereas the index m is attributed to radiation modes. The position vector is denoted by $\mathbf{r}$. The linear combination in (1) and (2) is called mode expansion. The set $\{C_j, C_m\}$ is the set of expansion coefficients. They are the actual unknown parameters for describing the complete acoustic system. Note that the integral in (1) and (2) spans from nill to infinity. This means that evanescent waves also are included. This requirement for completeness also can be found in [22] and [23]. If necessary, the expansion coefficients also can be made position dependent, whence rough surfaces can be considered as well. Furthermore, the expansion coefficients in each structure are related to each other by expressing continuity conditions on the interface that separates the two substructures, e.g., the z-axis in Fig. 2. This latter continuity condition, therefore, relates the sound fields in the substructures to one another and therefore reduces the number of independent expansion coefficients. The remaining independent expansion coefficients are related to boundary conditions. Such boundary conditions are, for example, a Gaussian bounded beam incident on a given spot under a given angle. For a more detailed explanation of the basics of RMT, we kindly refer to [9]–[19].

In what follows, the term relative amplitude always means the amplitude of the particle displacement parallel to the solid-liquid interface ($|\mathbf{u}_z|$), divided by the incident amplitude. The incident amplitude is the amplitude of the maximum total particle displacement ($|\mathbf{u}_x| + |\mathbf{u}_z|$) of the incident wave. For example, for a Gaussian beam, the incident amplitude is the total particle displacement at the center of the incident beam. For an incident surface wave, it is the amplitude along the surface.

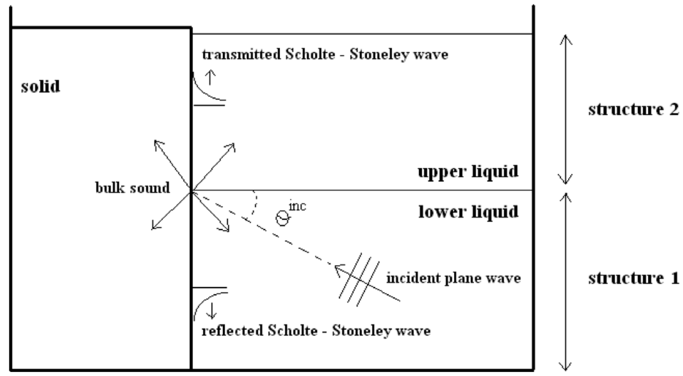

Fig. 3. Geometrical configuration of a liquid wedge.

III. Applications

A. Half Spaces

Even though the RMT was well established in electromagnetism [7], [8], it took until 1990 before the same concept was first used in acoustics. The pioneering work can be found in a paper by Leroy and Shkerdin [9] for a so-called solid wedge, which is simply two solids attached to one another, both being bounded by vacuum on one side. This pioneering work describes the interaction of a bulk wave and of a Rayleigh wave with the transition between both solids. The aim of that paper actually was to show that a translation of the RMT from electromagnetism to acoustics was possible and worked pretty well. Later on, the search for a challenge for the RMT began. The first challenge came from a dispute between two scientific groups. Like so often in science, insight and progress follows disputes between people who are courageous enough to defend their opinion. Around 1993, there were two quite different views on the subject of generating Scholte-Stoneley waves by means of a liquid wedge technique. Scholte-Stoneley waves are known to travel along a liquid-solid interface without radiating energy into one of the two media. This is due to the fact that such surface waves have a velocity that is less than any of the bulk sound velocities in the surrounding media. However, this low velocity is also the reason why such waves cannot be generated on a liquid-solid interface by means of an incident sound beam. One way of surmounting this handicap is the application of a liquid wedge. The principle is depicted in Fig. 3 and is based on complicated scattering effects in the region in which the three involved media are in contact with each other. The first opinion on the mechanism of Scholte-Stoneley wave generation by means of a liquid wedge is described in references 1 and 2 in [10], and states that, according to a formula similar to the classical Snell's law, Scholte-Stoneley waves mainly would be generated at one particular angle that resulted from that formula. Experiments on an alcohol-water wedge (incidence from the alcohol side) confirmed indeed that Scholte-Stoneley waves were generated at that angle. It was not believed that Scholte-Stoneley waves also could be generated by means of a water-alcohol wedge because this would contradict the posed formula. However, there was also the opinion of J. Chamuel (private communication with R. Briers and O. Leroy) that, based on extended experiments, Scholte-Stoneley waves actually would be generated at every angle of incidence (from the alcohol side) and not just the one corresponding to the experiments in cited references. This dispute challenged the further development of the RMT in order to clarify the problem. Briers *et al.* [10] found numerical results that were quite astonishing. They found that, indeed, all angles of incidence produce Scholte-Stoneley waves, but the largest amplitude corresponded to an angle of approximately 87°. Furthermore, they found that Scholte-Stoneley waves also could be excited by incidence from the water side (instead of the alcohol side), which was surprising and proved that the formula which looked like Snell's law is not applicable in all situations. This study of the liquid wedge was later followed by a more thorough study [11] also indicating that incidence at the Rayleigh angle produced larger stimulation of Scholte-Stoneley waves if compared to other angles, though not as large as the one in the vicinity of 87° as described in [10]. Furthermore, in practical situations one often is faced with incident Gaussian beams instead of incident plane waves or plane waves diffracted by a narrow slit (as was the case in [10]). Therefore, in [11] the RMT decomposition of a Gaussian beam is presented. As far as we know, there is no such analogy described yet in electromagnetism.

