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14. ABSTRACT
Research is reported into the causes of large high frequency acoustic echoes from tilted bluntly truncated cylinders in water. As a consequence of the cylinder's tilt, the specular reflection by the cylinder's outer surface only weakly contributes to the backscattering. All of the enhancements considered are associated with the target's mechanical response. An enhancement is discovered and analyzed for plastic and rubber cylinders usually considered to have weak backscattering. Helical contributions for cylindrical shells were also studied.

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I. Introduction

This grant was an AASERT award to facilitate the support of a US citizen graduate student (Florian J. Blonigen). Blonigen was supported by this grant from July 1, 1997 through August 15, 2000. The parent award for related scattering research was from ONR Code 331 (grant N00014-92-J-1600). The research summarized below conforms with the original AASERT proposal, the abstract of which indicates, "The AASERT student will extend and test ray theory for situations where elastic responses are known (or anticipated) to give bright high-frequency sonar images." The AASERT grant (as well as the broader parent grant) involves scattering research where the approaches include: (1) identifying and (2) modeling mechanisms that produced enhanced scattering. A significant component of the modeling concerns situations where thin shell theory does not apply, as is the case for all of the research supported by this AASERT grant. The AASERT supported research concerns scattering by tilted cylinders in situations where illumination of the cylinder by short tone bursts can produce strong scattering contributions. It concerns the following three issues.

1. For tilted solid cylinders made of plastic or rubber, there is a new *backscattering* enhancement associated with a merging of farfield-Airy caustics. These caustics are associated with rays transmitted by the cylinder and internally reflected. The enhancement is especially strong near a predicted critical tilt angle.

2. For empty tilted cylinders having metal walls that are sufficient thick (and/or at sufficiently high frequencies) flexural waves can become supersonic so that there is strong coupling with acoustic waves in the surrounding water. (This is in contrast to the case of subsonic flexural waves where the coupling is weak.) The research concerns the observations and modeling of helical wave scattering enhancements for situations where thin-shell mechanics is not directly applicable. The frequencies investigated are above the coincidence frequency of the shell in water.

3. When the thick cylindrical shell studied in item 2 was filled with water, an additional set of scattering contributions appeared associated with rays that were transmitted through the shell into the water filled portion. The scattering contributions associated with the helical waves were modified as a consequence of the leakage of energy by the flexural waves from both the inner and the outer surfaces of the shell.

As a consequence of the cylinder's tilt, the specular reflection by the cylinder's outer surface only weakly contributes to the backscattering. All of the enhancements considered are associated with the target's mechanical response. As summarized below, Blonigen's Ph.D. dissertation addresses each of these issues [B4]. The principal research results on item 1 have been published [B1] and will not be repeated here. One manuscript has been submitted on item 2 [B2]. The most complete description of the AASERT supported research will appear in Blonigen's dissertation. Readers interested in obtaining a copy may contact the Principal Investigator at: **marston@wsu.edu** or may contact the Washington State University library. The parent grant has also supported research directly relevant to high frequency imaging. This has included (but is not limited to) imaging of cylinders [A1] and holographic imaging of elastic disks [A2-3].

II. Backscattering enhancements for tilted solid plastic cylinders in water due to the caustic merging transition: Observations and theory

The abstract of our journal article with this title [B1] is reproduced below:

Bulk shear and longitudinal waves give rise to important contributions to the scattering of ultrasound by tilted finite plastic and rubber cylinders in water. This occurs in situations where either the shear or longitudinal speed is less than the speed of sound in the surrounding water. At a certain critical tilt angle, large backscattering enhancements are observed for finite cylinders, where the wave vector can reverse direction upon reflection from the cylinder truncation. The scattering process is analogous to the enhancement produced by the merging of rainbow caustics of primary rainbow rays in the scattering of light by long dielectric cylinders, also known as the caustic merging transition [C. M. Mount, D. B. Thiessen, and P. L. Marston, "Scattering observations for tilted transparent fibers: evolution of Airy caustics with cylinder tilt and the caustic merging transition," Appl. Opt. 37, 1534–1539 (1998)]. A ray theory was developed to model the backscattering mechanism at the critical tilt angle. It employs the idea of the Bravais effective refractive index, convenient for constructing ray diagrams for the projections of rays in the base plane of the cylinder. There is general agreement between the theory and the experiment down to relatively low ultrasonic frequencies (*ka* as small as 10). The enhancement is the most significant backscattering contribution for a wide range of tilt angles.

