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Final Technical Report for Office of Naval Research grant N000141912039

December 2022

Acoustic Scattering Experiments and Models

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I. Summary: Objectives of this project include improving methods for acquiring acoustical signatures of targets in water and models for understanding such signatures and methods of extracting, displaying, and using signatures. One of the approaches in the proposed research concerns aspects of target responses to acoustic radiation forces of focused sound beams. This component involves laboratory experiments and development of underlying theory. Other components of the research concern complications resulting from target proximity to interfaces or target placement in waveguides. Aspects of the research involve elastic responses of targets at high frequencies and associated signature contributions. Related aspects concern the transmission of sound through the walls of targets and associated contributions to signatures and acoustical images. These include laboratory-based tests. This research should aid in discriminating between natural acoustic clutter and man-made objects of interest. Thus the research is relevant to improving the use of acoustic scattering for object identification and improving naval capabilities.

II. Introduction and Organization of this Report: (a) Most of the grant resources were used to support the activities of graduate students. One way to summarize the results of those activities is to list the associated Dissertations including the information concerning where those are abstracted and archived. That list is included in this report. (b) Another way to summarize the results of some of the activities is to list the journal publications and associated links. (c) A third way of summarizing the research is to compile in sequence the Annual Reports submitted to ONR in 2019, 2020, 2021, and 2022. Those Annual Reports provide additional background information and are reproduced here in the from required at the time of submission.

III. Information on Ph.D. dissertations completed between 2019 and 2022:

[1] Title of Ph.D. Dissertation by Timothy Daniel (2019)
I. Harmonic Stress excitation of modes of solid objects
II. Analysis and scattering of focused acoustic beams
III. High frequency scattering by truncated solid cylinders
Ph. D. dissertation (Washington State University, Pullman, WA, July 2019).

This Dissertation was also supported in part by ONR Award N000141512603 to Philip L. Marston, P. I. Dissertation Abstract and archive URL:
https://hdl.handle.net/2376/111572

[2] Title of Ph.D. Dissertation by Auberry Renaud Fortuner (2021)
I. Acoustic Line-Scan Imaging of Interface Scattering Effects
II. Spectral Analysis of Scattering from Elastic Spherical Shells in Water
III. Testing of Low-Frequency Elastic Modes
Ph. D. dissertation (Washington State University, Pullman, WA, 2021).

This Dissertation was also supported in part by ONR Award N000141512603 to Philip L. Marston, P. I. Dissertation Abstract and archive URL:
https://doi.org/10.7273/000002462

[3] Title of Ph.D. Dissertation by Bernard Richard Hall (2022)
Exploring High and Mid-Frequency Elastic Mechanisms in Acoustically Illuminated Targets in Water
Ph. D. dissertation (Washington State University, Pullman, WA, May 2022).

Dissertation archive URL is currently unavailable. The URL and abstract will be listed at:
https://rex.libraries.wsu.edu/esploro/

IV. List of Journal Publications and Associated Links

A. Peer Reviewed:

1] P. L. Marston, "Phase-shift derivation of expansions for material and frequency dependence of progressive-wave radiation forces and backscattering by spheres," J. Acoust. Soc. Am., 145, EL39–EL44 (2019); https://doi.org/10.1121/1.5087646 -- *Open Access*

2] P. L. Marston, "Scattering and radiation force dependence on properties of empty elastic spherical shells: Low-frequency phase-shift derivation," J. Acoust. Soc. Am., 146, EL145-EL150 (2019); https://doi.org/10.1121/1.5121576 -- *Open Access*

3] P. L. Marston, 'Comment on "Acoustic deformation for the extraction of mechanical properties of lipid vesicle populations",' Phys. Rev. E 100, 057001 (2019); https://doi.org/10.1103/PhysRevE.100.057001

4] P. L. Marston, "Comment on oscillatory optical and acoustical radiation pressure," Journal of Quantitative Spectroscopy & Radiative Transfer 254, 107226 (2020); https://doi.org/10.1016/j.jqsrt.2020.107226

5] V. Bollen & P. L. Marston, "Phase and amplitude evolution of backscattering by a sphere scanned through an acoustic vortex beam: measured helicity projections," J. Acoust. Soc. Am., 148, EL135-EL140 (2020); https://doi.org/10.1121/10.0001697 -- *Open Access*
Erratum: J. Acoust. Soc. Am., 148, 1784 (2020); https://doi.org/10.1121/10.0002100 -- *Open Access*

6] S. M. Smith, T. D. Daniel, & P. L. Marston, "Maxwell stress excitation of wire vibrations at difference and sum frequencies of electric currents in separate circuits," J. Acoust. Soc. Am., 148, 1808–1816 (2020); https://doi.org/10.1121/10.0002104

7] G. C. Eastland & P. L. Marston, "Time evolution of bistatic acoustic scattering: mechanism loci identification for broadside cylinder near a flat interface," IEEE Journal of Oceanic Engineering 46, 1024-1033 (2021); https://doi.org/10.1109/JOE.2020.3028675

8] P. L. Marston, T. D. Daniel, A. R. Fortuner, I. P. Kirsteins, & A. T. Abawi, "Specular-reflection contributions to static and dynamic radiation forces on circular cylinders," J. Acoust. Soc. Am. 149, 3042-3051 (2021); https://doi.org/10.1121/10.0004304

9] P. L. Marston, T. D. Daniel, & A. R. Fortuner, "Specular reflection contributions to dynamic radiation forces on highly reflecting spheres (L)," J. Acoust. Soc. Am. 150, 25-28 (2021); https://doi.org/10.1121/10.0005438

10] P. L. Marston & A. R. Fortuner, "Radiation forces on highly reflecting circular cylinders in two slanted plane waves: specular-reflection contributions," J. Acoust. Soc. Am. 152, 1337–1344 (2022); https://doi.org/10.1121/10.0013828

11] B. R. Hall & P. L. Marston, "Backscattering by a tilted intermediate thickness cylindrical metal empty shell in water," JASA Express Letters 2, 114001 (2022); https://doi.org/10.1121/10.0015069 -- *Open Access*

B. Conference Publication (may have required only Editorial Review):

1] T. D. Daniel & P. L. Marston, "Modification of the time, frequency, and sonar image domain signatures of cylinders due to a material junction," Proceedings of Meetings on Acoustics 40, 045001 (2020); https://doi.org/10.1121/2.0001333 -- *Open Access*

C. Peer Reviewed but associated only with prior ONR support from a much earlier period:

1] P. L. Marston & M. I. Mishchenko, “Scattering by relatively small oblate spheroidal drops of water in the rainbow region: T-matrix results and geometric interpretation,” Journal of Quantitative Spectroscopy & Radiative Transfer 283, 108142 (2022); https://doi.org/10.1016/j.jqsrt.2022.108142

D. Note on conference abstracts: These are Open Access and are listed with the Annual Reports

V. Annual Reports submitted to ONR in 2019, 2020, 2021, and 2022

Contract Number: N000141912039

Title: Acoustic Scattering Experiments and Models

Major Goals:

The main objective of this project is to improve methods for acquiring acoustical signatures of targets in water and to improve models for understanding such signatures and methods of extracting, displaying, and using signatures. One of our approaches concerns aspects of low-frequency target responses to modulated acoustic radiation forces (MARF) of focused sound beams. These include methods for identifying the shape as well as the frequency of a mode of a particular target in the presence of other objects. This component involves laboratory experiments and development of underlying theory (which includes radiation force and focused beam theory as well as issues related to target response). In some cases it may be helpful to use time-dependent electromagnetic Maxwell stresses (instead of MARF) to excite a given target mode to be acoustically detected. Other components of the research concern complications resulting from target proximity to interfaces or target placement in waveguides. Aspects of the research involve elastic responses of targets at high frequencies and associated signature contributions. In the case of man-made shells the responses reveal material composition and shell thickness. Related aspects concern the transmission of sound through the walls of targets and associated contributions to signatures and acoustical images. These include laboratory-based tests.

This research should aid in discriminating between natural acoustic clutter and man-made objects of interest. Thus the research is relevant to improving the use of acoustic scattering for object identification and improving naval capabilities.

Some additional background information is available in the report for the now-depleted prior grant: N000141512603.

Accomplishments Under Goals:

Note: The emphasis of this summary is on developments subsequent to the start-date of this award (12/15/2018). For prior activities see the report for N000141512603. In some cases reports on the prior award may be consulted for background information.

A.Target response to modulated acoustic radiation forces: An important accomplishment is the archiving of Timothy Daniel's experimental and theoretical results in his Ph.D. dissertation (submitted May 2019). Important experiments subsequent to the start of this grant include: (a) Assembly and testing of second lens mount design (Lens-2) for the generation of modulated focused ultrasound beams. The design allows for greater depth in the water and relatively remote operation (Fig. 1). The beam had the expected focal properties. (b) Verification of substantial target response to modulated acoustic radiation force (MARF): Since a laser vibrometer was not available, tests with Lens 2 were restricted to hydrophone measurements of target response. Fig. 2 shows that a very large SNR is achievable for resonance excitation. The double-sideband-suppressed-carrier method of generating ultrasonic radiation force oscillations at a single frequency is discussed in [1]. (c) Supplemental hydrophone measurements were carried out by Auberry Fortuner to confirm proper hydrophone operation.

B.High-frequency and wide-bandwidth scattering measurements and/or calculations for shells: (a) Backwards waves: Bernard Hall continued his investigation of backwards-wave scattering processes useful for revealing the thickness of a shell studied originally at WSU on spheres [2]. Hall's investigation includes improved measurements for an empty acrylic (PMMA) cylindrical shell and preliminary measurements with an empty cylindrical aluminum shell (Fig. 3). Both confirm the backscattering enhancement for which the frequency determines the shell thickness. Hall has also improved computational and theoretical models of this process. Preliminary measurements in the water-filled aluminum-shell case confirm the enhancement is present in that case also. (b) Understanding bistatic scattering by shells: Bistatic mechanisms can be important for objects near interfaces as a consequence of grazing reflection from the surface. Auberry Fortuner has extended to shells a method previously developed at WSU and APL-UW for displaying the global bistatic scattering properties of solid spheres and cylinders [3]. As with the prior analysis the cause of the global spectral features (as a function of the bistatic scattering angle) is explained using ray theory. This way of interpreting the structure involves the computation of guided wave properties for the shell as well as constructive and destructive interference loci with the specular reflection. See Fig. 4.

C.Other Scattering Physics for Targets Adjacent to Flat Surfaces: As part of Auberry Fortuner's approach to this situation, he has devised a way of quantitatively extracting multiple scattering contributions from line-scan holographically constructed images. (This is a convenient form of reversible processing and masking developed at WSU.) He has successfully demonstrated this method for echoes from a sphere close to a free surface. This supports a simple geometric approximation for the earliest surface-reflection multiple-scattering contribution (Fig. 5).

D.Other calculations in support of radiation force and scattering physics effort: (a) Timothy Daniel applied his prior method of computing focused wave-fields [4] to the analysis of the scattering by a rigid sphere in such a wave-field. The emphasis was on the high ka case where the results could be compared and confirmed with geometrically-based physical-optics models incorporating Fresnel integrals. The physics-based approximations for the shadow-boundary structure support the exact results. This approach may be useful for radiation force calculations pertinent to our goals. (b) Expansion of radiation forces and scattering by spheres based on scattering phase shifts: In prior publications in 2017 Marston showed some advantages of using expansions based on scattering phase shifts for extracting the material dependence of standing-wave acoustic radiation forces. In his recent publication [5] he shows how to apply this method to traveling-wave radiation forces and backscattering where coefficients are known for fluid and solid spheres.

