Novel Acoustic Scattering Processes for Target Discrimination

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Award Number: N000140410075 and N000141010093
http://www.physics.wsu.edu/Research/acoustics.htm

LONG TERM GOALS

The grant that expired during FY10 (N000140410075) was part of the Shallow-Water Autonomous Sensing Initiative to improve the reliability of acoustic methods using a wide frequency range and scattering data not necessarily limited to monostatic signatures. The related follow-on grant (N000141010093) that started in mid-FY10 has similar goals.

OBJECTIVES

The objective of these grants is to improve the understanding of acoustic scattering processes relevant to man-made objects in the shallow water environment. The current emphasis is on the interpretation of the effects on signatures of placing objects close to an interface. Synthetic aperture sonar, acoustic holographic images, spectral properties of scattering, and bistatic scattering are also examined. Other objectives involve improved understanding and modeling of scattering mechanisms.

APPROACH

A multifaceted research approach appears to be advisable because some acoustic strategies may not *always* be applicable and different strategies may require widely different amounts of time to acquire data for a region of interest. Consequently it appeared to Marston that this project should retain research concerning both low frequency and high frequency sonar technologies. Beginning in FY07, the experimental effort at WSU was shifted to emphasize scaled targets directly relevant to the planning and interpretation of experiments carried out at the NSWC-PCD pond in cooperation with UW-APL. Thus, as explained in the Reports for FY07-09 [1-3], measurements at WSU were extended to include bistatic and monostatic acoustic properties of solid aluminum cylinders in the free field and adjacent to interfaces. This kind of target was selected because experiments at the NSWC pond have used aluminum cylinders of various dimensions. Furthermore, scattering by an aluminum cylinder has become a test case for development of finite element methods for the evaluation of both free-field scattering and scattering by targets adjacent to an interface [4,5]. In support of those efforts the experiments at WSU have been concerned with frequency domain ("acoustic color") displays of the scattering as well as time domain and spatial SAS and holographic imaging displays. Beginning in FY08, measurements in the scattering by tilted aluminum cylinders were extended over a wider range of scaled frequencies by fabricating targets that were small in size. We demonstrated at WSU that elastic modes of tilted aluminum cylinders produce strong scattering for a wide k*a* range.

Report Documentation Page					*Form Approved* *OMB No. 0704-0188*
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1. REPORT DATE **2010**		2. REPORT TYPE			3. DATES COVERED **00-00-2010 to 00-00-2010**
4. TITLE AND SUBTITLE **Novel Acoustic Scattering Processes for Target Discrimination**					5a. CONTRACT NUMBER
					5b. GRANT NUMBER
					5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)					5d. PROJECT NUMBER
					5e. TASK NUMBER
					5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Washington State University,Physics and Astronomy Dept,Pullman,WA,99164-2814**					8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)					10. SPONSOR/MONITOR’S ACRONYM(S)
					11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Measurements of the scattering from aluminum cylinders with k*a* from 10 to 30 show prominent features in the scattering associated with elastic waves guided by the surface of the cylinder. Those features would not be present if it were possible to replace the cylinder by a rigid cylinder and may be referred to as elastic glints. In addition to understanding scattering effects associated with the elastic response of the target and modifications of the scattering associated with the proximity to an interface, the research during FY08 and 09 was extended to examine the potential advantages of bistatic scattering associated with simple specular reflection from the outside of various targets having a vertical symmetry axis. New phenomena examined during FY10 are emphasized in this report.

Professor P. L. Marston directs the research. During FY10 the graduate students supported at least in part by this grant are listed below together with the nature of their research. These students were: J. R. La Follett (scattering experiments with cylinders and other shapes near flat surfaces); A. R. Smith (elastic features visible in SAS imaging); and G. Eastland (scattering by metallic cylinders near flat surfaces). With partial support from this grant, Samantha Damiano (an EE major) has been upgrading our software. Postdoctoral contributors to this effort in FY10 are listed as follows: Dr. T. Marston (a wide range of experiments including SAS imaging, signal processing, and experiment design and fabrication) and Dr. D. B. Thiessen (experiment design, FEM computations and oversight tasks). T. Marston has a Ph. D. in acoustics from Penn State Univ. Thiessen is a WSU Research-Faculty member. J. R. La Follett completed his Ph.D. [6] and both La Follett and T. Marston are currently employed at NSWC-PCD. A prior student Baik [7] is now a postdoc at Woods Hole Oceanographic Institution.