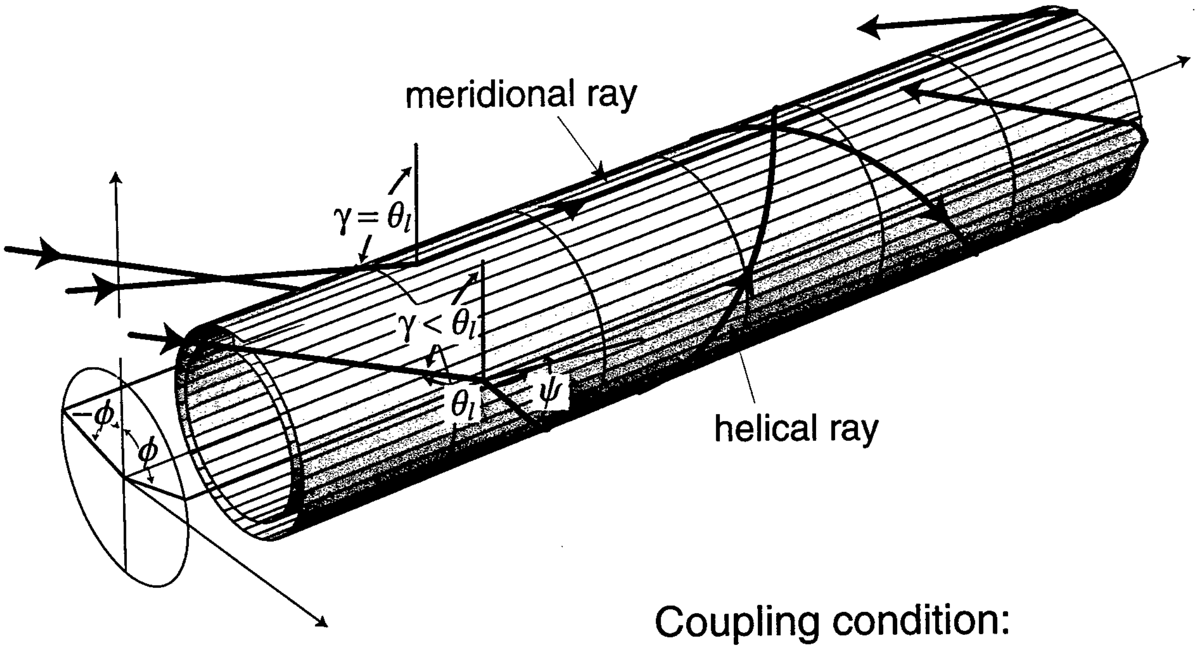
In addition, there have been presentations of this and related research at various meetings [C1,2,4-6].

III. Leaky helical flexural wave scattering contributions for tilted cylinders

The theory Blonigen developed to model these scattering contributions have several significant differences compared to ray theories previously developed for the theory of helical rays associated with compressional waves (symmetric Lamb waves) on thin shells. Consequently, it was appropriate to test the ray theory with a computational benchmark. The benchmark chosen was scattering into the meridional plane by an empty infinite tilted cylinder. The results of this comparison indicate that the flexural wave parameters used in the ray theory must include a wave-vector anisotropy for the propagation of the helical waves on the cylindrical shell. The sign and magnitude of this anisotropy turns out to be different than for previous results by other authors for thin shells at low frequencies. Only when this anisotropy is included does the ray theory produce the results of the benchmark problem. Preliminary results were presented in an invited paper at the joint ASA/EAA meeting in Berlin in 1999 [C3] and a detailed manuscript has been submitted for publication [B2]. The abstract of the manuscript is reproduced below:

