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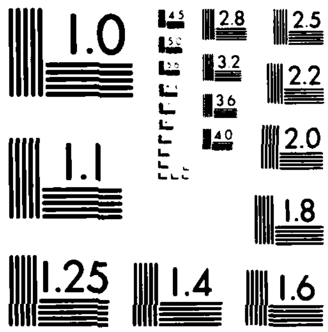

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FINAL TECHNICAL REPORT

(Technical Report No. 8)

Linear and nonlinear ultrasonic interaction on liquid-solid boundaries

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The experimental and theoretical work performed under this Contract was concerned with linear and nonlinear ultrasonic interactions on liquid-solid boundaries. The objectives of the project centered around the fact that propagation characteristics of water-borne ultrasonic signals are frequently explained and various calculations are done by applying a plane wave theory. This approach can, to a good approximation, explain some observed results of sound propagation, reflection, and transmission phenomena but fails to describe these effects whenever the sonic signal is confined to a bounded beam or when a solid reflector has a thickness which is comparable to the sonic wavelength or when the medium of propagation is nonlinear or when the reflecting solid is itself nonlinear, i.e., if its response to an impinging sonic signal depends on the beam width and frequency.

The objective of the present project thus was the theoretical and experimental investigation of the propagation, reflection, and transmission of a bounded sonic beam in a nonlinear layered medium. In order to accomplish this work a number of research topics were considered which can be roughly classified in the following manner:

Limitations governing propagation of leaky waves on interfaces
Influence of absorption on reflection and reradiation of interface waves
Nonspecular effects for layerd media
Generation of second harmonics in Lamb waves
Green's function representation of nonlinear Lamb waves
Harmonic content in a bounded ultrasonic beam
Nonspecular reflection and transmission measurements via acousto-optics
Influence of material inhomogeneities in nonspecular effects.

Many of thes topics are interdependent and thus it was one of the goals of the effort to attempt a development of a theory which can explain most of the relations between these phenomena.

The results obtained were published as individual papers in the open literature or by means of Technical Report submitted to the Sponsoring Code. Since detailed descriptions of the background, the methodology used in the work, and the results obtained are given in detail in these publications this Final Technical Report does not repeat this information, instead, it consists of reproductions of the titles and abstracts of the various published papers with some text material added to provide continuity.

It has been known for many years that a plane wave theory could not explain why an ultrasonic beam was reflected from a solid so that a lateral beam displacement occurred when the incidence from the liquid was at the Rayleigh angle. It was suspected that leaky Rayleigh waves were set up in the process. Therefore, the first topic of investigation was to compare the predictions of plane wave reflection theory to actually observed beam reflections from asymmetrically loaded solid plates.

Plane Wave Reflection from a Plate Immersed in and Floating on a Liquid ①

The reflection coefficient for a solid plate bounded by dissimilar fluids is derived. The expression can be made to be consistent with Brekhovskikh's n-layered system reflection coefficient and can be reduced to the reflection coefficient for a two-layered system derived by Schoch and to the dispersion equation for a liquid-solid-vacuum system given by Ewing, Jardetsky and Press provided one takes into account the appropriate forms of wave propagation and coordinates of the systems.

In the course of this work it was found that some plate modes cannot be excited easily by incidence at the appropriate Lamb angle. Thus a more fundamental theoretical problem had to be solved first, that is, the investigation of restrictions on the excitation of Rayleigh waves.

Restrictions on the Existence of Leaky Rayleigh Waves ②

NEAL G BROWER, DOUGLAS E. HIMBERGER, AND WALTER G. MAYER

Abstract—The Rayleigh wave, an inhomogeneous surface wave, exists for all isotropic elastic solid infinite half-spaces. When the free surface of the solid is bounded by a liquid a leaky Rayleigh wave does not necessarily exist for all liquid/isotropic solid systems. The well-known condition for the existence of a leaky Rayleigh wave, the sound velocity in the liquid must be less than the shear wave velocity in the solid, is shown to be a necessary but not a sufficient condition. Additional conditions on density ratios and velocity ratios are given. Examples are listed showing liquid/solid combinations which satisfy the liquid-shear wave velocity condition but not the additional restrictions and thus do not support a leaky Rayleigh wave.