B. Plates

Until 1996, only half spaces had been described in RMT. An extension to a plate was the next challenge and was performed in [12]. This model shows how Scholte-Stoneley waves are scattered at the extremity of a fluid-loaded plate. Because of the complexity, a zero order approximation was performed, followed by a first order approximation. The difference between the two approximations is the leaky Rayleigh wave traveling from top to bottom along the extremity edge of the plate, i.e., included in the first order approximation and excluded in the zero order approximation. The results for the transmitted bulk wave in a zero order approximation for a 5 MHz Scholte-Stoneley wave at the end of a water-loaded aluminum plate of 1 cm thickness

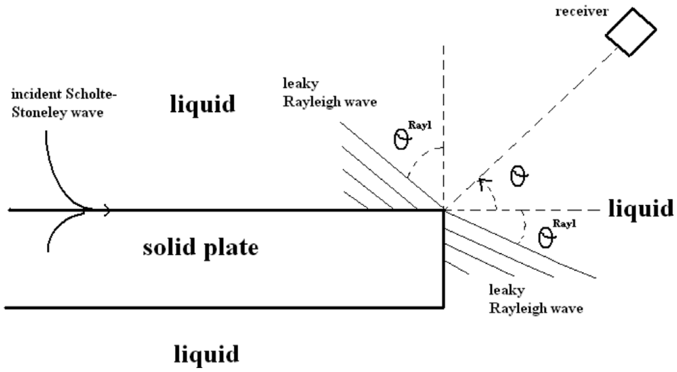

Fig. 4. Experimental configuration for the scattering and mode conversion of Scholte-Stoneley waves at the edge of a fluid loaded thick plate.

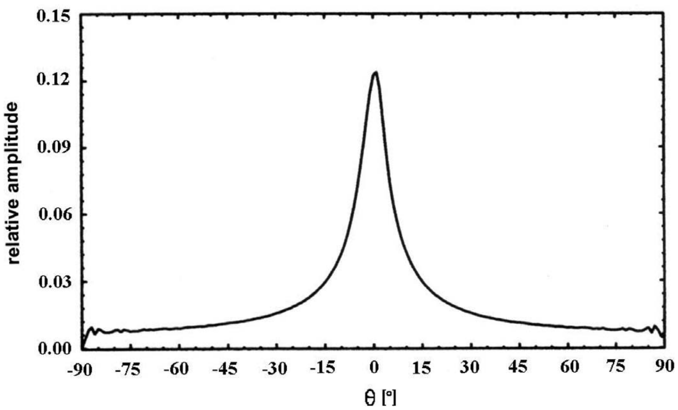

Fig. 5. Transmitted amplitude as a function of the transmission direction θ for a 5 MHz Scholte-Stoneley wave on a water loaded 1-cm thick aluminum plate (zero order).