> "Leaky helical flexural wave scattering contributions from tilted cylindrical shells: ray theory and wave-vector anisotropy," by Florian J. Blonigen and Philip L. Marston.
> At sufficiently high frequencies cylindrical shells support a wave whose properties are analogous to those of the lowest antisymmetric Lamb wave on plates. When the shell is in water and the frequency exceeds the coincidence frequency, the flexural wave is a leaky wave that can be a major contributor to the scattering by tilted shells [G. Kaduchak, C. M. Wassmuth, and C. M. Loeffler, "Elastic wave contributions in high-resolution acoustic images of fluid-filled, finite cylindrical shells in water," J. Acoust. Soc. Am. 100, 64-71 (1996)]. While the meridional ray scattering contributions for such leaky flexural waves were previously modeled, the helical contribution can also be significant. A ray theory for those contributions is compared with the exact partial wave series (PWS) solution for infinitely long empty shells. The agreement between the ray theory and the PWS is only possible when a weak anisotropy of the flexural wave parameters is included in the evaluation of the ray theory. The anisotropy is determined numerically from the roots of a denominator in the PWS because approximations for the anisotropy from thin-shell mechanics are not applicable significantly above the coincidence frequency.

Following this success, Blonigen extended the model to describe the backscattering contribution by helical flexural waves on empty bluntly truncated tilted cylinders in water [B3,C8]. This model was tested and was found successful under situations where the helical wave reflection coefficient at the truncation could be well approximated by unity. In that case there was also an approximate benchmark analytical model for the steady-state backscattering. The (approximate) benchmark partial-wave series by Morse, Marston, and Kaduchak [A4,5] is an extension of a thin-shell partial wave series by Rumerman. The experiments used tone bursts which were sufficiently long so that the measured backscattering would approximate the steady-state backscattering contributions of flexural (a_0 antisymmetric Lamb waves) on the tilted shell. The relevant rays are shown in Fig. 1. Figure 2 shows a three-way comparison for the case of a stainless steel shell in water having a thickness to radius ratio of $h/a = 0.1625$ with $ka = 20$ where k is the wavenumber in water. The length to radius ratio $L/a = 11.7$. The solid curve is the aforementioned approximate partial wave serves solution. The dashed curve is the ray theory that includes only the ray contributions associated with the flexural wave. The points are measurements obtained using a moderately short tone burst of type that could be used in a sonar imaging system having high spatial resolution. Both curves, as well as the points, display a large peak near 43° associated with a meridional ray that reflects off the truncation at the end of the shell. (The form function normalization is such that geometric reflection from a rigid sphere having the same radius as the cylinder would produce a unimodular form function. On this scale a form function of greater than unity is a very large signal. Both curves (as well as the measurements) show similar oscillations associated with helical flexural waves as the tilt angle is decreased to about 20°. As expected however, neither the ray model nor the measurements reproduced the narrow peaks of the approximate partial wave series present near tilts of 20° and smaller. That is because those peaks are associated with waves on the shell (such as compressional waves) that are relatively weakly coupled with the acoustic field. Detection of those contributions would require using very long acoustic



Coupling condition:

$$k_l / k = \sin \theta_l$$

Figure 1. Diagram showing leaky meridional and helical rays on a bluntly truncated cylindrical shell that produce large contributions to the backscattering. The backscattering contributions require reflection from the blunt truncation at the end of the cylinder. The helical rays are excited for a wide range of the tilt angle γ and the backscattering amplitude is predicted to have a non-monotonic dependence on the tilt angle. This is partly because the waves excited along different parts of the path can interfere constructively or destructively with the waves excited along other parts of the path. In the situation considered, the important leaky rays are associated with antisymmetric Lamb waves (that is high frequency flexural waves) on the shell. It is necessary to include the anisotropy of the flexural wave properties in the model and an example is shown in Fig. 2.