References & Selected Publications:

[1] PL Marston (PLM) & RE Apfel, J. Acoust. Soc. Am. 67, 27-37 (1980); https://doi.org/10.1121/1.383738
[2] G Kaduchak, DH Hughes, & PLM, "Enhancement of the backscattering of high-frequency tone bursts by thin spherical shells associated with a backwards wave: Observations and ray approximation," J. Acoust. Soc. Am. 96, 3704-3714 (1994).
[3] AM Gunderson, AL España, & PLM, "Spectral analysis of bistatic scattering from underwater elastic cylinders and spheres," J. Acoust. Soc. Am. 142, 110–115 (2017); https://doi.org/10.1121/1.4990690
[4] TD Daniel, F Gittes, IP Kirsteins & PLM, "Bessel beam expansion of linear focused ultrasound," J. Acoust. Soc. Am., 144, 3076–3083 (2018). https://doi.org/10.1121/1.5080602
[5] PLM, "Phase-shift derivation of expansions for material and frequency dependence of progressive-wave radiation forces and backscattering by spheres," J. Acoust. Soc. Am., 145, EL39–EL44 (2019); https://doi.org/10.1121/1.5087646

Training Opportunities:

A. Graduate student research participant supported entirely or in part by this grant during this period include:
(1) T. Daniel (Ph. D candidate)
(2) A. Fortuner (Ph. D candidate)
(3) B. Hall (Ph. D candidate)
B. Undergraduate student research participants:
(1) S. Smith
(2) J. C. Stotts
C. Discussion & Details:
All of these students were mentored by the PI (Marston) though Smith & Stotts were partially mentored by Daniel & Fortuner. Hall completed the final stage of his Ph. D. candidacy process. He also completed his MS Thesis on signal processing of gravitational-radiation signals. Smith & Stotts took undergraduate science & math classes and contributed to scattering experiments & related data processing.
D. Acoustical Society of America Attendance by Students:
In early May 2019 this grant supported one graduate student (Daniel) to attend the Acoustical Society of America Spring 2019 meeting. Note: both T. Daniel and A. Fortuner have attended one or more meetings of the Acoustical Society of America through the support of ONR.
E. This grant also helped make it possible for a graduate student (Daniel) to make acoustics research presentations in spring 2019 at:
NRL-Stennis, NSWC-PCD, & NRL-DC.

Results Dissemination

Note: This summary refers to activities beginning with the start-date of this award (12/15/2018). For prior activities see the report for N000141512603.

A. Publications appearing during the period of this report include:
[1] Philip L Marston (PLM), "Phase-shift derivation of expansions for material and frequency dependence of progressive-wave radiation forces and backscattering by spheres," J. Acoust. Soc. Am., 145, EL39-EL44 (2019); https://doi.org/10.1121/1.5087646

B. Professional Conference Presentations during this period:
[1] Timothy Daniel & PLM, "Identifying Acoustic Scattering Mechanisms for Tilted Solid Cylinders in Water by Comparing Ray Theory with Multi-domain Processing," Paper & Abstract MS289, SIAM Conference on Computational Science and Engineering, Spokane WA, February 2019:
https://www.siam.org/Portals/0/Conferences/cse19/CSE19_Program_with_abstracts.pdf
[2] TD Daniel and PLM, "Scattering of focused beams by spheres: Understanding the high-frequency angular structure," J. Acoust. Soc. Am. 145, 1692 (2019), https://doi.org/10.1121/1.5101203
[3] TD Daniel, Ivars P. Kirsteins, Ahmad T. Abawi, and PLM, "A focused lens for measuring object response to modulated radiation pressure," J. Acoust. Soc. Am. 145, 1692 (2019), https://doi.org/10.1121/1.5101205

C. Ph. D. Dissertations:
Timothy Derek Daniel, Jr.
Title:
I. Harmonic Stress Excitation of Modes of Solid Objects
II. Analysis and Scattering of Focused Acoustic Beams
III. High Frequency Scattering by Truncated Solid Cylinders
(Washington State University, Pullman, Submitted May 2019)
Abstract:
This work covers three main topics. First is the excitation of elastic modes of solid objects using localized harmonic stresses. Both radiation and Maxwell stresses were used as an exciting mechanism. These are analogous techniques taking advantage of either amplitude modulated focused acoustic fields or oscillating magnetic fields to produce harmonic stresses on various objects. The oscillation frequency and spatial location of the resulting stresses is tuned to selectively excite the elastic modes in various objects. This technique can be used to investigate the mode shape of the target, information that is not available with typical techniques like plane wave sonar. The second part of this work focuses on methods of describing, analytically, focused sound fields and the scattering of objects in these fields. Using a geometric propagation model close to the source of sound facilitates the calculation of expansion coefficients. The coefficients allow the focused sound field to be represented by a superposition of Bessel beams. We can use this representation to solve analytically the scattering by spheres in a focused field. This description provides a frame work for future work in analytically describing the force on an object in a focused beam. The final part of this thesis discusses high frequency scattering by solid cylinders with material junction. Solid cylinders have enhanced back scattering associated with a merdional wave, a Rayleigh wave launched down the axis of the cylinder. We investigate how a material junction changes this back scattering signature. This change is investigated in the time, frequency, and image domains.

Plans Next Reporting Period

A. Target response to Modulated Acoustic Radiation Force: We plan additional tests of Lens 2 and to attempt measurements of low-frequency target modes for the first time in WSU's 5500 gallon facility. Timothy Daniel will be passing off his knowledge to current students at WSU.
B.High-frequency and wide-bandwidth scattering measurements and/or calculations for shells: (a) Bernard Hall plans to improve his models and measurements, including the case of liquid-filled shells. Model testing will include quantitative ray theory and computational as well as experimental tests. (c) Auberry Fortuner plans to extend and document his computational results.
C.Other Scattering Physics for Targets Adjacent to Flat Surfaces: Auberry Fortuner hopes to quantify any limitations on his models previously summarized.
D.Other calculations in support of radiation force and scattering physics effort: (a) additional documentation of Timothy Daniel method of computing scattering of focused beams may be possible. (b) Marston would like to extend the range of target properties for which his method of expanding radiation forces and scattering may be used.
E.Supplemental experiments: (a) Additional multiple scattering measurements at WSU have been suggested by APL-UW as helpful for scattering-model development. (b) Some new Maxwell-stress methods for the

selective excitation of Low-Frequency target modes are planned at WSU. S. Smith is involved with the modulated Maxwell-stress experiments.

Honors and Awards

Nothing to Report

Protocol Activity Status

Technology Transfer

Note: Summary refers to activities beginning with the start-date of this award (12/15/2018). For prior activities see the report for N000141512603.
(1) DoD research personnel currently associated with aspects of this Washington State University (WSU) based project:
Ivars P Kirsteins (NUWC, Newport, RI) —Visits WSU for experiments and interacts with students annually (visited in March 2019).
(2) DoD funded research personnel currently associated with aspects of this WSU based project:
(a) Ahmad T. Abawi (HLS, Res., La Jolla, CA) —Visits WSU for experiments and interacts with students annually (visited in March 2019).
(b) Timothy M. Marston (Applied Physics Lab., Univ. of Washington, Seattle) —Visits WSU and/or interacts with current WSU students approximately semiannually.
(c) Aubrey L Espana, Daniel S. Plotnick, Kevin L. Williams and Steven G. Kargl (Applied Physics Lab., Univ. of Washington, Seattle)— Former WSU graduate students who visit occasionally and make helpful suggestions to current WSU students.
(3) Other Technology Transfer mechanisms:
Timothy Daniel (one of the supported Research Assistants) during the period of this report made research presentations of results at NRL-Stennis, NSWC-PCD, and NRL-DC.

Distribution Statement:

Approved for public release; distribution is unlimited.

Participants

First Name: Philip **Last Name:** Marston

Project Role: PD/PI

National Academy Member: N **Months Worked:** 2

Countries of Collaboration

Fig. 1: Left & Right: Diffraction-limited ultrasonic lens and source corrected for spherical aberration. The lens material is a low-loss solid polymer. The focal length is 150 mm and the outer diameter of the lens element is 3.44 inches. This ruggedized mount and driver combination is designated as Lens-2. It is driven by an internal flat piezoceramic-circular-disc having a 350 kHz thickness mode. It is powered through a sealed removable connector & cable visible on the lower right.

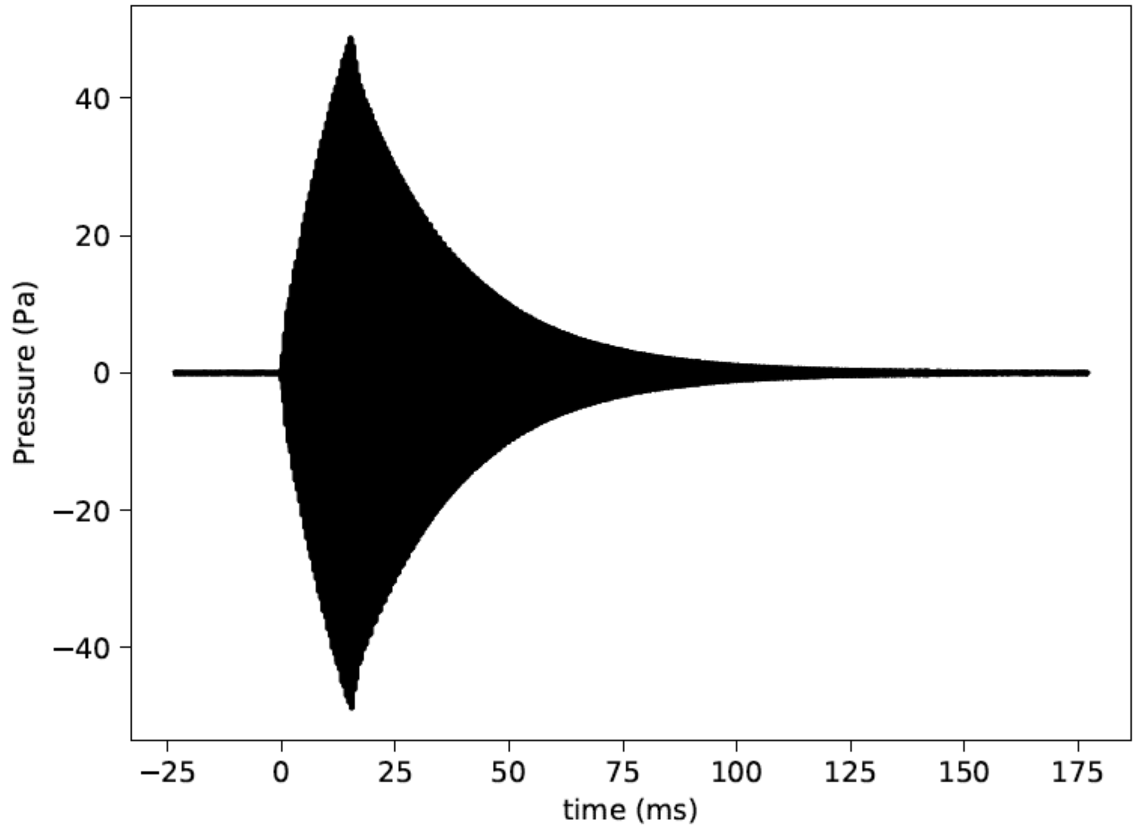

Fig. 2: This figure shows the evolution of a hydrophone signal (converted to acoustic pressure) for a circular aluminum plate hung in water with modulated ultrasound focused on the plate by Lens-2 (shown in Fig. 1). The excitation is a double-sideband-suppressed-carrier (DSSC) tone-burst adjusted to excite a mode of the plate at 1.956 kHz. (The tone burst duration corresponds to 30 cycles of excitation at the mode frequency.) The record displaces the ring-up excitation of the plate mode during the driven phase, followed by a long-slow-ring-down of the mode after the excitation has ceased. The signal-to-noise ratio is excellent. The hydrophone was in the water tank near the plate. The data was acquired at WSU.