(see Fig. 4) are shown in Fig. 5. This shows that the largest amplitude is transmitted in line with the plate. There was good agreement with experiments of Tinel and Duclos [24], except in the vicinity of the Rayleigh angle, at which they measured an amplitude dip. The latter shortcoming was swept away by using a first order approximation. This generated results in perfect agreement with experiments of Tinel, see Fig. 6. It proves that the dip in the graphs of Tinel were due to a leaky Rayleigh wave traveling from top to bottom along the extremity edge of the plate. In [12], it also is shown that the incident Scholte-Stoneley wave generates a leaky Rayleigh wave on the upper interface of the plate and also on the lower interface of the plate. This is visible in Fig. 4(a) and (c) of ref [12] as maxima in the radiated fields at the angles corresponding to the leakage of energy of those leaky Rayleigh waves. An important consequence is, of course, that, due to the reversibility of mode conversion phenomena, Scholte-Stoneley waves also can be generated by means of sound incident at the Rayleigh angle on the edge of the plate. Hence, Scholte-Stoneley waves can be generated by means of sound incident on the edge of a plate.

Because the liquid wedge technique had proved to be excellent for generating Scholte-Stoneley waves, as described

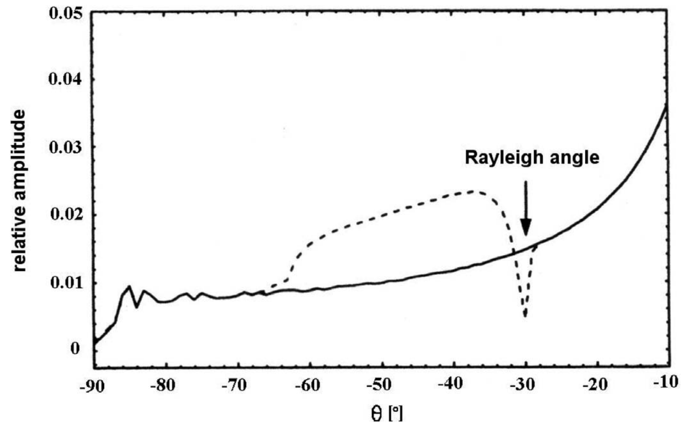

Fig. 6. Same as Fig. 5, though shortened angle interval. Dashed line is the first order approximation and solid line is zero order approximation.

previously, the question remained as to how the generation of Lamb waves could be described. It was widely known that Lamb waves also could be stimulated by means of a liquid wedge technique. The technique existed in generating leaky Lamb waves on a plate in a liquid whence those leaky Lamb waves could propagate in the plate to the liquid-free half space (vacuum or air) and be turned into pure (nonleaky) Lamb waves. No one had ever described this well established phenomenon numerically. Besides generating Lamb waves, the technique also can be used to stimulate Rayleigh waves. Both phenomena have been extensively described and simulated by Briers *et al.* [14].

For an additional example of a plate in water and in air, see [25].

C. Layered Systems

Once the problem of a plate had been tackled extensively, a study of a bilayered system was the next road ahead. The impetus for this study came from the gained knowledge that Scholte-Stoneley waves could be generated by means of scattering effects in a liquid wedge. The question to be answered was if one would be able to generate Scholte-Stoneley waves at the down step of a thin layer on a substrate, see Fig. 7. If the answer was positive [13], [15], a new technique would be born that would be much more practical than the use of a liquid wedge. It was found indeed that Scholte-Stoneley waves could be generated at an angle of incidence of approximately 87° and at the Rayleigh angle. The numerical results are shown in Fig. 8. It also was shown that the amplitude at the Rayleigh angle is actually independent of the coating material and is dependent only on the substrate characteristics. Recently, the RMT also has been further extended to multilayered systems [18].