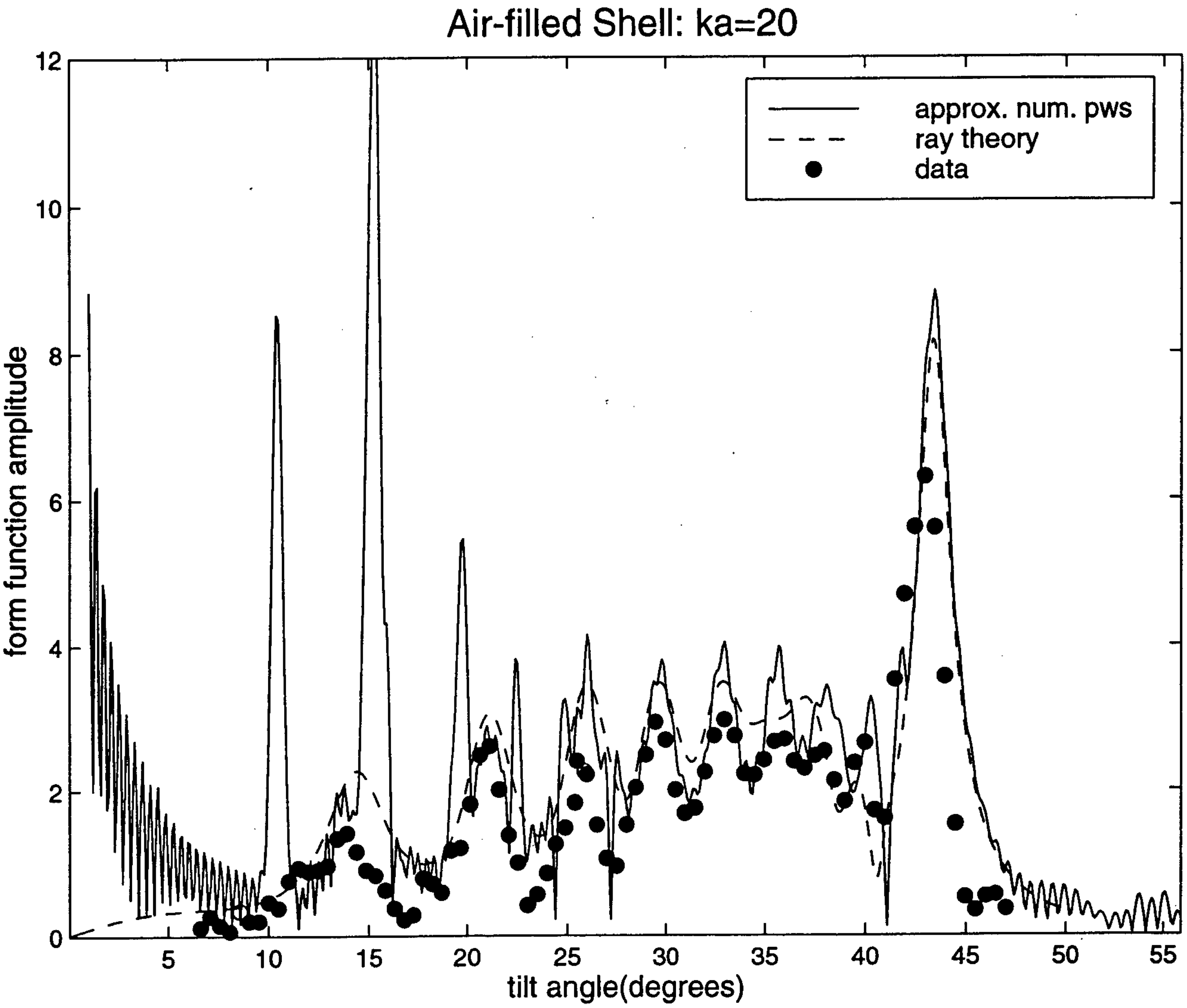


Figure 2. The points show the measured magnitude of the form function for backscattering by an empty stainless steel cylinder as a function of the tilt angle where zero tilt corresponds to broadside illumination. The incident wave was a 34 cycle tone burst having a frequency of 225 kHz. The radius, thickness, and length of this shell are 21 mm, 3.42 mm, and 116 mm. The dashed curve is the ray theory prediction for the backscattering contribution of helical flexural waves where the reflection coefficient at each end of the cylinder is taken to be unimodular. The solid curve is an approximate partial wave series result that includes compressional and shear wave contributions that are not observed unless a very long tone burst is used.

tone bursts that may not be practical for imaging sonar. The success of the ray theory was only possible because the anisotropy studied in [B2] was included in the analysis. The magnitude of the backscattering was typically much larger than would have been found if the cylinder had been a tilted bluntly truncated rigid cylinder of the same length.

IV. Backscattering by water-filled tilted cylindrical shells

Large backscattering enhancements were also observed for the water-filled shell case. The dependence on tilt angle as well as tone burst length was investigated at selected frequencies. The ray theory was modified to allow for the leakage of energy from both sides of the shell [B3]. There was significant additional complexity due to the contributions of rays within the water inside the shell. Different versions of the theory were capable of bracketing the magnitude of the observed signals. There was general agreement with the ray explanation of the various scattering contributions and the signal magnitudes observed were much larger than would have been found if the cylinder had been a tilted bluntly truncated rigid cylinder of the same length.