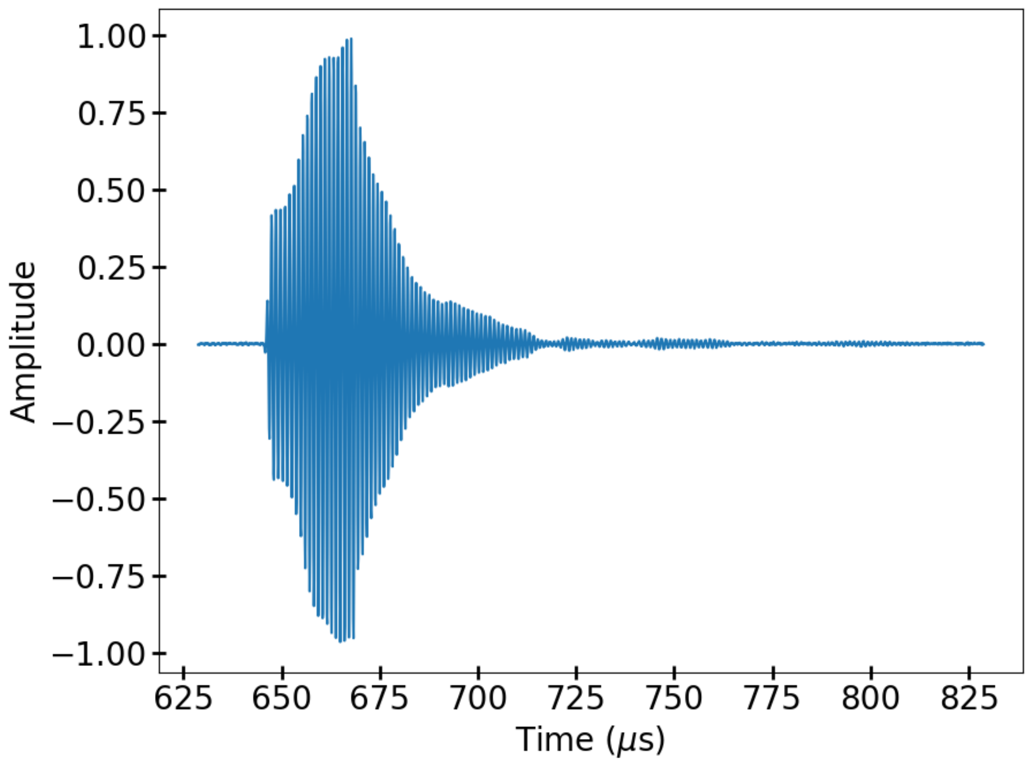

Fig. 3: Backscattering of a 892 kHz 20-cycle-long tone-burst by an empty 2.25-inch dia. aluminum cylindrical shell in water viewed broadside. There is an initial specular-reflection response followed by a gradual buildup of an elastic-echo contribution. That is followed by a long ring-down (after the end of the incident burst) and indicates a high-Q resonant feature. Both the elastic effects (ring-up and ring-down) are suppressed if the tone-burst frequency is shifted away. The frequency condition for these elastic responses reveals the thickness of the shell. The associated backwards-guided-wave mechanism (previously discovered and studied at WSU for a thin stainless-steel spherical shell [2]) does not require elastic energy to propagate around the rear-side of the shell. If a denotes the outer radius of the shell, for this tone burst and shell combination ka = 108.

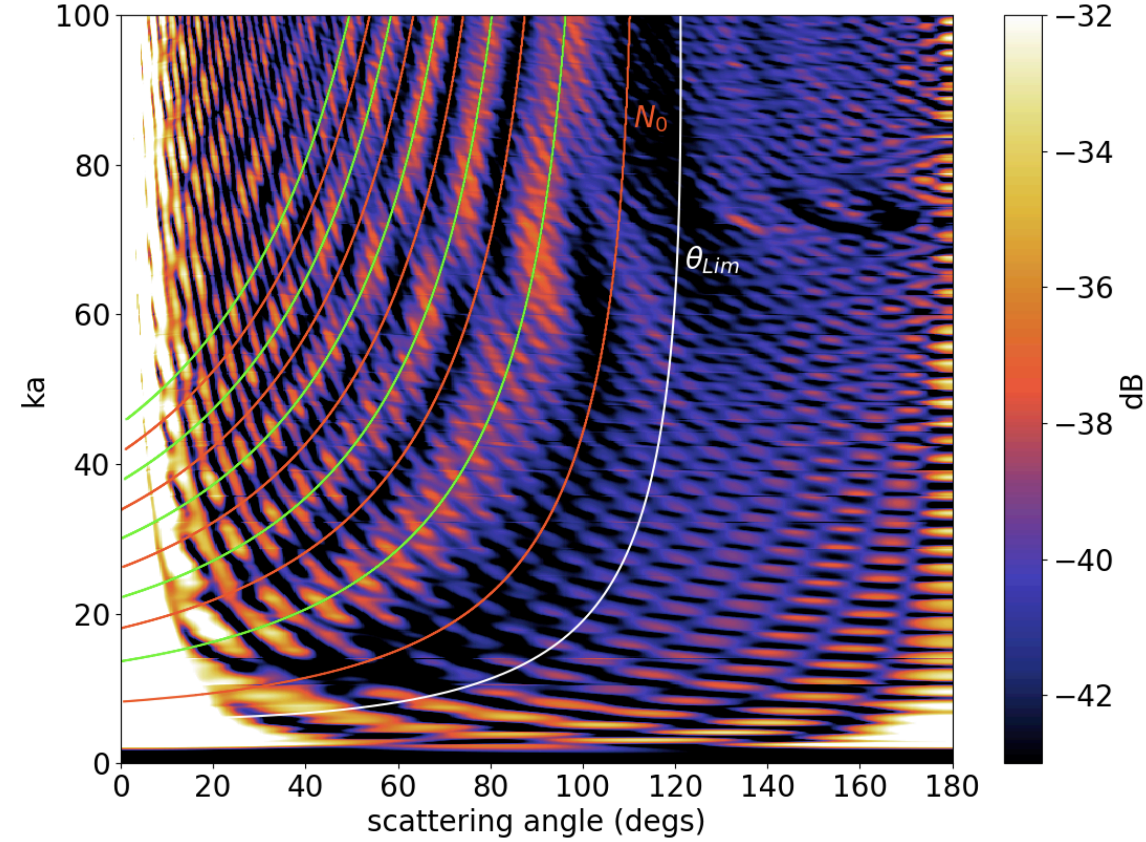

Fig. 4: Computed bistatic scattering, plotted as Target Strength, for a 440-C stainless steel spherical shell in water. The shell is 16.2% thick with an outer radius of 19.05 mm, and has been used in prior experiments at WSU. Superposed on those calculations are curves descriptive of interference between the specular reflection and the a_0 shell-generalized Lamb wave that radiates toward the scattering direction from the same "near-side" of the shell surface as the specular reflection. This way of understanding the structure was previously developed and demonstrated at WSU & UW-APL for solid spheres and cylinders [3]. The present case is more complicated and requires numerical solution of wave dispersion on the shell. The plotted loci are obtained by solving for the condition of interference between the ray paths of the specular and a_0 Lamb waves. The orange and green curves represent destructive and constructive interference respectively, with N_0 representing the first condition for destructive interference. The white curve represents the *maximum* scattering angle, for a given dimensionless frequency k*a*, that allows the a_0 Lamb wave to scatter from the "near-side" without having to circumnavigate the back side of the shell. That condition is curved due to the frequency dependence of the coupling angle for the a_0 Lamb wave caused by dispersion. Some other structure present at large ka is associated with a different generalized Lamb wave.

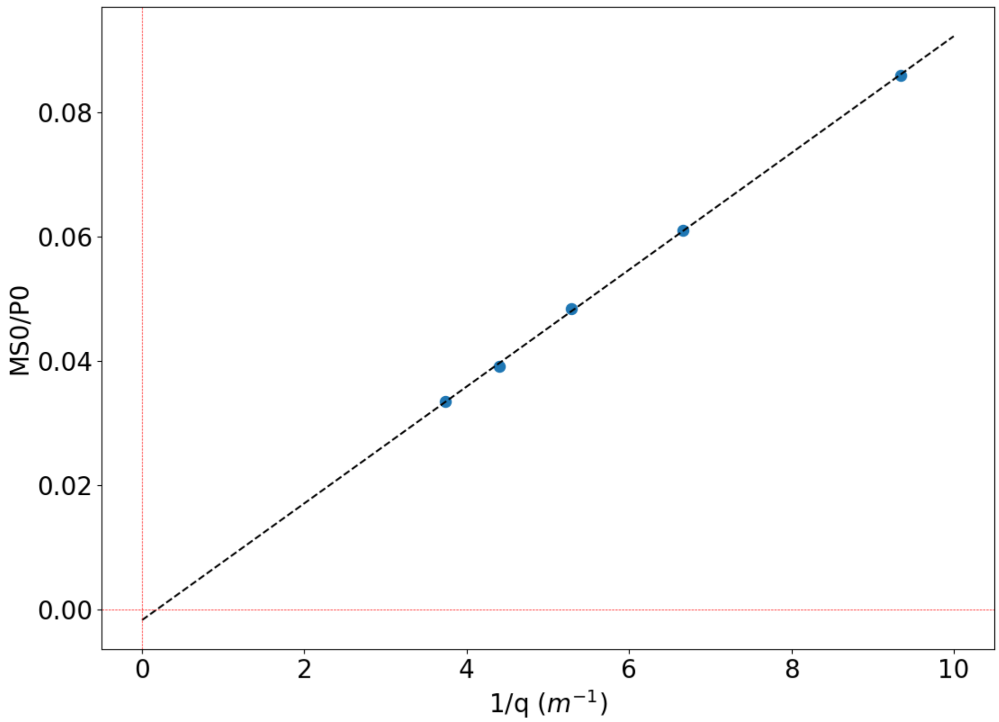

Fig. 5: Comparison of the measured amplitudes of direct Specular Reflection (designated as P0) from a sphere and the earliest Multiple-Scattering contribution (designated as MS0) between the sphere and an adjacent free surface. The MSO signal reflected first off the sphere followed by a reflection off of the flat surface followed by a second reflection off the sphere's curved surface. The results are from a measurement of the monostatic scattering by a sphere near a flat water-surface while vertically linearly scanning the transducer. Each scan is repeated for varying target depth resulting in different distances between the target and the water surface. The resulting Quasi-Holographic LSAS images separate the P0 and MS0 scattering contributions as distinct focused peaks in each image. The MS0 scattering amplitude is expected to scale with the inverse of twice the target depth due to the spherical spreading between the target and water surface. The ratio of the image peak values between MS0 and P0 are plotted here as a function of 1/q, where q=2H is the distance between the target and its image, with H being the depth of the target center from the water surface. The line is the best-two-parameter fit.

N000141912039 : Acoustic Scattering Experiments and Models

Reporting Period: JUN 16, 2019 to JUN 15, 2020

Date Received: 2020-05-27 22:24:44.0

Submitter: Philip Marston

Major Goals

The main objective of this project is to improve methods for acquiring acoustical signatures of targets in water and to improve models for understanding such signatures and methods of extracting, displaying, and using signatures. One of our approaches concerns aspects of low-frequency target responses to modulated acoustic radiation forces (MARF) of focused sound beams. These include methods for identifying the shape as well as the frequency of a mode of a particular target in the presence of other objects. This component involves laboratory experiments and development of underlying theory (which includes radiation force and focused beam theory as well as issues related to target response). In some cases it may be helpful to use time-dependent electromagnetic Maxwell stresses (instead of MARF) to excite a given target mode to be acoustically detected. Other components of the research concern complications resulting from target proximity to interfaces or target placement in waveguides. Aspects of the research involve elastic responses of targets at high frequencies and associated signature contributions and ray theory. In the case of man-made shells the responses reveal material composition and shell thickness. Related computational investigations include a better understanding of how shell thickness affects the target echoes. Related aspects concern the transmission of sound through the walls of targets and associated contributions to signatures and acoustical images. These include laboratory-based tests.

