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Research proposed in "Geometrical Aspects of Scattering and Physical Effects of Sound," P. L. Marston, principal investigator. Telephone (509) 335-5343. Email: marston@wsu.edu.

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13. ABSTRACT *(Maximum 200 words)*

Research is reported in the following areas: [1] High-frequency enhancements of the scattering of sound by tilted elastic cylinders in water are analyzed and observed. (A novel formulation approximates meridional as well as helical wave amplitudes. Both the formulation and the experiments concern solid cylinders as well as shells.) [2] The interaction of sound with sound mediated by dilute aqueous suspensions was studied using the frequency shift of a resonator. [3] The coupling of oscillating magnetic fields to the quadrupole quasi-flexural and torsional modes of a stainless steel spherical shell in water is investigated. (Sound radiated by these magnetically excited modes is detected and resonances are identified.) [4] As an extension of the experimental methods developed for item (1), a PVDF sheet source was used to excite elastic responses of a target but now the target is a large spherical shell in a lake. (Acoustic tone bursts and impulses are generated and used outside the laboratory and resonances are identified.) [5] Transmitted ray contributions and a caustic merging transition for penetrable tilted cylinders are studied using an optical analogy. (The results suggest possible enhancements in the scattering of sound by plastic cylinders.)

14. SUBJECT TERMS
Acoustical Scattering, Ray Methods, Elastic Shells, Plates, Particle Suspensions, Nonlinear Acoustics, Rayleigh Waves

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GEOMETRICAL ASPECTS OF SCATTERING AND PHYSICAL EFFECTS OF SOUND

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June 1997

Annual Summary Report for Grant N00014-92-J-1600

1 June 1996 - 31 May 1997

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TABLE OF CONTENTS

The project description, approaches, and summary of accomplishments are grouped according to Projects I, II, III, IV, and V.

I. A. Project Description: Transient and High-Frequency Enhancements in Scattering from Elastic Objects -- The objective is to identify and model physical processes that are likely to be important for the classification of scatterers in water based on high frequency scattering signatures and acoustical images. When possible, quantitative ray approximations are formulated to predict scattering amplitudes and experiments are used to test the approximations. The task emphasis this year has been on scattering by tilted truncated elastic cylinders.

B. Approach: *(i) Theoretical*: During this past year, Marston developed and numerically tested a novel ray formulation for approximating large leaky wave contributions to high frequency scattering by smooth objects that may have truncations. The analytical approach was to approximate a leaky wave "point spread function" for the contribution of each illuminated surface patch to the leaky wavefield on the object. Comparisons with previous special cases were checked and truncated and infinite tilted cylinders were considered. *(ii) Experimental*: Backscattering was measured as a function of tilt angle for cylindrical shells (S. Morse) and a solid stainless steel cylinder (K. Gipson). Some of the experiments were done with the sheet PVDF source configured as shown in the 1996 Annual Summary Report. *(iii) Computational*: With assistance from G. Kaduchak (UT:ARL), Morse has been applying an approximate computational model applicable to thick finite tilted cylinders.

C. Accomplishments:

- *Theory*: Marston's model was tested for canonical geometries and was shown to recover previous results such as from a helical ray model for scattering due to compressional leaky waves on thin cylindrical shells developed by Norris and Rebinsky (JASA 1994). It was also applied to a cylinder with a partial coating and used to clarify the relevant coupling regions [P. L. Marston, "Spatial approximation of leaky wave surface amplitudes for three-dimensional high-frequency scattering: Fresnel patches and application to edge-excited and regular helical waves on cylinders," JASA (accepted for publication)]. That work also generalizes approximations of background-induced phase shifts for thick shells verified for spheres in: S. G. Kargl and P. L. Marston, "Background contributions and coupling coefficients for backscattering by thick shells," JASA *101*, 3792-3797 (1997). Scattering contributions by meridional rays on tilted cylinders were also approximated. For the case

of Rayleigh waves on an infinite solid cylinder, the result was tested by comparison with exact partial wave series results for a tilted cylinder [see Appendix I and P. L. Marston, "Approximate meridional leaky ray amplitudes for tilted cylinders: end-backscattering enhancements and comparisons with exact theory for infinite solid cylinders," JASA (accepted for publication)]. When applied to the case of the backscattering contributions by meridional rays on truncated cylinders, farfield magnitudes of end contributions are typically larger than for reflection off a rigid sphere having the same radius as the cylinder and much greater than predicted by GTD for a rigid finite cylinder. The results at least qualitatively explain properties of acoustical images reported by G. Kaduchak et al., JASA *100*, 64-71 (1996)].