It was found that leaky Rayleigh waves cannot always be excited even if the velocity difference between liquid and solid suggests that excitation can be accomplished. This study and its extension to surface waves in general formed the basis for subsequent work.

(3)

ZZ11. Investigation of the conditions for the existence of a leaky Rayleigh wave. W. G. Mayer, N. G. Brower, and D. E. Himberger (Department of Physics, Georgetown University, Washington, DC 20057)

The Rayleigh wave, an inhomogeneous surface wave, exists for all isotropic elastic solids. When the free surface of the solid is bounded by a liquid, a leaky Rayleigh wave, or inhomogeneous damped interface wave, may exist. In the limit that the density of the liquid goes to zero, the leaky Rayleigh wave tends to the free Rayleigh wave. However, the leaky Rayleigh wave does not exist for all liquid/isotropic solid systems. A well-known condition for the existence of the leaky Rayleigh wave is that the velocity of sound in the liquid must be less than that of the shear in the elastic solid. Upon investigation of the secular equation for the leaky Rayleigh wave velocity, other necessary conditions for existence become apparent. The conditions are influenced by the density ratio and the ratios of the various velocities in the liquid/solid system. [Work supported by ONR.]

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RESTRICTIONS ON EXCITATION OF SURFACE WAVES AT LIQUID-SOLID INTERFACES (4)

It is shown why the usual condition, $V_{liquid} < V_{shear}$, for the generation of Rayleigh waves on a liquid-solid interface is necessary but not sufficient. Necessary conditions are given on density and velocity ratios of the media forming the interface.

It had been known for some time that nonspecular reflection effects occurred when the incident bounded ultrasonic beam impinged at the Rayleigh angle or at a Lamb angle. It was not clear whether a similar phenomenon might be observable at other critical angles of incidence. While the investigation of nonspecular reflection for Rayleigh and Lamb mode incident angles was continuing it was found that nonspecular effects do indeed exist at other critical angles and specific conditions for the observability of nonspecular reflection at and near the longitudinal critical angle were found.

(5)

LL3. Ultrasonic nonspecular reflectivity near longitudinal critical angle. T. D. K. Ngoc and W. G. Mayer (Physics Department, Georgetown University, Washington, DC 20057)

The intensity profile of an ultrasonic beam reflected from a liquid-solid interface is determined by a numerical integration method. This numerical approach takes into account the influence of absorption in the media and is valid for all angles of incidence. The reflected profile is calculated for a specific case: incidence near the longitudinal critical angle for a water–Plexiglas interface. The calculated results demonstrate the existence of nonspecular reflectivity near this particular critical angle and provide a quantitative description of its basic features. Theoretical results and experimental measurements are compared. [Work supported by the Office of Naval Research, U.S. Navy.]

S8. **A general description of ultrasonic nonspecular reflection and transmission effects for layered media.** T. D. K. Ngoc and W. G. Mayer (Physics Department, Georgetown University, Washington, DC 20057) ⑥

A numerical integration method is used to determine the profile of an ultrasonic bounded beam reflected from or transmitted through a general layered structure. Calculations are presented for liquid/solid and liquid/solid/liquid systems. Nonspecular reflection phenomena at critical angles for some liquid/solid interfaces are discussed. For a liquid/solid/liquid system, water/brass/water in particular, nonspecular characteristics are investigated for both reflected and transmitted beams. Emphasis is placed on changes in the beam profiles as a function of angle of incidence and beamwidth. [Work supported by Office of Naval Research, U.S. Navy.]

Ultrasonic nonspecular reflectivity near longitudinal critical angle ⑦

A numerical integration method is developed to determine the intensity profile of an ultrasonic beam reflected from a liquid-solid interface near the longitudinal critical angle. The profiles are calculated for different combinations of frequencies and beam widths with the angle of incidence being varied about the longitudinal critical angle for a water-Plexiglas interface. These calculations demonstrate the existence of nonspecular reflectivity near this particular critical angle and provide a quantitative description of its basic features. Theoretical results and experimental measurements are compared.