This research should aid in discriminating between natural acoustic clutter and man-made objects of interest. Thus the research is relevant to improving the use of acoustic scattering for object identification and improving naval capabilities.

Some additional background information is available in: (a) the prior Annual Report for this grant, and (b) the Final Technical Report for the expired prior grant N000141512603 (DTIC Report AD1093528 by P. L. Marston),

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Accomplishments Under Goals

The emphasis of this summary is on developments subsequent to the prior Annual Report (submitted in May 2019). A. TARGET RESPONSE TO MODULATED ACOUSTIC RADIATION FORCES (MARF) & MAXWELL STRESSES: Since all of the MARF measurements described in T. Daniel’s thesis [1] & our related work [2] were made in a 180-gallon small tank (ST), it appeared desirable to transition to a larger tank (LT): the WSU 12 ft diameter x 7.5 ft deep facility. This task was started by A. Fortuner in stages: (a) First it was desirable to test tank floor coverings in the ST since it is undesirable to put a sand bottom in the LT. The intent was to find a material that targets could stably rest on that would have some sea floor like properties. In addition, it was desirable to test a wider selection of targets. A bumpy polymer floor covering was introduced and tested in the ST, and subsequently transferred to the LT. Modes were Maxwell-stress magnetically excited and acoustically recorded for proud targets, an example is shown in Fig. 1. (b) Much of August and

September and parts of October 2019 were devoted to LT measurements of MARF target responses. This required introducing ways to scan the location of a focused source near targets on the LT floor and in some cases scan a hydrophone. Fortuner developed new ways to mount sources & hydrophones. With the hydrophone near a solid cylinder prior results for identifying mode shape from source scanned were confirmed. See Fig. 2. (c) A significant complication in the LT environment is the complication of wall reverberation and long-time-scale tank modes that were not an issue in ST measurements. Various configurations were tested with targets on the bumpy polymer floor, but this issue was not fully resolved. (d) To gain a better understanding of the complications of tank reverberations it was decided to investigate the MARF response of a tethered stainless-steel spherical shell suspended away from the tank walls. Measurements with various target and hydrophone locations reveal that radiation by the sphere reflects from the curved wall of the LT in such a way as to generate focused wall echoes of appreciable magnitude. Measurements were started to help determine if favorable use could be made of this effect to detect and isolate MARF responses. University regulations and recommendations introduced in March 2020 in response to the COVID crisis have hampered progress though computational aspects have been explored. B. WIDE-BANDWIDTH SCATTERING MEASUREMENTS, RAY-THEORY AND/OR CALCULATIONS FOR SHELLS: (a) As noted in the prior Annual Report, Fortuner began a computational study of bistatic scattering properties of spherical shells with the overall objective of obtaining a broader perspective on phenomena. He presented aspects of that work [3] and of his shell boundary related scattering experiments [4] at the fall 2019 ASA meeting. He also carried out a computational investigation of backscattering by empty spherical shells of different wall thicknesses and material composition to get a better understanding of the normalized frequency (ka) dependence of the Target Strength (TS) for different thicknesses. An example is shown in Fig. 3. In related computational work the significance of various enhancement loci have been identified. (b) Bernard Hall has been continuing to investigate scattering by empty & water-filled cylindrical shells [5]. During parts of the year when experimental facilities were available, he carried out high-frequency measurements of elastic contributions for metal shells differing in composition. The emphasis was initially on a high-frequency backscattering enhancement discussed in prior reports for an acrylic (PMMA) shell, associated in part with thickness reverberations and in part with backwards waves. He also carried out computational and modeling studies for other guided waves, some of which are still in progress. Figure 4 shows examples of measured backscattering echoes for an empty metal shell in which the elastic waves that circumnavigate the shell were identified using ray theory. (c) During these investigations it appeared appropriate to get a better understanding of what is sometimes described as the mid-frequency enhancement previously modeled using ray theory for thin shells. In Hall's investigation an improved understanding of the relatively thick shell situation is needed (such as for capped empty shells that naturally sink). Soon after this became evident the COVID restrictions were in place so that at the time of this writing Hall has only been able to do computational studies. Hall has been able to confirm that a generalization of the prior ray theory is helpful in explaining some of the computed thick-shell mid-frequency scattering processes. Figure 5 shows a ray theory model of the magnitude of one of those contributions. C. OTHER TARGET PHYSICS FOR TARGETS ADJACENT TO FLAT SURFACES & MULTIPLE SCATTERING: (a) Auberry Fortuner presented some of his results on quantitatively extracting multiple scattering contributions for a spherical shell next to a free surface using line-scan holographically constructed images [4]. (b) During summer 2019 with assistance from T. Daniel and A. Fortuner, B. Hall was able to measure backscattering by small parallel aligned solid aluminum cylinders which revealed strong highly frequency-dependent interference & multiple scattering processes. In addition to those highly frequency dependent processes the expected average increase in backscattering was observed. D. EXCITING LOW FREQUENCY VIBRATIONS USING HIGH-FREQUENCY ELECTRIC CURRENTS: During the summer of 2019, Sterling Smith (an undergraduate assistant), with assistance from T. Daniel, investigated a novel electromagnetic mechanism for exciting low frequency vibrations of a structure (a tight metal wire) using only high-frequency oscillating electric currents & associated magnetic fields. This method may prove applicable to situations where it is not advisable to use low-frequency magnetic fields. In addition some radiation force & scattering hybrid experiments were started by undergraduate students, Smith & J. C. Stotts, in January & February 2020 but were stopped due to COVID regulations. E. RADIATION FORCE & SCATTERING THEORY PUBLICATIONS: Marston published two different radiation force and scattering papers. The first of these concerned extending prior expansions based on powers of ka to include significant higher-order terms for spherical shells [6]. The other concerned the deformation of spherical objects induced by radiation pressure in relation to Marston's prior publications from the 1980s & 1990s [7]. F. COLLABORATION WITH T. D. DANIEL AT NSWC-PCD: Following Dr. Daniel's departure from WSU in Aug. 2019 to commence research at NSWC-PCD, it has been mutually advantageous to continue research interactions related to scattering (concerning experiments & WSU models) and acoustic beams (extensions of [8]). REFERENCES & SELECTED PUBLICATIONS OR ABSTRACTS: [1] T. D. Daniel, Ph. D. Thesis (Washington State University, May 2019), abstracted in prior report. [2] A. T. Abawi, I. P. Kirsteins (IPK), P. L. Marston (PLM), and T. D. Daniel (TDD), 146, 3019(A) (2019). [3] A. R. Fortuner (ARF) & PLM, J. Acoust. Soc. Am. 146, 2796(A) (2019). [4] ARF & PLM, J. Acoust. Soc. Am. 146, 2796(A) (2019). [5] B. R. Hall & PLM, J. Acoust. Soc. Am. 146, 2797(A) (2019). [6] PLM, J. Acoust. Soc. Am., 146, EL145-EL150 (2019). [7] PLM, Physical Review E 100, 057001 (2019). [8] TDD, F. Gittes, IPK, & PLM, J. Acoust. Soc. Am., 144, 3076–3083 (2018).

Plans Next Period

GENERAL OBSERVATIONS: Circumstances pertaining to summer 2019 required minor adjustments in the pursuit of research tasks. Unfortunately with the introduction of COVID-induced Washington State University (WSU) regulations and recommendations in March 2020 major adjustments were needed. The regulations and recommendations pertain to access to research facilities, to offices, and to the operation of Technical Services (such as the machine shop) needed for experiment fabrication and maintenance. The authorized procedure for return to normal WSU laboratory and office access is not available as of the time of this writing. Consequently the establishment of definite research plans remains difficult, especially concerning all experiments. Interactive research related to theory has also become less efficient given the suppression of face-to-face interactions and all in-office interactions. The ideal plans shown below modify those of the prior report with some adjustments in the direction of theory and computation. Additional adjustments will likely be appropriate. The situation becomes even more complicated because of requirements placed on students for the completion of earned degrees. There has been a greater emphasis now on reading research papers instead of doing experiments.

PLANS & TOPICS: A. Target response to Modulated Acoustic Radiation Force: We plan additional tests of Lens 2 (see prior report) and to continue to attempt measurements of low-frequency LF target modes in WSU's 5500 gallon large tank (LT) facility. This will likely involve continued exploration of possible beneficial focusing of delayed low-frequency responses by the curved tank walls. A wider range of targets may be explored. Additional modeling could be difficult but helpful. B. Target response to Modulated Acoustic Radiation Force: If Timothy Daniel finds time at his current NSWC-PCD research position, it could be helpful to publish the results of the WSU small tank (ST) experiments. C. High-frequency and wide-bandwidth scattering measurements and/or calculations for shells: (a) Bernard Hall plans to continue to extend the frequency range and improve his ray models and measurements. He may include the case of liquid-filled shells. Eventually he will need access to the large tank (LT) facility since most of his experiments were in the ST facility. We hope he can transition to tilted cylindrical shells &/or cylindrical shells near surfaces. (c) Auberry Fortuner plans to extend and document his computational results concerning spherical shells. D. Other Scattering Physics for Targets Adjacent to Flat Surfaces: Auberry Fortuner hopes to quantify any limitations on his models previously summarized. E. Other calculations in support of radiation force and scattering physics effort: (a) Additional documentation of Timothy Daniel's method of computing scattering of focused beams may be possible. (b) Marston would like to extend his method of expanding radiation forces and scattering and to document related prior results & applications. (For example Marston recently discovered a new way for evaluating integrals related to radiation force & scattering.) F. S. Smith has been working on documenting his work (with T. Daniel) on Maxwell-stress methods for the selective excitation of LF modes. This will be Smith's Senior Thesis. G. Marston & T. Daniel find it mutually advantageous to continue research interactions related to scattering (concerning experiments & WSU models) and acoustic beams. This also involves applications of scattering-related computational resources previously developed at WSU. H. Supplemental experiments: (a) Multiple-scattering measurements were made in 2019 at WSU helpful for APL-UW scattering-model development. If the large tank becomes available, these could be extended if needed. (b) Early in 2020 some undergraduate students started some hybrid acoustic radiation force light scattering experiments that were discontinued due to COVID restrictions. Under favorable circumstances these could resume since it could become a suitable Senior Thesis project.