- *Experiments*: Morse obtained high resolution measurements of the spectrum backscattered by two different finite cylindrical shells for an incident pressure impulse. These were measured as a function of tilt angle and the frequency-angle loci for helical and meridional ray backscattering enhancements were approximated with ray theory and used to identify observed spectral features [S. F. Morse et al., "High frequency backscattering enhancements by thick finite cylindrical shells in water at oblique incidence: experiments, interpretation and calculations," JASA (submitted in 1997)]. Strong enhancements were observed for highly tilted cylinders near the coincidence frequencies of the different shells studied. K. Gipson confirmed the presence of meridional ray backscattering enhancements due to Rayleigh waves on a tilted truncated stainless steel cylinder.
- *Computations*: Comparisons with Morse's measurements of the backscattered spectrum as a function of tilt confirm that an approximate partial wave series approach displays many of the observed backscattering enhancements.

II. A. Project Description: Interaction of Sound with Sound Mediated by a Suspension of Particles -- The objective of this project is to understand the large effects that suspended particles can have on the interaction of sound with sound in water. Since large acoustic signatures are observed even with very small volume fractions ϕ of suspended particles, the interaction may have practical applications for the measurement of ϕ or the particle compressibility. More generally, the interaction process is of a class that has previously been ignored in nonlinear acoustics.

B. Approach: The emphasis of the research during the past year was on the shift in the resonance frequency of an ultrasonic standing wave resonator as a result of the particle migration due to the radiation pressure of the standing wave.

C. Accomplishments:

- Chris Kwiatkowski completed his Ph.D. thesis ("Ultrasonic probes of aqueous particle suspensions: collinear four-wave mixing and resonator detuning") since some of the results for Bragg reflection by induced particle layers in a collinear pump-probe geometry were summarized in a previous report, the detuning effect will be emphasized here. Bragg and detuning effects may be detected even if the volume fraction ϕ is small (e.g. < 0.001). The detuning calculated from adiabatic invariance agrees with the magnitude of the observed shift and also with an approximate model based on a novel application of the transfer matrix method for wave propagation through a layered medium.

III. A. Project Description: Electromagnetic Excitation of Elastic Modes of a Shell -- The objective is to use oscillating magnetic fields to excite specific modes of electrically conducting shells so as to produce easily detectable acoustic radiation in the surrounding fluid. This type of transduction has potential application to mode spectroscopy of fluid loaded shells having no exact mode solutions, to hybrid electromagnetic - acoustic object detection, and to excitation of modes weakly coupled with sound.

B. Approach: The emphasis was on driving the modes of a thick stainless steel spherical shell in water in the absence of a separate magnet to supply a bias field. As previously described [1996 Report and JASA (abstract) *99*, 2594 (1996)] even in the absence of a static bias field, an oscillating magnetic field B produces oscillating stresses. Since the stress is proportional to B^2, the stress oscillates at twice the frequency of the oscillating field. Our previous experiments were on aluminum shells in air.

C. Accomplishments: B. T. Hefner easily excited the quadrupole mode (where the shell oscillates in water between an oblate and a prolate shape) either by driving current though a coil at the frequency of the mode or half the mode frequency, the coil diameter being much larger than that of the shell. The sound radiated was detected by a hydrophone. It was also found that the low-lying high-Q torsional modes of the spherical shell could also be excited and acoustically detected on a shell that had previously been magnetized. This is a significant result since torsional modes are not normally acoustically excited or acoustically detected for spherical shells.