Based on this, two theoretical approaches were developed to describe reflection and transmission effects. One is based on an analytical method and the other on a numerical integration technique. These aspects of the work resulted in a general description of ultrasonic nonspecular effetcs for layered media.

Nonspecular Transmission Effects for Ultrasonic Beams Incident on a Solid Plate in a Liquid ⑧

The nonspecular phenomena are investigated theoretically for an ultrasonic beam transmitted through a solid plate immersed in a liquid. The analytical method used by Bertoni and Tamir [3] to describe the nonspecular profile of a beam reflected from a liquid-solid interface is extended to the problem under consideration, taking into account all existing poles. To solve the integral representing the transmitted beam, the amplitude plane wave transmission coefficient is replaced by a simpler approximate form. The transmitted beam profile is then calculated from both single-pole and multiple-pole formulations.

Numerical integration method for reflected beam profiles near Rayleigh angle (9)

A numerical integration method is devoloped to calculate the intensity profile of an ultrasonic beam reflected from a liquid–solid interface. This numerical treatment is used to calculate nonspecular reflectivity at a range of angles of incidence near and at the Rayleigh angle. Calculations for a water–stainless steel interface are compared to a known approximate analysis for various beamwidths and frequencies. The theoretical predictions of the reflected beam profile near the Rayleigh angle of incidence are compared to experimental results.

A General Description of Ultrasonic Nonspecular Reflection and Transmission Effects for Layered Media (10)

Abstract – **A numerical integration method is used to calculate the intensity distribution in reflected and transmitted beams for liquid-solid-liquid layered media. It is shown that the formulation describes all nonspecular reflection and transmission phenomena for all angles of** ***incidence, including*** **critical angles. It is found that the existence of nonspecular phenomena not only depend on the angle of incidence and the product frequency times solid thickness but also on the product frequency times beamwidth. Various examples are given for reflection and transmission for incident angles corresponding to critical angles, plate-mode angles, and between-mode angles.**

As a result of these theoretical considerations the reflected and transmitted sound fields can now be calculated for any width of the sonic beam and any thickness of reflecting solid. The previously used versions of the reflection coefficient, based on a plane wave theory, for plates and for half spaces differed in form and, in the limit, did not lead from one to the other. A mathematical model was established which made this transition possible. A worked out example, letting the plate thickness increase to infinity, showed the gradual change of the reflection coefficient from a plate-like behavior to an infinite half space, allowing a judgement whether a thick plate immersed in a liquid can or cannot be treated as a plate or as an infinite medium.

CCC11. **A unified picture of plane wave reflectivity from a liquid-solid interface and a solid plate in a liquid.** T. D. K. Ngoc, W. G. Mayer (Physics Department, Georgetown University, Washington DC 20057), J. M. Claeys, and O. J. Leroy (K. U. Leuven Campus Kortrijk, Kortrijk, Belgium) (11)

The ultrasonic plane wave reflection coefficient for a solid plate immersed in a liquid must be reducible to that for a liquid-solid interface as the solid plate thickness becomes very large. This can be achieved when absorption is taken into account. The calculated results describe the reflectivity characteristics of a thick solid plate and provide practical criteria to determine the lower limit of the solid sample thickness that can be considered as a half-space. [This work was supported by the Office of Naval Research, U.S. Navy, and the Scientific Affairs Division, NATO.]

REDUCIBILITY OF PLANE WAVE REFLECTIVITY FROM A SOLID PLATE IN A LIQUID TO A LIQUID-SOLID INTERFACE. (12)

The ultrasonic plane wave reflection coefficient for a flat solid plate immersed in a liquid should be reducible to that for a liquid-solid interface as the plate thickness becomes very large. Existing formulae, which are based on the assumption that propagation vectors are real quantities, do not provide this reducibility. It is shown that reducibility can be achieved only when the propagation vectors are complex quantities, i.e., when absorption is taken into account. The approach given here can thus be used to determine reflectivity for material thicknesses which are neither truly infinite nor very thin. The results provide practical criteria to determine the lower limit of sample thickness that can be considered a half-space.