Results Dissemination

A. Publications appearing during the period of this report include: [1] Philip L Marston (PLM), "Scattering and radiation force dependence on properties of empty elastic spherical shells: Low-frequency phase-shift derivation," J. Acoust. Soc. Am., 146, EL145-EL150 (2019); https://doi.org/10.1121/1.5121576 [2] PLM, 'Comment on "Acoustic deformation for the extraction of mechanical properties of lipid vesicle populations",' Phys. Rev. E 100, 057001 (2019); https://doi.org/ 10.1103/PhysRevE.100.0570

B. Professional Conference Presentations during this period: [1] PLM, "Acoustic radiation force and scattering series expansions for spheres at low frequencies," 72nd Annual Meeting of the APS Division of Fluid Dynamics, Seattle WA (2019); http://meetings.aps.org/Meeting/DFD19/Session/Q06.1 [2] A. R. Fortuner (ARF) & PLM, "Interference structure in the form function for bistatic scattering from elastic spherical shells in water," J. Acoust. Soc. Am. 146, 2796(A) (2019); 178TH Meeting of the Acoustical Society of America (ASA); https://doi.org/10.1121/1.5136687 [3] ARF & PLM, "Line-scan imaging of monostatic scattering by a sphere near a flat interface: Identification of direct, indirect, and multiple-scattering paths," J. Acoust. Soc. Am. 146, 2796(A) (2019); https://doi.org/10.1121/1.5136684 [4] B. R. Hall & PLM, "High-frequency backscattering enhancements from elastic cylindrical shells in water: Observations and ray theory," J. Acoust. Soc. Am. 146, 2797 (2019); https://doi.org/10.1121/1.5136688 [5] A. T. Abawi, I. P. Kirsteins, PLM, & T. D. Daniel, "Measuring the modal shapes of elastic targets using modulated radiation pressure," J. Acoust. Soc. Am. 146, 3019 (2019); https://doi.org/10.1121/1.5137467

C. Video-Archived Special Public Colloquium: [1] P. L. Marston, "Decades of Acoustical, Optical, & Fluid Wave Physics with Students & Associates," Washington State University (February, 2020): https://www.youtube.com/watch?v=qa9-I1dAvAk&feature=youtu.be Abstract: Following introductory comments concerning a Washington State College Physics MS degree recipient from 1928, selected research from four recent decades will be summarized. Some examples to be considered include the close relationship between optical and acoustical scattering research and the value of understanding short and long wavelength scattering processes. Novel forms of rainbow and glory scattering were discovered. In some cases waves can be simultaneously used to probe and control the shape and position of drops and bubbles and to stabilize liquid columns; investigations outside the laboratory included reduced-gravity aircraft and the Space Shuttle. Related developments concern radiation torque, vortex beams, and tractor beams. In other developments, lessons from short-wavelength scattering experiments were applied to acoustical situations having reduced symmetry, facilitating improved interpretation of acoustical images and signatures of objects in water. Participation of students and program alumni in acoustical field experiments for the remediation of unexploded ordnance (UXO) will be noted.

Honors and Awards

Nothing to Report

Training Opportunities

A. Graduate student research participant supported entirely or in part by this grant during this period include: (1) A. Fortuner (Ph. D candidate), (2) B. Hall (Ph. D candidate) B. Undergraduate student research participants: (1) S. Smith, (2) J. C. Stotts C. PhD-completed-former Graduate student partially supported during part of summer 2019 in compensation for assistance provided: (1) Dr. T. Daniel D. Discussion & Details: All of the students were mentored primarily by the PI (Marston). Hall & Smith were partially mentored by Daniel. Smith & Stotts took undergraduate science & math classes and contributed to acoustics experiments & related data processing. E. Acoustical Society of America Attendance by Students: In early December 2019 this grant supported two graduate students (Fortuner & Hall) to attend the Acoustical Society of America Fall 2019 meeting.

Technology Transfer

(1) DoD research personnel associated with aspects of this Washington State University based project during report period: (a) Ivars P Kirsteins (NUWC, Newport, RI) —Visited for MARF experiments and interacted with students (visited in parts of August & September 2019 in addition to intervals mentioned in prior reports). (b) Timothy D. Daniel (NSWC-PCD): P. Marston has continued frequent interactions concerning scattering research by telephone & email (see Report).

(2) DoD funded research personnel currently associated with aspects of this Washington State University based project: (a) Ahmad T. Abawi (HLS, Res., La Jolla, CA) —Visited for MARF experiments and interacted with students (visited in parts of August & September 2019 in addition to intervals mentioned in prior reports). (b) Timothy M. Marston (Applied Physics Lab., Univ. of Washington, Seattle) —Visits and interacts with students approximately semiannually. P. Marston visited at APL for scattering discussions November 2019. (c) Aubry L Espana (Applied Physics Lab., Univ. of Washington, Seattle)—Former WSU graduate student. Provided with WSU multiple scattering experimental results from Summer 2019. (d) Kevin L. Williams and Steven G. Kargl (Applied Physics Lab., Univ. of Washington, Seattle)— Former WSU graduate students who visit occasionally and make helpful suggestions to students. P. Marston visited at APL for scattering discussions November 2019.

Participants

Name	Role	Person Months
Fortuner, Auberry	Graduate Student (research assistant)	6
Hall, Bernard	Graduate Student (research assistant)	6

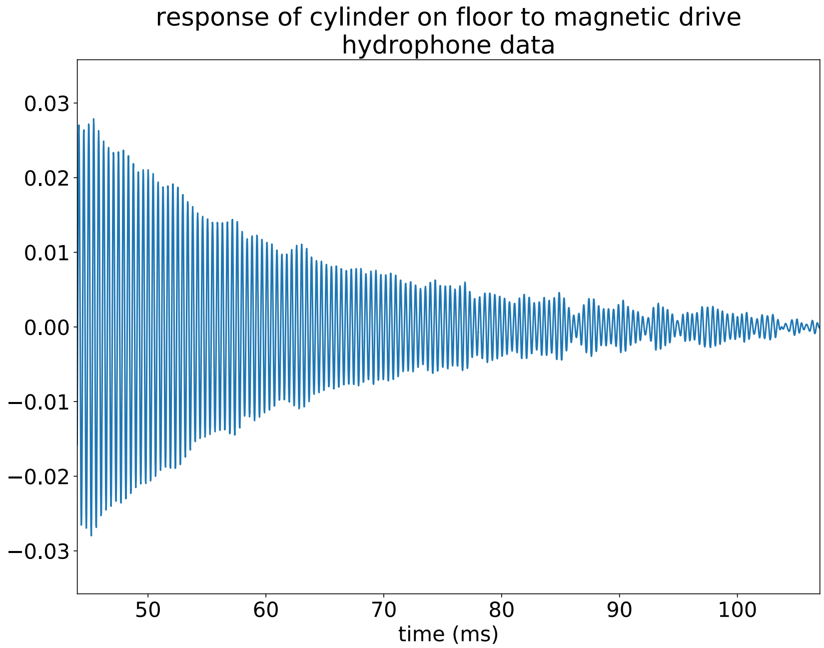

Fig. 1: Modulated Maxwell stress excitation and free decays of vibrations of a mode of a solid stainless-steel cylinder in water resting proud on a bumpy polymer floor. The amplified hydrophone record is shown for a time interval following the termination of the resonant excitation of an elastic mode of the cylinder.

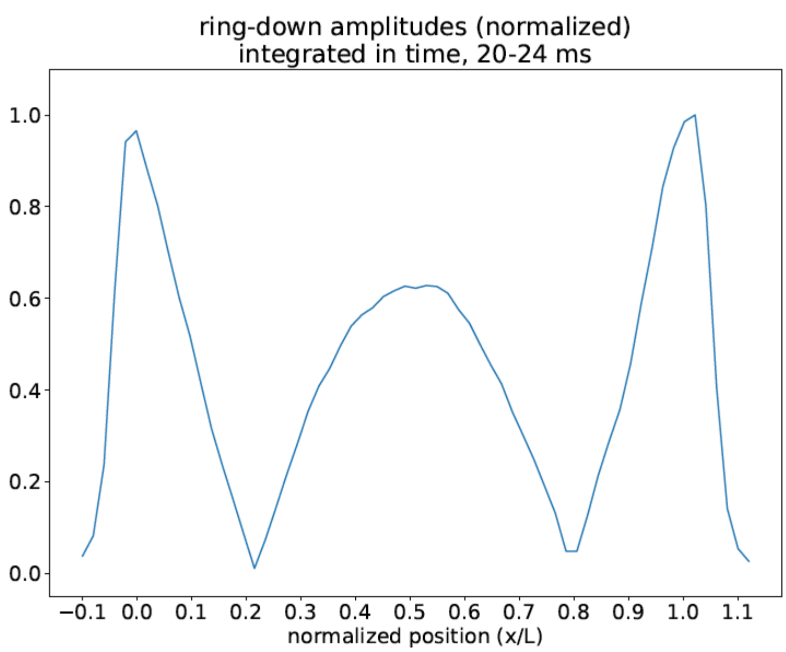

Fig. 2: Mode shape for a solid stainless-steel cylinder resting proud in the large tank on a bumpy polymer floor identified using modulated acoustic radiation force. The hydrophone was close to the cylinder and the focused source was axially scanned.

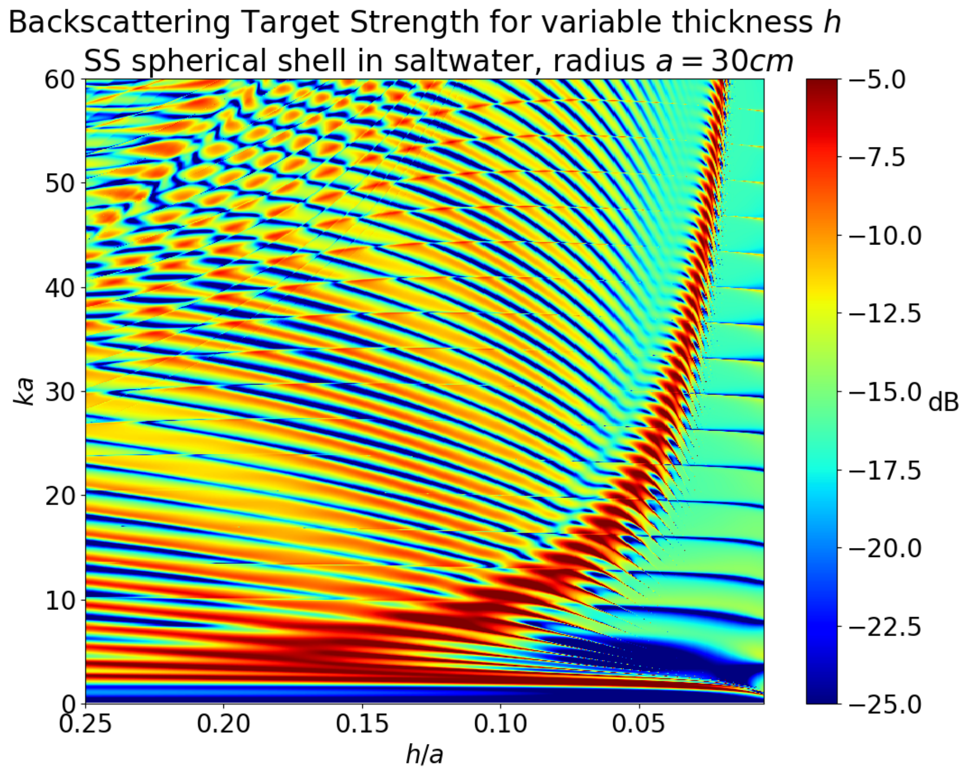

Fig. 3: Computed backscattering target strength TS evolution for an empty stainless-steel spherical shell computed as a function of normalized wall thickness h/*a* and dimensionless frequency k*a* where *a* is the radius of the sphere; right: TS in dB.

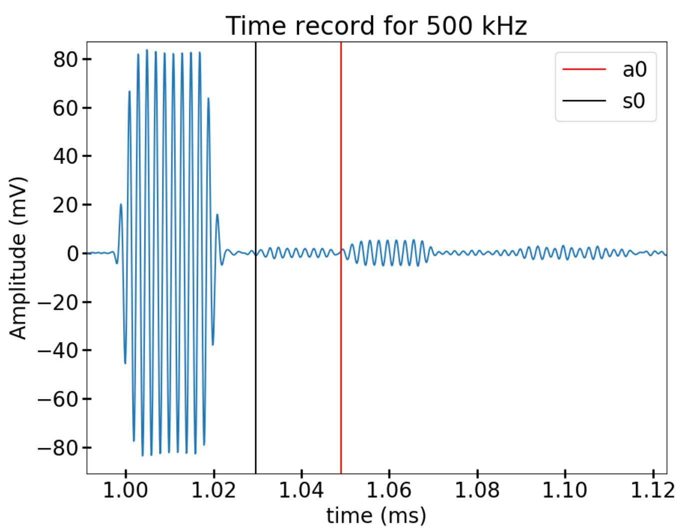

Fig. 4: Measured backscattering from an empty cylindrical metal shell in water in which ray theory was used to identify the s_0 and a_0 guided wave echoes following the specular reflection. (Measurements of January 2020 with ray theory for the delay in arrival time.)