IV. A. Project Description: Resonance and Impulse Excitation of a Large Spherical Shell in Lake Union Using a PVDF Sheet Source -- This project concerns the application of one of the experimental methods used in our scattering

experiments (Project I) to a situation outside the laboratory. The specific project was to assist Kevin L. Williams (UW: Applied Physics Laboratory) in the characterization of a large stainless steel spherical shell (o.d. 59.7 cm, thickness 1.52 cm) that has been used for studying environmental factors in high frequency scattering. (Though no funds were transferred to WSU from APL in support of this project, the project did not require significant resources from grant N00014-92-J-1600.)

B. Approach: APL made available the R. V. Henderson test barge at the edge of Lake Union (Seattle). All transducers and electronic and data acquisition components used were provided by WSU. A large PVDF sheet source was placed adjacent to the submerged shell and hydrophones were positioned to detect backscattering and (in the shadow of the shell) nearfield forward scattering. WSU students (S. F. Morse and B. T. Hefner) recorded the data.

C. Accomplishments:

- The low-lying high-Q resonance features of the shell were easily resolved by driving the PVDF sheet with tone bursts. There was no ringing of the transducer so by carefully tuning the carrier frequency of the burst the ring-up and ring-down of distinct modes in the 1.5 to 5 kHz region were observed and the mode frequencies were found to agree with predictions. These modes were also detected with pressure impulse excitation as were higher frequency scattering mechanisms such as coincidence frequency and leaky Lamb wave responses.

V. A. Project Description: Transmitted Ray Scattering by Penetrable Tilted Cylinders and the Caustic Merging Transition -- Some solid scatterers of interest in physical and underwater acoustics (e.g. many plastics) do not support leaky Rayleigh waves because their shear wave velocity is less than that of water. In such cases the enhancement mechanisms studied in Project I are not applicable, though certain internally transmitted rays become significant. This project investigates a novel class of such rays for a tilted circular cylinder.

B. Approach: Since the ray optics is analogous to the refraction of light by a tilted dielectric circular cylinder, the scattering of light by such a cylinder was investigated.

C. Accomplishments:

- *Theoretical*: The refraction by the tilted cylinder was analyzed leading to the prediction that

the projection of the Descartes (or rainbow) ray on the base of the cylinder varies with the tilt angle γ. At a critical tilt angle (which depends on the refractive index), the resulting farfield Airy caustics are predicted to merge in the meridional plane.

- *Experimental*: C. Mount measured the farfield scattering as a function of the tilt γ for a plastic PMMA fiber and confirmed the existence of the predicted caustic merging transition. There is a large enhancement of the meridional plane scattering at (and near) the predicted critical value of γ.

OFFICE OF NAVAL RESEARCH
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS REPORT
for
01 June 96 through 31 May 97

Contract/Grant Number: N00014-92-J-1600

Contract/Grant Title: Geometrical Aspects of Scattering and Physical Effects of Sound

Principal Investigator: Philip L. Marston

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Washington State University
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a. Number of papers submitted to refereed journals but not yet published: 3

b. Number of papers published in refereed journals (ATTACH LIST): 1

c. Number of books or chapters submitted but not yet published: 1

d. Number of books or chapters published (ATTACH LIST): 2

e. Number of printed technical reports & non-refereed papers (ATTACH LIST): 4

f. Number of patents filed: 0

g. Number of patents granted (ATTACH LIST): 0

h. Number of invited presentations at workshops or professional society meetings: 1

i. Number of contributed presentations at workshops or professional society meetings: 8

j. Honors/awards/prizes for contract/grant employees, such as scientific society and faculty awards/offices (ATTACH LIST): 0

k. Number of graduate students supported at least 25% this year this contract/grant: 5

l. Number of post docs supported at least 25% this year this contract/grant: 0

How many of each are females or minorities? These six numbers are for ONR's EEO/Minority Reports. Minorities include Blacks, Aleuts, Amindians, etc., and those of Hispanic or Asian extraction/nationality. The Asians are singled out to facilitate meeting reporting semantics re "underrepresented".