WORK COMPLETED

During FY10, in addition to La Follett's thesis [6] a publication appeared based primarily on collaborations with UW-APL and NSWC-PCD [5] and various papers using Dr. T. Marston's reversible method of SAS processing (the development of which was partly supported by this grant) were submitted and published and presented at *IEEE Oceans* [8-11]. Selected aspects of our research were presented at meetings of the *Acoustical Society of America* [12-20]. With the partial support of this grant T. Marston and P. Marston helped with NSWC-PCD pond experiments in March 2010.

RESULTS

(1) *Acoustic backscattering enhancement for tilted solid cylinders adjacent-to or breaking-through a free surface:* During FY10 La Follett discovered a new type of backscattering enhancement relevant to mid-*ka* scattering by horizontal cylinders in close proximity to a free surface or breaking-through a free surface [6]. This may be relevant to the detection of certain classes of threats. In La Follett's experiment the backscattering was measured with grazing incidence sound (with the grazing angle held near 20 degrees) as the azimuthal angle was spun from 0 to 90 degrees. A solid aluminum cylinder was used for which the free-field scattering mechanisms are well understood in the *ka* range of the experiment. A plot of the time dependence of the scattering in response to a short pulse is shown in **Figure 1**. The surprising result is the uniform brightness and magnitude of the late arc that is especially visible between 35 and 65 degrees. (Here 0 degrees designates broadside orientation while 90 degrees designates end-on.) Most of the bright features away from 0 degrees and 90 degrees are associated with known elastic coupling mechanisms [5-7]; however, the slowly varying intensity of the late bright arc strongly suggests that it is not associated with the elasticity of the cylinder. Additional measurements were taken of backscattering as a function of the vertical position of the cylinder at fixed azimuth for selected values between 35 and 65 degrees. Those measurements indicate that the brightness and the timing of the late arc depends on the separation of the crest of the cylinder from the

free surface such that the enhancement is greatly diminished in amplitude if the separation is greater than about 6 mm. The cylinder diameter was 63.5 mm and length 190.5 mm and the spectral frequency of the incident burst was about 220 kHz. The enhancement is still present when the crest of the cylinder is raised above the free surface. The most plausible explanation is that an acoustic wave in water is partially guided near the smooth crest of the cylinder and is partially reversed at the abrupt truncation at the end of the cylinder. From reciprocity (as well as consideration of the wave-vector components) the reversed wave sheds energy back towards the source of sound. The guiding is thwarted when the gap is too large since in that case the acoustic wave can make it over the crest of the gap since the associated angular waveguide is not cut-off. While estimates of the cut-off condition are of the proper magnitude to explain aspects of the observations, additional research is needed, some of which is underway by one of the current graduate students (Smith).

(2) *Evolution of the backscattering by proud tilted solid cylinders adjacent to a free surface (elastic features):* During FY10 La Follett discovered and modeled additional elastic backscattering enhancements relevant to mid-*ka* backscattering by horizontal metallic cylinders adjacent to or breaking through a free surface [6]. The evolution of the coupling of sound to elastic mechanisms is relevant to viewing proud or partially buried metallic cylinders at grazing incidence. This is a significant extension of prior work noted in reports [2,3], in La Follett's thesis and Baik's publication [21] on the evolution of specular features. In La Follett's research the elastic features may be interpreted from geometrical consideration of the ways that acoustic waves couple to guided elastic modes of the cylinder. Placing the cylinder proud on a flat surface usually introduces additional ways for acoustic waves to couple to guided elastic modes of the cylinder. One approach is to view the evolution of features in either the time or the frequency domain as a function of either the tilt angle or the cylinder or the distance from the interface. La Follett's observations of this type during FY2010 viewed at grazing incidence (20 degrees) a solid aluminum cylinder. His geometric models were especially important for understanding the relevance of surface proximity to the excitation of helical and face crossing rays associated with Rayleigh waves on the cylinder. Perhaps the most important result is the discovery that proximity to a flat surface significantly extends the range of tilt angles over which helical rays can contribute to the backscattering [6]. The extension is a consequence of reflection of sound from the adjacent flat surface. A ray model shows the extension is especially important for short cylinders. This is relevant to the interpretation of scattering by an aluminum cylinder having an aspect ratio L/D = 2 proud on sand obtained at the NSWC pond facility [5]. The extension of tilt angles for helical ray coupling will also apply to guided waves on cylindrical shells.