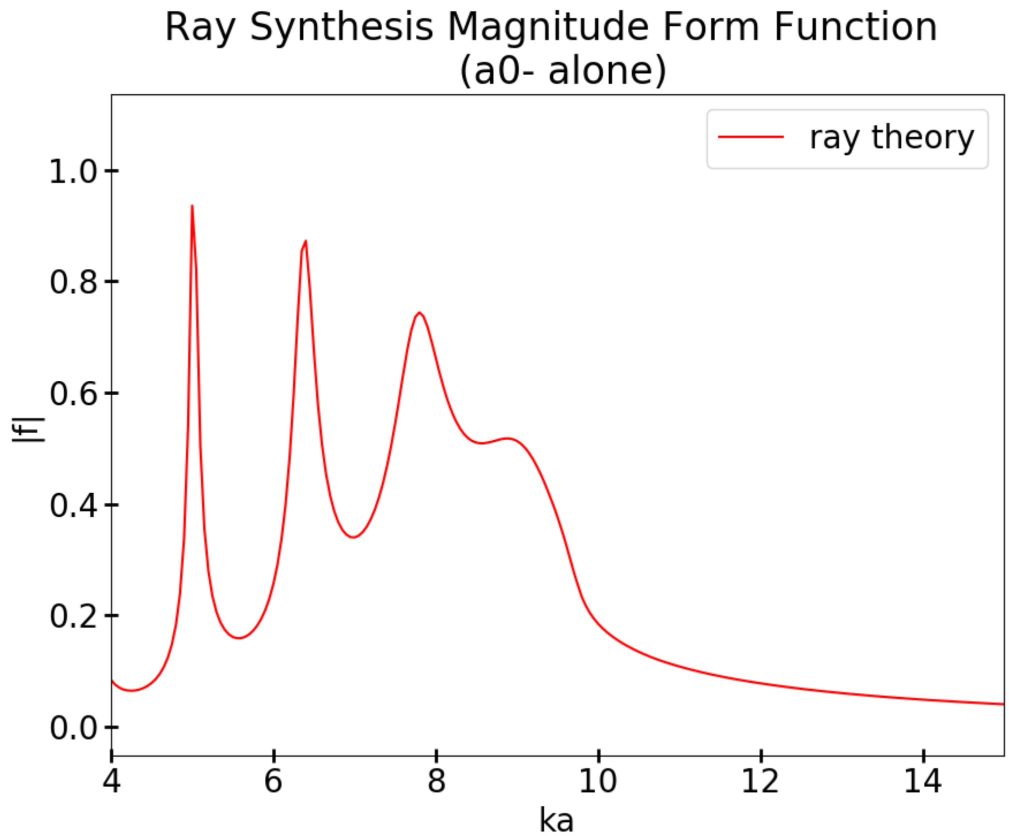

Fig. 5: Computed approximate ray-theory backscattering contribution form function magnitude for the mid-frequency backscattering enhancement from a moderately thick empty stainless steel cylindrical shell. The contribution is computed for a subsonic guided wave on the shell. The dimensionless frequency k*a* and shell thickness were selected in a way that the enhanced region corresponds to an enhanced region in the analogous spherical shell case, Fig. 3. The general shape of the curve resembles prior ray theory for a thin cylindrical steel shell example [Fig. 4 of P. L. Marston & N. Sun, "Backscattering near the coincidence frequency of a thin cylindrical shell: Surface wave properties from elasticity theory and an approximate ray synthesis," J. Acoust. Soc. Am. 97, 777-783 (1995)] except that here the enhancement is significantly larger in magnitude and shifted to smaller k*a*. The enhancement should be easily observable even though this contribution will be superposed on a specular echo having a form function magnitude near unity and another weaker contribution (not shown).

N000141912039 : Acoustic Scattering Experiments and Models

Reporting Period: JUN 16, 2020 to JUN 15, 2021

Date Received:

Submitter: Philip Marston

Distribution Statement: Approved for public release; distribution is unlimited.

Major Goals

The main objective of this project is to improve methods for acquiring acoustical signatures of targets in water and to improve models for understanding such signatures and methods of extracting, displaying, and using signatures. One of our approaches concerns aspects of low-frequency target responses to modulated acoustic radiation forces (MARF) of focused sound beams. These include methods for identifying the shape as well as the frequency of a mode of a particular target in the presence of other objects. This component involves laboratory experiments and development of underlying theory (which includes radiation force and focused beam theory as well as issues related to target response). Double sideband suppressed carrier modulation (DSB-SCM) of the acoustic illumination results in a MARF that oscillates at a single low frequency. Low-frequency (LF) signatures become detectable using only high-frequency (HF) illumination. In some cases, it may be helpful to use time-dependent electromagnetic Maxwell stresses (instead of MARF) to excite a given target mode to be acoustically detected. Other components of the research concern complications resulting from target proximity to interfaces or target placement in waveguides. Aspects of the research involve elastic responses of targets at high frequencies and associated signature contributions and ray theory. In the case of man-made shells, the responses reveal material composition and shell thickness. Related computational investigations include a better understanding of how shell thickness affects the target echoes. Related aspects concern the transmission of sound through the walls of targets and associated contributions to signatures and acoustical images. These include laboratory-based tests. The HF elastic contributions of interest are relevant to the development of ATR algorithms.

This research should aid in discriminating between natural acoustic clutter and man-made objects of interest. Thus, the research is relevant to improving the use of acoustic scattering for object identification and improving naval capabilities.

Some additional background information is available in: (a) the prior Annual Reports for this grant submitted by June 2019 and June 2020, and (b) the Final Technical Report for the expired prior grant N000141512603 (DTIC Report AD1093528 by P. L. Marston): https://apps.dtic.mil/sti/pdfs/AD1093528.pdf

Note on the impact of Covid-19 research protocols: Beginning March 2020 research plans were modified to allow for the revised protocols. Other revisions were needed since certain supplies became unavailable during the Covid crisis. Progress was facilitated by: (i) analysis (and in some cases journal submission and publication) of previously obtained data; (ii) modification of target design to facilitate preliminary measurements in available facilities; and (iii) renewed and/or modification of theoretical and computational approaches.

The emphasis of the "Accomplishments" summary is on developments and publications submitted after the prior Annual Report (submitted in May 2020). Some of these accomplishments are illustrated in the Figures "Upload" Section of this report.

Given the educational component of this research, for ease of reading and evaluation, the students and former students involved in the research or publications listed (during the relevant report period) are noted here: WSU Graduate Students: Auberry R. Fortuner, Bernard R. Hall, Chris Powers; WSU Undergraduate Student transitioning to WSU Graduate Student: Sterling M. Smith; WSU Undergraduate Students (current or recent graduates): J. C. Stotts, Laina M. Wyrick; Former WSU Graduate Students (PhD recipients) & current affiliation: Viktor Bollen (HistoSonics Inc., Ann Arbor, MI); Timothy D. Daniel (NSWC-PCD, FL); Grant C. Eastland (Naval Undersea Warfare Center Division, Keyport, WA)

Accomplishments Under Goals

[A] TARGET RESPONSE TO MODULATED ACOUSTIC RADIATION FORCES (MARF) EXPERIMENTS: As in the 2020 report, Fortuner excited low-frequency deformation modes of a spherical shell tethered in the 12-foot diameter water tank. The focused Lens-2 ultrasonic source with DSB-SCM was used to supply the oscillating force. The low-frequency (LF) acoustic signature was detected with a hydrophone typically approximately 2 m away. The effect of focusing of reflections from the cylindrical tank walls was identified in the recorded signatures and improved models were developed.

[B] WIDE-BANDWIDTH SCATTERING MEASUREMENTS, RAY-THEORY AND/OR CALCULATIONS FOR SHELLS: (a) As noted in the 2020 report, Hall computationally investigated complex guided-wave roots for metal cylindrical shells in water. Relevant scattering properties were examined using ray-theory approaches developed in Marston's WSU program in the 1990s [1]. It was evident that there was a significant gap in ray-theory based understanding for shells between the thick and thin cases previously investigated at WSU. To facilitate scattering measurements in an available tank, scaled small shells were fabricated at WSU in July 2020. Broadside backscattering measurements revealed a significant mid-frequency enhancement. Of greater interest, however, are new backscattering enhancements for tilted shells displayed in the (tilt-angle) – (frequency) domain plotted in Fig. 1. The theoretical coupling arc is for the ideal far field case and is based on a simplified calculation of the A0+ wave coupling locus [1]. Large distinctive enhancements of this type are relevant to the development and understanding of ATR algorithms. (b) T. Daniel published a summary of his experiments and analysis of backscattering by solid cylinders from his Thesis. The emphasis was on tilted joined aluminum and brass cylinders displayed in the angle-time, spectral, and CSAS domains [2]. Signatures from the metal junction are easily seen.

[C] OTHER TARGET PHYSICS FOR TARGETS ADJACENT TO FLAT SURFACES & MULTIPLE SCATTERING: (a) In this task area Fortuner significantly extended his prior analysis to include observable subsonic surface guided wave (SGW) contributions for his spherical target adjacent to a flat surface. The associated new signature contributions observed and analyzed included single reflection (P1) paths, Fig. 2, and various multiple scattering multi-reflection paths. (b) Eastland published Thesis results on bistatic scattering by solid cylinders near a flat surface [3].

[D] MODULATED ACOUSTIC RADIATION FORCE (MARF) THEORY: (a) In keeping with prior plans & preliminary results by Marston and T. Daniel presented at an ASA meeting in 2018, the task of computing radiation forces associated with specular HF reflection was extended to MARF and were published [4]. Fig. 3 shows the simplest case of reflection from a right-circular cylinder. Fig. 3 also shows for HF illumination (large ka) the radiation forces on a rigid cylinder directly relevant to understanding static forces on an aluminum cylinder in water. Fig. 4 shows that the normalized magnitude of the dynamic force computed this way agrees with the result found using an idealized partial wave series (PWS) approach. These results and others documented there (or not yet published) support the relevance of the specular approximation. This facilitates novel approximations of MARF. (b) In related work Marston noticed a systematic analytical error in recent modulated radiation force publications by a popular author. Marston published a peer-reviewed corrective explanatory comment in summer 2020 [5]. (c) In other developments, Fortuner carried out preliminary calculations of focal properties of a previously planned larger-diameter polymer lens (Lens-3) needed for the next generation of MARF-target-response experiments. The preliminary design (Fig. 5) builds on the prior success with piezoceramic disks coupled to the relevant lens material. This lens design should also facilitate the generation of high-power HF acoustic vortex beams.

[E] EXCITING LOW FREQUENCY VIBRATIONS USING HIGH-FREQUENCY ELECTRIC CURRENTS: In summer 2019, Smith and T. Daniel demonstrated a novel electromagnetic mechanism for exciting LF vibrations of a structure (a tight metal wire) using only high-frequency (HF) oscillating electric currents & associated magnetic fields, Fig. 6. This work was submitted to JASA in July 2020 and published in October [6].