A10. Ultrasonic reflection measurements of floating ice. Neal G. Brower (Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20702), Kim W. Ng, and Walter G. Mayer (Department of Physics, Georgetown University, Washington, DC 20057) (13)

An experimental investigation of reflection of ultrasonic, bounded beams from floating ice has been conducted. Ultrasonic frequencies and ice thicknesses corresponding to frequency thicknesses of between 2 and 5 mm·MHz are considered. Nonspecular reflection profiles are obtained using schlieren techniques. These nonspecular profiles are compared to theoretical profiles calculated for water/ice plate/air systems. [Work supported by ONR.]

Reflection and transmission are greatly influenced by beam profile and plate mode structure where any local material variation in the plate manifets itself as a distinct change in the beam reflection profile. The important features of these phenomena were described and shown bothe experimentally and theoretically.

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ACOUSTO-OPTIC MEASUREMENT OF ULTRASONIC BEAMS REFLECTED FROM FLAT BOUNDARIES

Bounded ultrasonic beams reflected from liquid-solid flat interfaces frequently show phase incoherence. These phase shifts are clearly manifest in Schlieren images of the reflection. Measurements of the overall reflection coefficient, which can be calculated for different geometries, are thus made difficult.

Light diffraction techniques have been used in the past to determine the amplitude of sound fields; it is shown under what conditions of beam reflection it is still possible to use an acousto-optic technique to determine the reflection coefficient as a function of angle of incidence.

Work supported by the Office of Naval Research.

OPTICAL METHOD FOR MEASUREMENT OF ULTRASONIC REFLECTION FROM SOLID PLATES. (15)

An acousto-optic interaction method was used to measure the modulus of the reflection for ultrasonic waves impinging at various angles on solid plates immersed in water. Theory and experiment are shown to agree qualitatively when the product frequency times plate thickness is small

Influence of Plate Mode Structure and Gaussian Beam Profile Characteristics on Ultrasonic Reflection and Transmission (16)

TRAN D. K. NGOC AND WALTER G. MAYER

Abstract – It is shown why ultrasonic beam reflection from, and transmission through, a solid plate immersed in a liquid may be nonspecular, depending on beamwidth and the structure of the normal modes of vibration of the plate. The analysis is carried out for Gaussian incident beams.

T5. Acousto-optic method to locate surface inhomogeneities on solids. Walter G. Mayer and Tran D. K. Ngoc (Physics Department, Georgetown University, Washington, DC 20057) (17)

Changes in the profile of a reflected ultrasonic beam incident at the Rayleigh angle are observed and are used to locate small inhomogeneities in the surface of a solid. These beam profile changes are caused by minute changes in the Rayleigh wave velocity. Whether the inhomogeneity is related to variation in the longitudinal wave velocity is determined by observation of longitudinal critical angle reflectivity. [Supported by the Office of Naval Research, U.S. Navy and in part through an award (WGM) by the Alexander von Humboldt Foundation, Bonn.]

Nonspecular Effects for a Finite Incident Beam Modeled by an Even-Ordered Polynomial (18)

TRAN D. K. NGOC AND WALTER G. MAYER

Abstract—The reflection of non-Gaussian ultrasonic beams, expressed in terms of *n*th-ordered polynomials, is discussed and it is shown that at critical longitudinal and Rayleigh angles of incidence deviations from the Gaussian profile case occur, varying with the polynomial representation chosen. Examples are given for water-Plexiglas and water-stainless steel flat interfaces.

Another aspect of the work was concerned with nonlinear propagation effects, specifically the nonlinear behavior of Lamb waves on solid plates. Optical means were used to observe harmonic generation; these methods also allow one to investigate nonlinear interactions of two ultrasonic Lamb waves which may generate a third Lamb wave. These investigations resulted in specific and general formulations describing these processes.