Graduate student FEMALE:	2	Post doc FEMALE:	
Graduate student MINORITY:	1	Post doc MINORITY:	
Graduate student ASIAN E/N:		Post doc ASIAN:	

1996 P^{3}H Report Supplement for Grant N00014-92-J-1600

b. Papers Published in Refereed Journals:

1. S. G. Kargl and P. L. Marston, "Background contributions and coupling coefficients for backscattering by thick shells," J. Acoust. Soc. Am. *101*, 3792-3797 (1997).

c. Printed Technical Reports & Non-refereed Papers:

1. P. L. Marston, "Scattering and radiation of high frequency sound in water by elastic objects, particle suspensions, and curved surfaces," Annual Summary Report for ONR Grant N00014-92-J-1600 (issued June, 1996) DTIC Number A310720.

2. C. S. Kwiatkowski, "Ultrasonic probes of aqueous particle suspensions: collinear four-wave mixing and resonator detuning." Ph.D. thesis (Wash. State Univ., 1997) 230 pages.

3. C. M. Mount and P. L. Marston, "Glare Points in the Refracted-Wave Scattering by Icicles and Other Tilted Dielectric Cylinders and the Caustic-Merging Transition," in *Light and Color in the Open Air,* Vol. 4, 1997 OSA Technical Digest Series pp. 14-16.

4. D. S. Langley and P. L. Marston, "Generalized Tertiary Rainbow of Slightly Oblate Drops: Observations with Laser Illumination," in *Light and Color in the Open Air,* Vol. 4 1997 OSA Technical Digest Series pp. 11-13.

d. Book chapters published:

1. P. L. Marston, "Quantitative Ray Methods for Scattering," in *Encyclopedia of Acoustics,* Vol. 1, M. J. Crocker, editor (John Wiley Press, New York, 1997) Chap. 43, pp. 483-492.

2. P. L. Marston, "Introductory Chapter–Ultrasonics, Quantum Acoustics, and Physical Effects of Sound," in *Encyclopedia of Acoustics,* Vol. 2, M. J. Crocker, editor (John Wiley Press, New York, 1997) Chap. 54, pp. 621-628.

k. Total Number of Graduate Students Supported at Least 25% This Year on This Grant.

Graduate Students: 5

Karen Gipson

Brian T. Hefner

Chris Kwiatkowski

Scot Morse

Catherine M. Mount

Appendix A: Approximate Meridional Leaky Ray Amplitude as a Function of the Cylinder Tilt

This Appendix illustrates one of the results calculated in P. L. Marston, "Approximate meridional leaky ray amplitudes for tilted cylinders: end-backscattering enhancements and comparisons with exact theory for infinite solid cylinders," JASA (accepted for publication). The example in this Appendix is for the infinite cylinder geometry shown in **Figure 1**. This example is important because unlike the actual meridional ray backscattering enhancement for finite cylinders observed with high frequency sonar, the infinite cylinder geometry has an exact solution. **Figure 2** compares the meridional ray contribution (points) with partial wave series computations (solid curve) for a solid stainless steel cylinder. These are shown as a function of the cylinder tilt γ for farfield scattering form functions for an observer in the meridional plane. A rigid background contribution has been subtracted from the partial wave series result to isolate the contribution of interest which is due to a Rayleigh wave which propagates down the cylinder's axis. The coupling is optimized when the tilt angle γ lies close to the Rayleigh wave coupling angle $\theta_l = 30.703°$ evaluated for a flat stainless steel surface in water. Near this tilt angle the dephasing of the excited Rayleigh wave relative to the incident acoustic wave is minimized. The function which is plotted in the dotted curve contains complementary error functions evaluated with real and complex arguments. In the approximation shown, the curvature of the radiated wavefront is taken to be the one calculated for $\gamma = \theta_l$ even for cases when $\gamma \neq \theta_l$. This is because the dominant effect of taking $\gamma \neq \theta_l$ is the effect of dephasing on the amplitude of the excited leaky wave.