[F] VORTEX BEAM THEORY AND SCATTERING EXPERIMENTS: Prior experiments and analysis (from V. Bollen's Ph.D. Thesis) concerning backscattering by a sphere in a vortex beam were submitted in late May 2020 and published in JASA-EL in August 2020 [7]. See Figs. 7 & 8. Sub-wavelength transverse position sensitivity is demonstrated.

REFERENCES & SELECTED PUBLICATIONS:

[1] SF Morse, PL Marston, & 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).

[2] TD Daniel & PL Marston, "Modification of the time, frequency, and sonar image domain signatures of cylinders due to a material junction," Proceedings of Meetings on Acoustics 40, 045001 (2020).

[3] GC Eastland & PL Marston, "Time evolution of bistatic acoustic scattering: mechanism loci identification for broadside cylinder near a flat interface," IEEE Journal of Oceanic Engineering, doi: 10.1109/JOE.2020.3028675

[4] PL Marston, TD Daniel, AR Fortuner, IP Kirsteins, & AT Abawi, "Specular-reflection contributions to static and dynamic radiation forces on circular cylinders," J. Acoust. Soc. Am. 149, 3042-3051 (2021).

[5] PL Marston, "Comment on oscillatory optical and acoustical radiation pressure," Journal of Quantitative Spectroscopy & Radiative Transfer 254, 107226 (2020).

[6] SM Smith, TD Daniel, & PL Marston, "Maxwell stress excitation of wire vibrations at difference and sum frequencies of electric currents in separate circuits," J. Acoust. Soc. Am. 148, 1808-1816 (2020).

[7] V Bollen & PL Marston, "Phase and amplitude evolution of backscattering by a sphere scanned through an acoustic vortex beam: measured helicity projections," J. Acoust. Soc. Am. 148, EL135-EL140 (2020).

Plans Next Period

Washington State University (WSU) is in the process of introducing plans and procedures for post-Covid-emergency operations. These will affect the operations during the next period, beginning

June 16, 2021. The progress and plan during this next period will involve: [P-A] existing dissertation topics; [P-B] splitting off from this grant of technical/engineering tasks which are not appropriate for grant-funds; [P-C] selected new explorations in keeping with exploratory experiments on grant objectives as well as suitable undergraduate STEM objectives; [P-D] relevant theoretical investigations that are not supported elsewhere by STTR funds.

[P-A] (a) Fortuner is working on bringing his thesis writing to completion. Exactly when this task will be completed is uncertain. (b) Bernard Hall plans improved experiments on the mid-frequency scattering by intermediate-thickness cylindrical shells. A main objective is to improve the spectrum versus tilt angle data in Fig. 1 of this Report through modifications of one of the tank facilities. In addition, it would be helpful to improve our observations of the partial reflections of most dominant surface guided waves (SGW) when the cylinder is in contact with a surface. Investigation of SGW contributions to SAS images would also be helpful. It is anticipated that results associated with these tasks should be included in Hall's thesis.

[P-B] In the prior Report, testing of a larger focused polymer lens (Lens-3) was planned for ultrasonic beams in water. With the support of this grant initial design studies were carried out assuming the excitation by 3-piezoelectric circular disks (Fig. 5). It is now appropriate to partition these studies into: (a) those related to specific Modulated-Acoustic-Radiation-Force (MARF) long-range source requirements and target related objectives to be supported by a pending STTR related subcontract with HLS-Inc.; and (b) objectives more closely related to acoustic-beam physics and scattering experiments. Graduate student S. Smith will be involved in these tasks with expenses split as appropriate. An example of a (b)-suitable grant task is acoustic vortex beams generated with Lens-3 (or modifications there-of) and related aspects of target scattering building on our recent publication by Bollen & Marston [7].

[P-C] (a) A major unresolved physics issue concerns when low-frequency (LF) modes of targets in water on sand are interrogated using: (i) conventional LF-SAS; (ii) MARF excitation; or (iii) Modulated-Maxwell-Stress (MMS) methods. The issue is: how effective is contact with sand or other objects in dissipating the vibrational energy of a mode. It is anticipated that the quality-factor of a typical mode will depend on burial depth. One effective way to explore this is with MMS excitation. [See Fig. 1 of the Report due June 2020, T. Daniel's 2019 thesis, and Hefner & Marston, J. Acoust. Soc. Am. 106, 3340–3347 (1999).] A new graduate student (C. Powers) is in the process of setting up to test a more effective technology for MMS excitation of target modes for metal targets. His extended goal is to explore environmental factors (such as contact with wet sand) on mode delay. (b) Another low-frequency MMS mode-related topic concerns the investigation of modification of mode properties using mode feedback. This involves STEM undergraduate student participation (Wyrick) and a modification of the apparatus used in Fig. 6. It is likely, because of his familiarity with group facilities, that Smith will also be involved with (a) & (b).

[P-D] Marston plans to continue background related theoretical investigations of a type that would not have been feasible without support from this grant. These include novel computational tests and applications of scattering and radiation force models and high-frequency scattering approximations.

[P-E] (a) Marston & T. Daniel find it mutually advantageous to continue research interactions related to scattering (concerning experiments & WSU models) and acoustic beams. This also involves applications of scattering-related computational resources previously developed at WSU. (b) With relaxed Covid-19 restrictions it may become practical to resume target-physics related interactions with APL-UW (Seattle).

[P-F] Concerning short-wavelength scattering & caustics: Marston has an obligation to complete some research related to the generation of caustics produced in scattering by penetrable spheroids. The basic phenomena were discovered by Marston & Trinh [Nature (December 1984)] while studying the scattering of laser light by acoustically levitated water drops. Various ray-theory predictions were worked out and tested in experiments by students at WSU supported by ONR in the early 1990s. Eventually there was significant interest in determining if such caustics would also be present in full-wave T-matrix calculations of short wavelength light scattering by oblate water drops. Working at NASA Goddard Institute for Space Studies in New York city, Michael I. Mishchenko, carried out relevant T-matrix calculations and sent them to Marston for collaboration. Unfortunately, Mishchenko died suddenly in July 2020 with the project uncompleted. Marston has an obligation to document these results. Analogous results should be present in acoustical signatures if such acoustical T-matrix calculations become feasible.

Results Dissemination

A. Journal publications appearing during the period of this report in chronological order:

[A1] PL Marston, "Comment on oscillatory optical and acoustical radiation pressure," Journal of Quantitative Spectroscopy & Radiative Transfer 254, 107226 (2020); doi: 10.1016/j.jqsrt.2020.107226

[A2] V Bollen & PL Marston, "Phase and amplitude evolution of backscattering by a sphere scanned through an acoustic vortex beam: measured helicity projections," J. Acoust. Soc. Am. 148, EL135-EL140 (2020); doi: 10.1121/10.0001697 Correction: doi: 10.1121/10.0002100

[A3] SM Smith, TD Daniel, & PL Marston, "Maxwell stress excitation of wire vibrations at difference and sum frequencies of electric currents in separate circuits," J. Acoust. Soc. Am. 148, 1808-1816 (2020); doi: 10.1121/10.0002104

[A4] TD Daniel & PL Marston, "Modification of the time, frequency, and sonar image domain signatures of cylinders due to a material junction," Proceedings of Meetings on Acoustics 40, 045001 (2020); doi: 10.1121/2.0001333

[A5] GC Eastland & PL Marston, "Time evolution of bistatic acoustic scattering: mechanism loci identification for broadside cylinder near a flat interface," IEEE Journal of Oceanic Engineering, doi: 10.1109/JOE.2020.3028675

[A6] PL Marston, TD Daniel, AR Fortuner, IP Kirsteins, & AT Abawi, "Specular-reflection contributions to static and dynamic radiation forces on circular cylinders," J. Acoust. Soc. Am. 149, 3042-3051 (2021); doi: 10.1121/10.0004304

B. Professional Conference Presentations during this period:

[B1] PL Marston, "Algebraic radiation force expansions beyond King, Yosioka and Kawasima, and Gor'kov, and related investigations of shape dynamics," Acoustofluidics 2020 (Aug. 2020, live Zoom, extended abstract available to conference registrants); no doi: https://www.acoustofluidics.net/

[B2] PL Marston & V Bollen, "Acoustic vortex beam scattering measurements and a review of modulated radiation pressure for levitation experiments," 73rd Annual Meeting of the APS Division of Fluid Dynamics (virtual Nov. 2020; prerecorded & interactive); http://meetings.aps.org/Meeting/DFD20/Session/S06.7

[B3] Invited: PL Marston, "Interfacial tension and acoustofluidics: some connections, instabilities, experimental results, and theory," J. Acoust. Soc. Am. 148(4), 2708-2708 (2020); doi: 10.1121/1.5147502 (virtual Dec. 2020; prerecorded & interactive).

[B4] The results in item [A4] were given by TD Daniel as a pre-recorded presentation at the Sept. 2020 virtual ECUA meeting.

C. WSU Undergraduate Honors College Senior Thesis:

[C1] SM Smith, “Maxwell stress excitation of wire vibrations at difference and sum frequencies of currents in separate circuits,” (WSU Undergraduate Honors College Senior Thesis, December 2020).

Honors and Awards

Honors:

Award to: SM Smith, “Pass with Distinction,” The Honors Council (WSU Honors College) December 2020 [recognition of Senior Honor’s College Thesis & Presentation supported in part by this grant]

Award to: SM Smith, “Dean’s Award,” (WSU Honors College) December 2020. This award should eventually be listed at: https://honors.wsu.edu/student-awards-and-recognition/honors-deans-award/

Training Opportunities

A. Graduate student research participant supported entirely or in part by this grant during this period include:

(1) A. Fortuner (Ph. D candidate),

(2) B. Hall (Ph. D candidate)

(3) C. Powers

(4) S. Smith (transitioned to graduate RA status, May 2021)

B. Undergraduate student research participants: (1) S. Smith, (2) J. C. Stotts, (3) L. Wyrick

C. Discussion & Details: All of the students were & are mentored primarily by the PI (Marston). Hall & Smith were partially mentored by Daniel early in this grant. Smith & Stotts took undergraduate science & math classes and contributed to acoustics experiments & related data processing. Smith received his BS in Physics in Dec. 2020 & Stotts in May 2021. Wyrick started helping in early 2020 but refrained from doing so during restrictive Covid rules. She resumed helping in May 2021.

Technology Transfer

(1) DoD research & engineering personnel associated with grant publications during the period of this report: (a) Timothy D. Daniel (NSWC-PCD) (b) Ivars P. Kirsteins (NUWC, Newport, RI) (c) Grant C. Eastland (Naval Undersea Warfare Center Division, Keyport, WA)

(2) other DoD funded research personnel currently associated with grant publications during the period of this report: (a) Ahmad T. Abawi (HLS Research, Inc., La Jolla, CA)

(3) Concerning the next grant period: (a) The priority of interactions with Abawi & Kirsteins will likely shift away from objectives of this grant towards fulfilling the technical objectives of a pending

STTR-ONR research subcontract with HLS Research, Inc. That contract will concern producing high-intensity modulated ultrasonic focused beams in water. (b) Increasing interactions with researchers at APL-UW (Seattle) concerning target-physics and acoustics.