(3) *Laboratory backscattering measurements and pressure gradient related coupling to elastic modes in preparation for NSWC-PCD pond scattering experiments:* Dr. Tim Marston did a series of experiments supported by this grant in preparation for NSWC-PCD pond experiments that were carried out during March and April of 2010. These were generally of two types: (a) As explained in the report for FY09, measuring the evolution of the backscattering as a function of target distance below a free surface and frequency is useful for classifying the symmetry of the excited target mode. In the case of cylinders the tilt angle of the cylinder is an additional variable; the grazing angle is generally held fixed. Grazing incidence and the adjacent free surface produces a vertical standing wave component to the incident wave and for small horizontal cylinders the coupling is generally maximized with the axis either on pressure anti-nodes (for "pressure coupled" modes) or on pressure nodes (for "gradient coupled" modes). Tim took measurements of this type for a variety of small cylinders. We selected one of the aluminum cylinders with a flat paddle on the end for enhanced coupling for fabrication at WSU of a scaled-up version. This cylinder was deployed at the NSWC-PCD pond and is the third shape from the left side of Fig. 1 of [10]. One important result is that some of the modes visible on the

small cylinder at WSU were also visible in the scaled proud cylinder in the NSWC-PCD pond experiment. (b) Tim carried out a series of relevant measurements of backscattering as a function of tilt angle for an open-ended water-filled aluminum cylindrical shell scaled to one deployed at the NSWC-PCD pond [11] with an aspect ratio Length/Diameter = L/D = 2. One of his important results is that when the shell is hung proud close to a free surface and viewed with grazing angle of 20 degrees, the evolution of the response spectrum as a function of tilt angle is very similar to the case in which the cylinder is hung adjacent to a flat floating platform of closed-cell extruded polystyrene foam ("Styrofoam™"). This method of simulating scattering by objects near an air-water surface was subsequently deployed at the NSWC-PCD pond.

(4) *Development of reversible SAS, CSAS, and line-scan holographic processing methods:* During FY10 until his departure for NSWC-PCD in August 2010, a significant fraction of Tim Marston's time went into the development of reversible synthetic aperture sonar (SAS), circular SAS (CSAS), and line-scan holographic processing methods. Some resources from this grant were used to support this work along with resources from other ONR grants to P. Marston's program at WSU [22]. The reversibility of the processing is useful since it facilitates the extraction of the portion of a recorded signature contributing to a specified portion of a SAS, CSAS, or holographic images. That is achieved by introducing a suitably located spatial filter. Applications demonstrated to date include: (a) the extraction of the spectral features associated with a specific portion of an image [8,11]; (b) in tank experiments extraction of target responses from data that also includes reverberation from sufficiently distant boundaries of the tank [8]; (c) in NSWC-PCD pond data extraction of target responses from line-scan data in which other targets are also viewed during same line-scan [10,11]; and (d) verification of the cause of certain feature loci when a broadside aluminum cylinder is lowered below a free surface with fixed grazing angle illumination and a vertically scanned bistatic SAS receiver (in work done with Eastland [9]). In addition to these applications one of the current students (Smith) has displayed large elastic features in CSAS images for metallic objects.

IMPACT/APPLICATIONS

La Follett's research on the scattering by cylinder close-to, or breaking through, a free surface has plausible implications for the identification of certain types of threats. Tim Marston's experiments on mode classification of small objects placed close to a free surface also has plausible implications for the identification of other types of threats. The SAS processing methods have broader applications to data acquisition and object identification. T. Marston and P. Marston helped with NSWC-PCD pond experiments (research not shown here) in March 2010.