ACOUSTO-OPTIC INTERACTION OF SECOND HARMONICS IN LAMB WAVES (19)

Résumé. - La possibilité de génération d'harmoniques d'ondes de Lambse propageant dans une plaque isotrope est examiné. Les conditions de la génération d'harmoniques sont discutées. Un système de détection utilisant l'intéraction acousto-optique permet de mettre en évidence l'existence de deuxièmes harmoniques en mesurant les disymetries de la figure de diffraction. Les résultats expérimentaux sont présentés.

Abstract. - The possibility of harmonic generation in Lamb waves propagating on isotropic plates is investigated. The conditions for harmonic generation are discussed. A detection scheme using the acousto-optic interaction is designed by which asymmetries in the diffraction pattern are measured to determine the existence of second harmonics. The results of the experiments are presented.

JJ11. An analytical solution to the problem of noncollinear three-phonon interaction in an isotropic solid plate. Tai-San Chao and Tran D K Ngoc (Physics Department, Georgetown University, Washington, DC 20057) (20)

Noncollinear three-phonon interaction of acoustic bulk waves has been treated analytically by solving the nonlinear equations of motion through the combination of the perturbative and the Green's function techniques. In particular, the Green's function was constructed by the imaging method. For the more complicated structure of a solid plate, noncollinear three phonon interactions take place in the form of two Lamb waves interacting to produce a third Lamb wave. Experimental evidence has been obtained in the latter case for a nonpiezoelectric isotropic solid plate [N. G. Brower and W. G. Mayer, J. Appl. Phys. 49, 2666–2668 (1978)]. In the present paper, a theoretical investigation of the noncollinear three-phonon interaction of Lamb waves in a nonpiezoelectric isotropic solid plate is presented. The same approach as that used for bulk waves is employed except that under the new boundary conditions the Green's function is to be constructed by the eigenfunction expansion technique. The theoretical solution is compared to the experimental findings of Brower and Mayer.

AN ANALYTICAL SOLUTION TO THE PROBLEM OF THREE-PHONON INTERACTION AND SECOND HARMONIC GENERATION IN A SOLID PLATE (21)

A Green's function approach is used to determine the conditions under which it is possible to generate second harmonics of Lamb waves on solid plates and to have two Lamb modes interact to produce a third phonon, i.e., anothe Lamb mode.

The propagation of a high-amplitude bounded beam in a nonlinear liquid was examined and the growth of harmonics within the various portions of the beam was mapped as a function of propagation distance. However, this field is rather complex and far-reaching. At present, research into the various aspects is still continuing and most of the results obtained within the time period of the present Contract should be considered a basis for ongoing research. Nevertheless, some interim results have been obtained and have been published in some form. It should be pointed out that the final version of publications should eventually contain additional information beyond that which is presently available. Some of the findings are now being written up for submission and the present state of completeness does not warrant inclusion of these drafts in this Report. Thus, listed below are only those contributions which have been completed.

ON THE PROPAGATION AND REFLECTION OF ULTRASONIC BOUNDED BEAMS IN A NONLINEAR MEDIUM (25)

A computational model is developed with which it is possible to determine the harmonic content of an ultrasonic beam of known initial profile as the energy propagates through a nonlinear medium and is reflected from a flat solid. The harmonic contents is calculated after reflection and for propagation beyond the reflector.

In addition to the investigations discussed above a number of other topics were examined in the course of the investigations. It was noted that in some rare cases the samples used to conduct reflectivity experiments were not as homogeneous as had been expected, resulting in reflection profiles which were locally different from those obtained at locations on the rest of the sample. This was examined more closely and the observations were subsequently related to the shape or the extent of the local inhomogeneity. The results of these investigations were described in the following publication:

Characterization of Localized Surface Elastic Defects by Nonspecular Reflection at the Rayleigh Angle (26)

The relationships between characteristics of elastic defects and nonspecular features of bounded ultrasonic beams reflected at the Rayleigh angle from a liquid-solid interface are investigated. The results can serve as a theoretical basis for interpretation of Rayleigh angle nonspecularly reflected beam profiles as characterization of localized surface elastic defects.