V. References

[A1] S. F. Morse, "High frequency acoustic backscattering enhancements for finite cylindrical shells in water at oblique incidence," Ph.D. thesis (Washington State University, 1998) 330 pages.

[A2] B. T. Hefner, "Acoustic Backscattering Enhancements for Circular Elastic Plates and Acrylic Targets, the Application of Acoustic Holography to the Study of Scattering from Planar Elastic Objects, and Other Research on the Radiation of Sound," Ph.D. thesis (Washington State University, 2000) 257 pages.

[A3] B. T. Hefner and P. L. Marston, “Backscattering enhancements associated with the excitation of symmetric Lamb waves on a circular plate: direct and holographic observations,” Acoustics Research Letters Online 2(1), 55-60 (2001); http://ojps.aip.org/ARLO/top.html.

[A4] S. F. Morse, P. L. Marston, and G. Kaduchak, “High frequency backscattering enhancements by thick finite cylindrical shells in water at oblique incidence: experiments, interpretation and calculations,” J. Acoust. Soc. Am. 103, 785-794 (1998).

[A5] S. F. Morse and P. L. Marston, "Degradation of meridional ray backscattering enhancements for tilted cylinders by mode conversion: Wide-band observations using a chirped PVDF sheet source," IEEE J. Ocean. Eng. (accepted for publication).

VI. Publications and dissertations supported or partially supported by this grant

[B1] F. J. Blonigen and P. L. Marston, "Backscattering enhancements for tilted solid plastic cylinders in water due to the caustic merging transition: Observations and theory," J. Acoust. Soc. Am. 107, 689-698 (2000).

[B2] F. J. Blonigen and P. L. Marston, "Leaky helical flexural wave scattering contributions from tilted cylindrical shells: ray theory and wave-vector anisotropy," submitted to J. Acoust. Soc. Am.

[B3] F. J. Blonigen and P. L. Marston, manuscript in preparation.

[B4] F. J. Blonigen, Ph.D. thesis (Washington State University, in preparation).

VII. Presentations supported or partially supported by this grant

[C1] F. J. Blonigen and P. L. Marston, "Backscattering enhancement for tilted plastic cylinders in water due to the caustic-merging transition: ultrasonic observations," J. Acoust. Soc. Am. 102, 3088 (1997).

[C2] P. L. Marston, B. T. Hefner, and F. J. Blonigen, "Backscattering enhancements for "plastic" scatterers in water and silt: Novel mechanisms and ray models for solids and shells," J. Acoust. Soc. Am. 104, 1783 (1998).

[C3] *Invited:* F. J. Blonigen and P. L. Marston, "Leaky wave scattering contributions of tilted thick cylindrical shells in water above the coincidence frequency: Ray theory and computational models, " J. Acoust. Soc. Am. 105, 1224 (1999) [EAA/ASA meeting, Berlin].

[C4] F. J. Blonigen and P. L. Marston, "The caustic merging transition in the scattering of light by tilted dielectric cylinders and ultrasound by tilted plastic cylinders," APS Northwest Section meeting (1999).

[C5] P. L. Marston, F. J. Blonigen, B. T. Hefner, K. Gipson, S. F. Morse, "Comparison of radiation and scattering mechanisms for objects having Rayleigh wave velocities greater than or smaller than the speed of sound in the surrounding water," Resonance meeting, Oxford, MS (1999).

[C6] F. J. Blonigen and P. L. Marston, "Backscattering enhancements of ultrasound by tilted solid plastic cylinders in water due to the caustic merging transition: High angular resolution scans," J. Acoust. Soc. Am. 107, 2846 (2000).

[C7] *Invited:* P. L. Marston, F. J. Blonigen, K. Gipson, B. T. Hefner & S. F. Morse, "Ultrasonic backscattering enhancements for truncated objects in water: quantitative models and tests and special cases," IUTAM Symposium Diffraction and Scattering in Fluid Mechanics and Elasticity (Manchester, UK, July 2000).

[C8] F. J. Blonigen and P. L. Marston, "Backscattering by tilted cylindrical shells above the coincidence frequency caused by helical flexural waves," J. Acoust. Soc. Am. 108, 2573 (2000).

VIII. Distribution List: AASERT final Technical Report

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