D. Inclusions

Mainly caused by the importance of nondestructive testing (NDT) and more precisely the technique of finding defects in materials and a lack of models that were able to

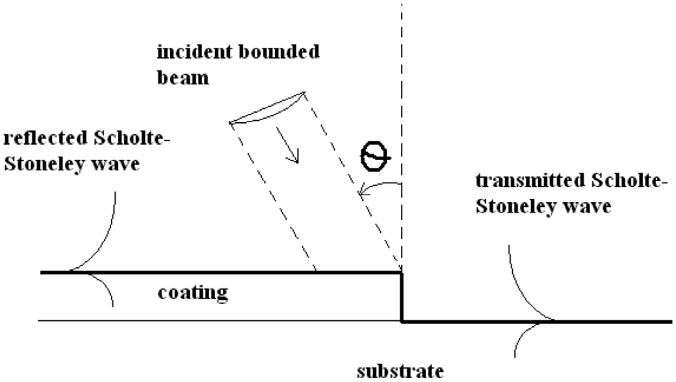

Fig. 7. Geometrical configuration of Scholte-Stoneley wave generation at downstep.

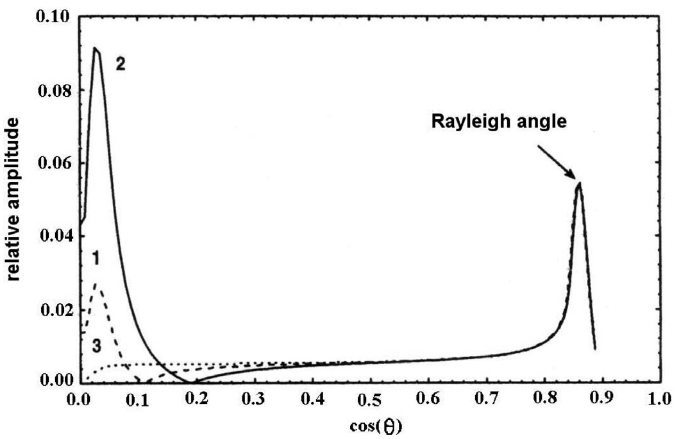

Fig. 8. Relative amplitude of the transmitted Scholte-Stoneley wave generated by a 4 MHz Gaussian beam (beam width 5 mm) at 15 cm radial distance from the downstep, incident from water as a function of the angle of incidence. The substrate is steel and the thin layer consists of (1) copper, (2) Pyrex glass, (3) steel.

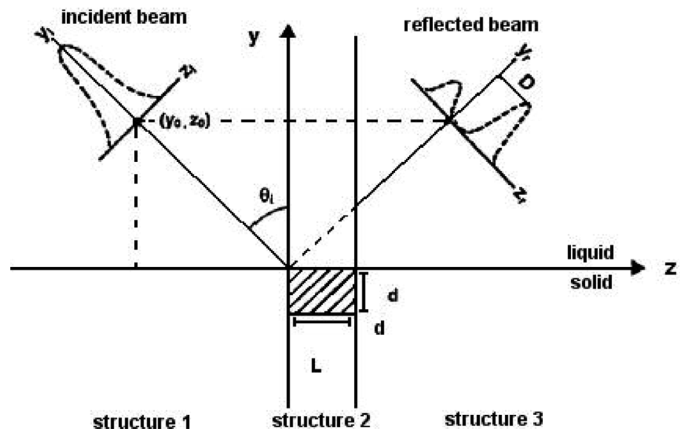

Fig. 9. The reflection of a Gaussian beam onto an inclusion near a liquid/solid interface. Geometrical configuration and definition of the parameters.