KEY WORDS: bounded ultrasonic beam reflectivity; Rayleigh angle; beam profile; surface defects; nonspecular reflection; NDE

Related to this were some follow-ups on reports of backscattering when the incidence angle was at the Rayleigh angle. Since this is very closely related to the present project, some manifestations of backscattering were investigated in detail and the results of this effort are published in the following three publications:

Theoretical prediction of a backscattering maximum at Rayleigh angle incidence for a smooth liquid–solid interface

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Walter G. Mayer
Physics Department, Georgetown University, Washington, DC 20057

(Received 27 June 1983; accepted for publication 22 September 1983)

A numerical integration method for the description of acoustic bounded beams is used to calculate possible backscattering strength from a smooth liquid–solid interface. It is shown that the backscattering strength is maximum for Rayleigh angle incidence. The influence of beam shape and beamwidth on the backscattering strength near the maximum is demonstrated.

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AAA6. Nonspecular reflection and transmission of ultrasonic bounded beams having an nth-polynomial intensity distribution. Tran D. K. Ngoc and Walter G. Mayer (Physics Department, Georgetown University, Washington, DC 20057)

Theoretical investigations of the nonspecular reflection or transmission effects in the past have been done mainly for an incident beam assumed to have a Gaussian intensity distribution. This may not be satisfactory in many cases where a beam is characterized by a non-Gaussian profile. This paper describes nonspecular effects for an incident beam whose intensity distribution is modeled by a general nth polynomial, providing more flexibility in simulating reflection and transmission phenomena for bounded beams. An extension of the spectral representation of bounded beams leads to calculations of reflected beam profiles at critical angles associated with a solid–liquid interface for an nth polynomial incident beam. Sample nonspecular reflection and transmission profiles are calculated for a more complex layered media system, i.e., a solid plate immersed in a liquid. Results are compared with known nonspecular characteristics associated with Gaussian incident beams. [Work supported by Office of Naval Research, U.S. Navy.]

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Q6. Backscattering at Rayleigh and other angles: A theoretical prediction. Walter G. Mayer and Tran D. K. Ngoc (Physics Department, Georgetown University, Washington, DC 20057)

The spectral representation approach used to calculate beam profile changes upon forward reflection [T. D. K. Ngoc and W. G. Mayer, IEEE Trans. Sonics Ultrason. SU-27, 229 (1980)] is extended to include negative angles of reflection, i.e., backscattering. Calculations show that the amplitude of the backscattered beam is a strong function of the incident beam profile. For example, backscattered intensity is predicted to be insignificant when the incident beam is Gaussian but quite measurable for profiles associated with commonly used transducers. This formulation enables one to evaluate reflected field profiles at backscattering and other angles. [Work supported by the Office of Naval Research, U.S. Navy.]

Finally, an initial attempt was made to look into the acousto-optic results when the probing light beam is used to investigate pulsed ultrasonic signals, the latter being used quite frequently in a host of applications. The first results of this investigation have been published during the last months the Contract was in force.

Asymmetric light diffraction by pulsed ultrasonic waves (30)

Low-MHz, continuous ultrasonic waves traveling in a transparent medium cause light to be diffracted into discrete diffraction orders when light and sound propagation directions are normal to each other. When pulsed ultrasonic waves are used the diffraction orders split into secondary orders which are asymmetric with respect to the central diffraction order. This splitting is derived and a general expression provided for the intensity as a function of the ultrasonic pulse Fourier spectra. Examples are provided which demonstrate the degree of asymmetry for an exponential driving pulse and the convergence to the classic Raman–Nath results when the pulse approaches a continuous wave.

LIGHT DIFFRACTION BY ULTRASONIC PULSES (31)

This paper is prompted by recent experimental work [1] which demonstrated the production of structured diffraction patterns by pulsed ultrasonic waves. Existing theory [2] is expanded to include arbitrary pulse shapes and it is shown that the diffracted light intensity distribution is asymmetric with respect to the central diffraction order. Experimental and analytic examples are provided which illustrate the theory.

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