TRANSITIONS

Dr. Jon R. La Follett, whose thesis work was primarily supported by this grant, is currently employed in acoustics research on the staff of NSWC-PCD. Dr. Timothy M. Marston, who was partially supported by this grant during FY10, is now employed there also. One of his methods for the spatial filtering of line SAS data was immediately applied to data acquired at NSWC-PCD in March 2010 [8,10,11].

RELATED PROJECTS

Some of this work was in coopertation with UW-APL and NSWC-PCD. Up to the time of his departure for NSWC-PCD, during FY10 Dr. Timothy Marston's work was jointly supported by some other ONR grants: N000140810024 and N000140910612.

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HONORS/AWARDS/PRIZES

Second Best Student Paper in Underwater Acoustics Award (October 2009 ASA San Antonio meeting) for J. La Follett’s presentation of: “Bistatic line-scan holography of scattering by metallic objects near a free surface.”

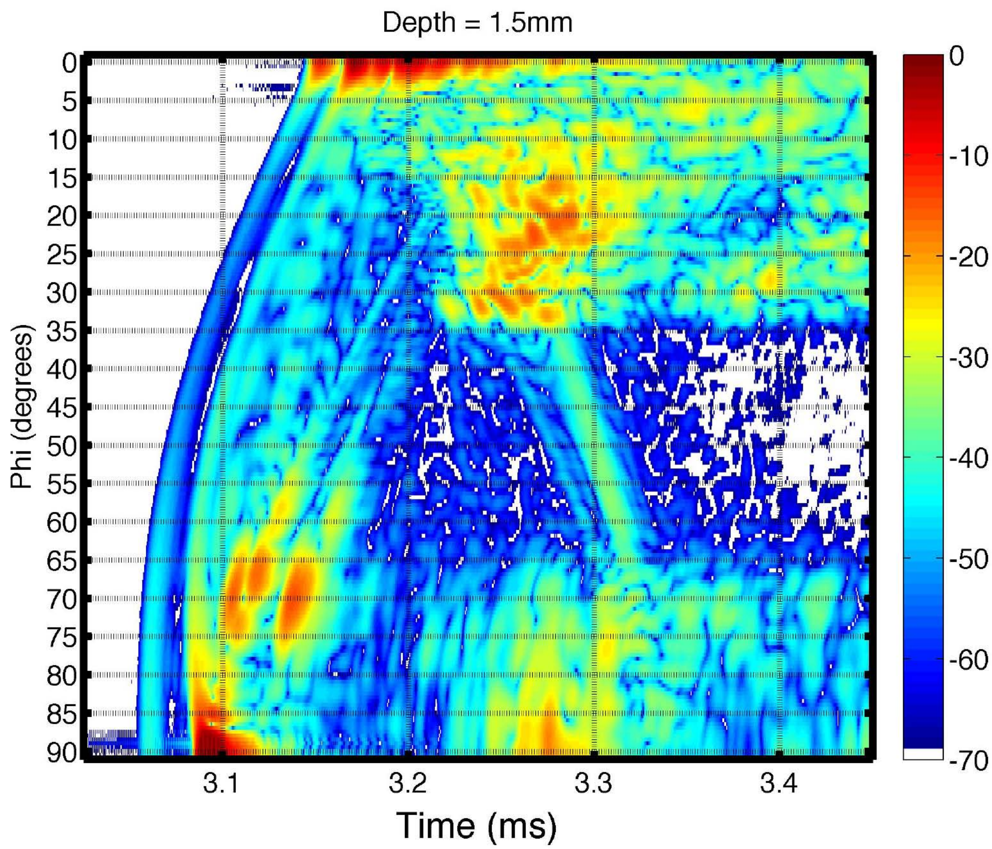

Figure 1. The figure shows the evolution of time-domain backscattering for a solid aluminum horizontal cylinder for a range of azimuthal tilt angles. The cylinder is placed with the top of the cylinder 1.5 mm below a free surface. The illumination is at a grazing angle of 20 degrees. The vertical axis is the azimuthal tilt angle Phi where 0 degrees is broadside illumination and one end is toward the source at 90 degrees. The horizontal axis is time. The late bright echo isolated from other features between about 35 and 65 degrees is a feature that is enhanced by proximity of the cylinder to a free surface. The enhancement remains even when the cylinder is raised so as to contact the free surface but it is significantly reduced for a sufficiently deep cylinder.