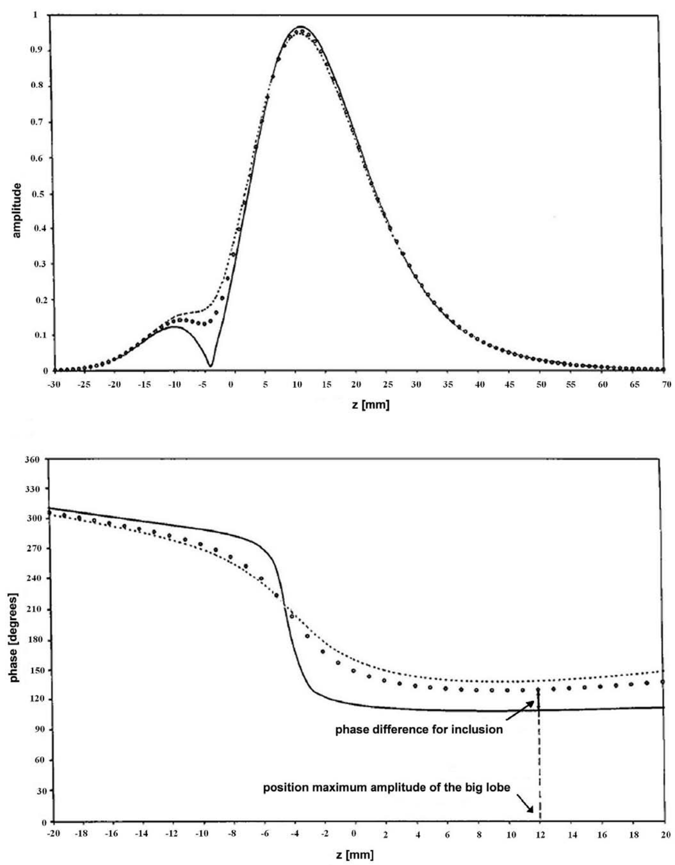

Fig. 10. Amplitude distribution (top), bottom: phase distribution (bottom) of a reflected 4 MHz Gaussian beam, of 12 mm half width, onto a stainless steel half space (solid line), onto a 5 μm layer on a stainless steel substrate (dashed line), onto an inclusion of 5 μm thickness (length 15 mm) in stainless steel (circles line). The Gaussian beam is incident at the Rayleigh angle. The arrow defines the phase difference.

describe the interaction of sound with inclusions, a study started that dealt with the interaction of sound with inclusions at the surface [15], [16]. It is intuitively reasonable that the Schoch effect, which is caused by leaky Rayleigh waves, must be sensitive to inclusions on or near the surface, because the accompanied Rayleigh waves must feel the presence of such inclusions as their amplitude is located mostly near the surface. Definitely the RMT showed that a measurement of phase differences between the specular and the nonspecular reflected lobe when the Schoch effect happens is an indication of the dimensions and position of inclusions, in a setup schematically given in Fig. 9. In Fig. 10, the characteristics of a reflected Gaussian beam are shown for incidence at the Rayleigh angle on a stainless steel half space, on a half space covered by a thin coating, and on a half space with a thin inclusion at the surface. The configuration is such that the center of the incident beam coincides with the beginning of the inclusion. The thickness of the inclusion and the coating is the same. It is seen that the reflected beam profile shows some important aspects related to the characteristics of such a thin coating/inclusion. It also is seen that the results for the coating fall in between the results for the inclusion.

Later, a study was performed on inclusions near the surface [19], similar results also were found for that case.

E. Viscoelastic Media

In all previous studies, damping was neglected in all considered materials. Therefore Vandeputte *et al.* [17] extended the RMT to the case of viscoelastic media. It was shown that absorption weakens the nonspecular lobe and amplifies the specular lobe in the case of the Schoch effect at Lamb angles of incidence. They also showed that beam focusing has effects on the presence or absence of a null zone when the Schoch effect occurs. This is because the Lamb wave profiles are disturbed by the focusing effect.

IV. Conclusions

The development of the RMT has been completed for 2-D isotropic systems. The theory has up until now showed its value in the understanding and simulation of the generation of Scholte-Stoneley waves, Rayleigh waves, and Lamb waves by means of a liquid wedge. It also showed how Scholte-Stoneley waves interact with the extremity of a plate. The RMT also paved the way for the use of a downstep an a substrate to generate Scholte-Stoneley waves. Lately extensions have occurred for multilayered media and for visco-elastic media. Further development is expected to happen for 3-D systems and for anisotropic media as well. The RMT is far from easy to apply, but it works and it is very powerful to deal with complicated problems. Among other theories, the RMT has become an important player.

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