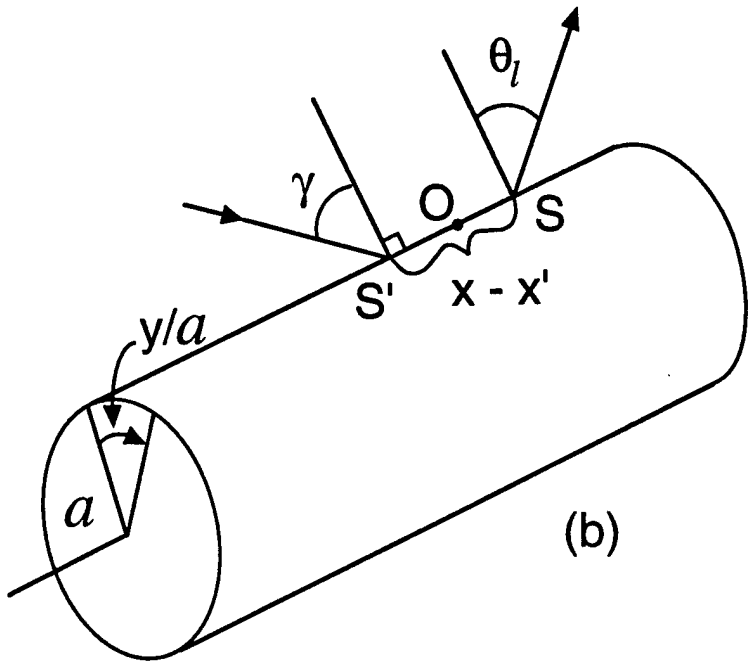

Figure 1

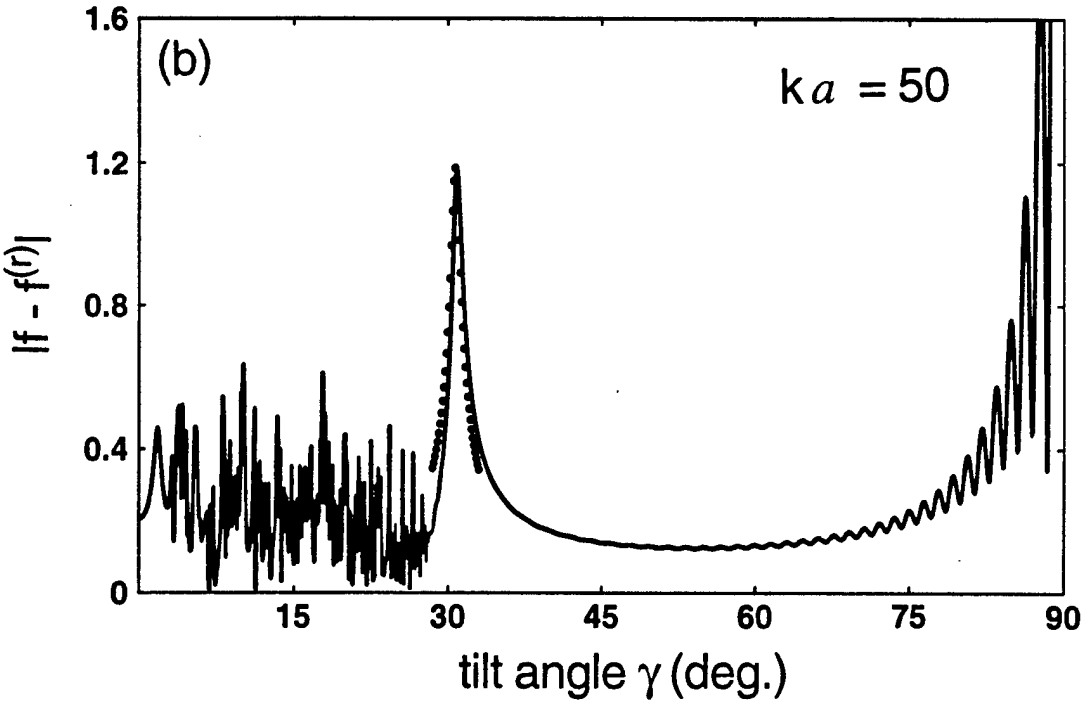

Figure 2

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