Participants

Name	**Role**	**Person Months**
Fortuner, Auberry	Graduate Student (research assistant)	6
Hall, Bernard	Graduate Student (research assistant)	6
Powers, Chris	Graduate Student (research assistant)	1
Smith, Sterling	Graduate Student (research assistant)	1
Marston, Philip	PD/PI	3
Smith, Sterling	Undergraduate Student	2
Stotts, John	Undergraduate Student	1
Wyrick, Laina	Undergraduate Student	1

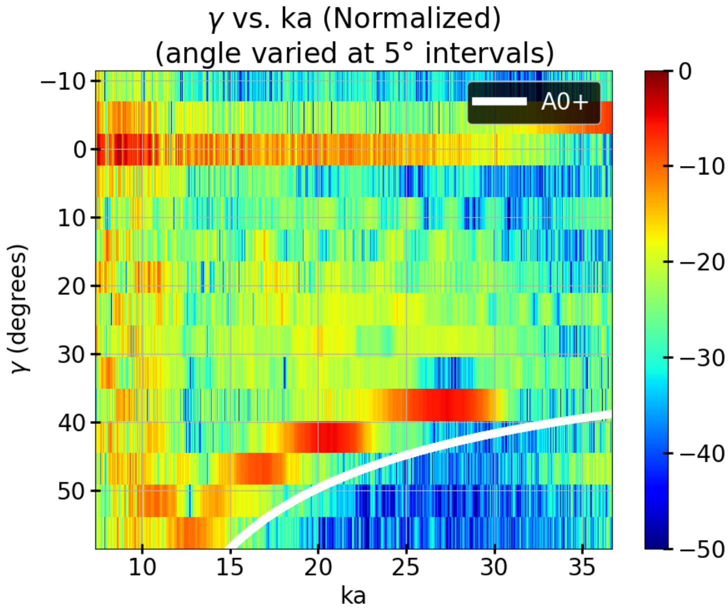

Fig. 1: Spectrum of a short pulse backscattered by a tilted empty cylindrical shell in water. The horizontal axis is normalized frequency ka. The vertical axis is the shell's tilt angle with broadside at zero tilt and a typical step size of 5 degrees. Though far-field conditions could not be achieved, the approximate predicted far-field meridional coupling locus is shown as the white arc. The enhancement is evident for a shell of intermediate scaled thickness [relative to Morse et al. (1998)].

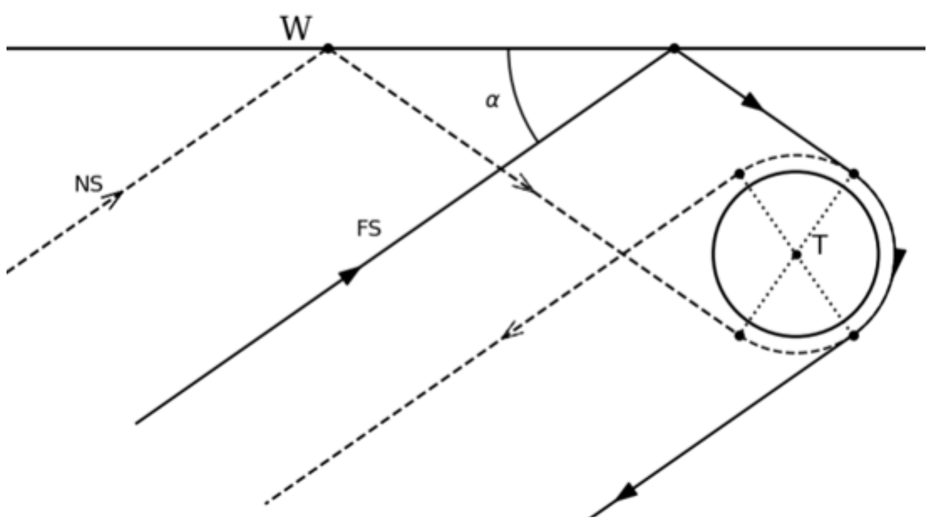

Fig. 2: Ray diagram for an example of a newly experimentally identified surface guided wave path for a thin spherical shell adjacent to a flat reflecting surface. The more significant of the guided portion is the solid arc. (From Fortuner's Thesis, in preparation.)

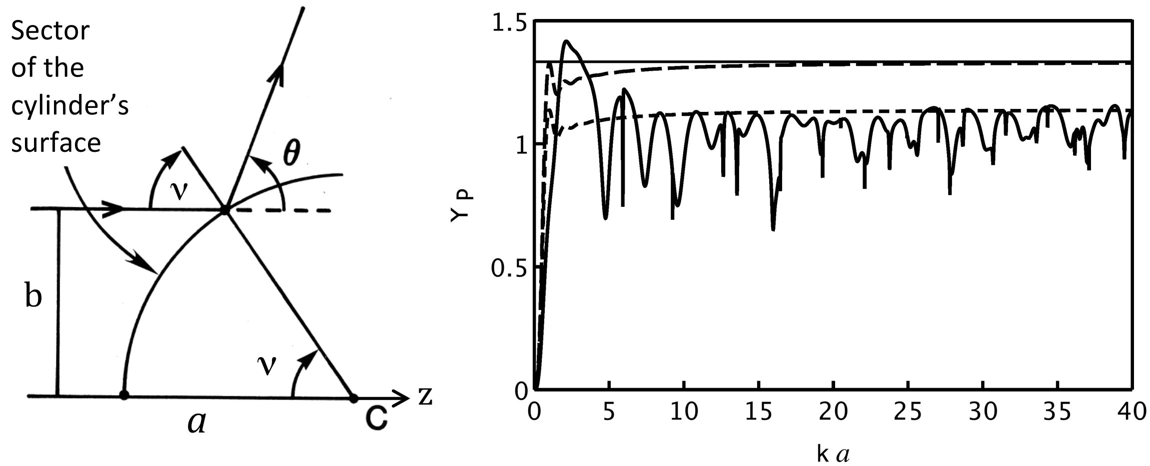

Fig. 3: Left: Ray diagram for calculating the radiation force on a circular cylinder. **Right:** Normalized steady radiation force Y_P as a function of the product of the cylinder's radius *a* and the acoustic wavenumber k. The solid curve is the partial wave series (PWS) result for an aluminum cylinder in water. The curve with long dashes (near the specular line $Y_P = 4/3$) is for a fixed rigid cylinder. The curve with short dashes supports the specular approximation. It is the rigid result scaled by a predicted factor.

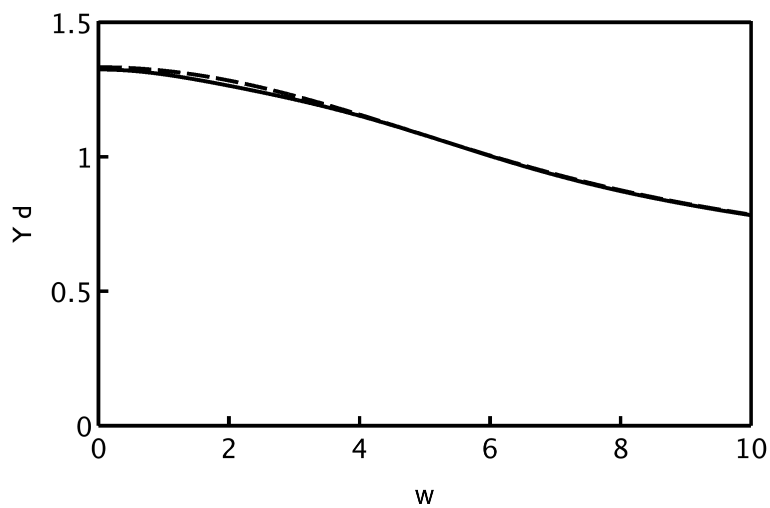

Fig. 4: The vertical axis is the normalized magnitude of dynamic force function Y_d. The dashed curve is the specular contribution for a rigid cylinder plotted as a function of w, the normalized dimensionless modulation frequency. The solid curve is the partial wave solution computed here for a fixed rigid cylinder with normalized carrier frequency $k_C a$ = 25. The agreement supports the relevance of the specular analysis. For applications related to target identification usually w will be small. Figures 3 & 4 are from our publication (J. Acoust. Soc. Am. May 2021) where additional information is given.

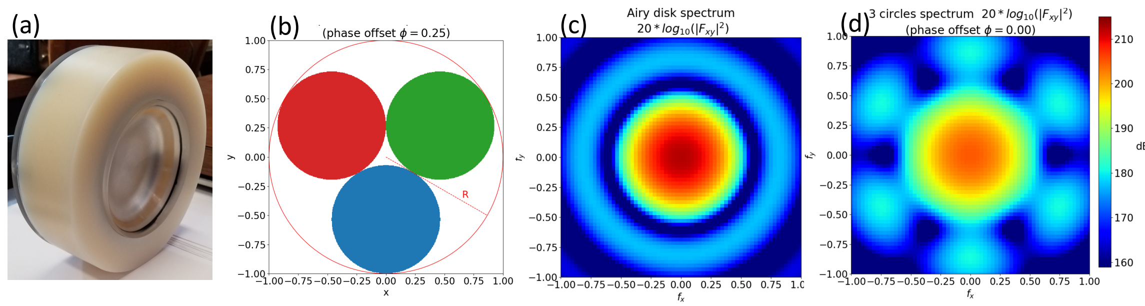

Fig. 5: (a) The existing Lens-2 previously fabricated at WSU. (b) Simplified diagram of planned Lens-3 module with 3-PZT-Circular-Disks (CD) shown as Red, Green, & Blue (RGB). In-reality, the CD are close but not in contact. (c) Ideal point spread function (PSF) intensity of a red-bounding-circle source in (b). (d) PSF for in-phase drive of the three RGB-PZT in (b) computed by WSU graduate student Fortuner. The result in (d) shows that while the three CD result is not as tightly focused as a large CD, the degradation may be permissible since the width of the intensity peak is relevant. The planned Lens-3 may be also used for vortex beam generation.

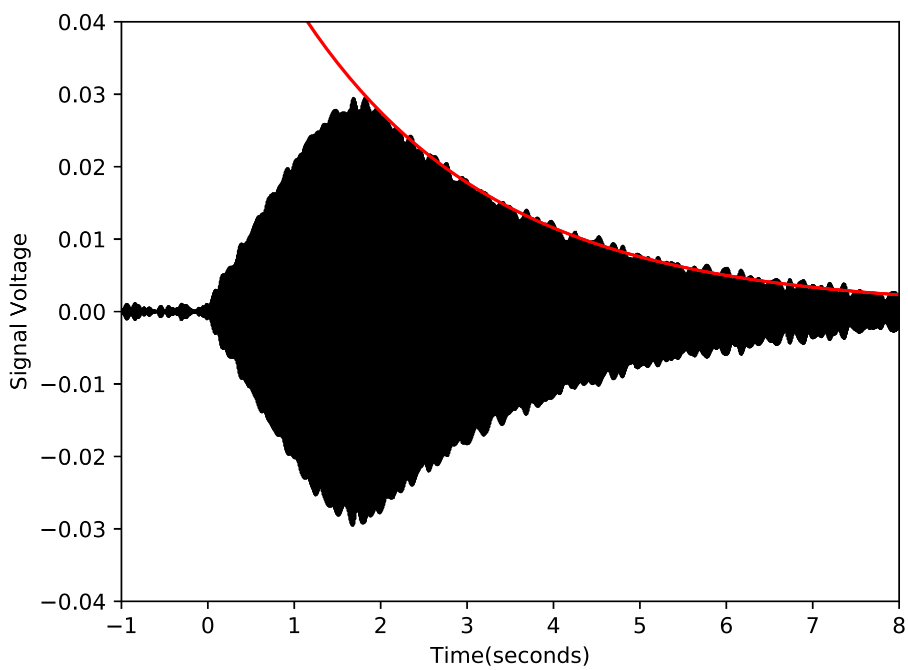

Fig. 6: The instantaneous amplitude of the fundamental mode of a vibrating wire plotted as a function of time. The initial build-up is the wire's response forced by low-frequency Maxwell stresses produced by high-frequency currents in separate electric circuits. The build-up is followed by a free decay period with an exponential envelope (red curve). From our publication (J. Acoust. Soc. Am. October 2021) where additional information is given. For some situations of interest, this type of excitation is relevant.

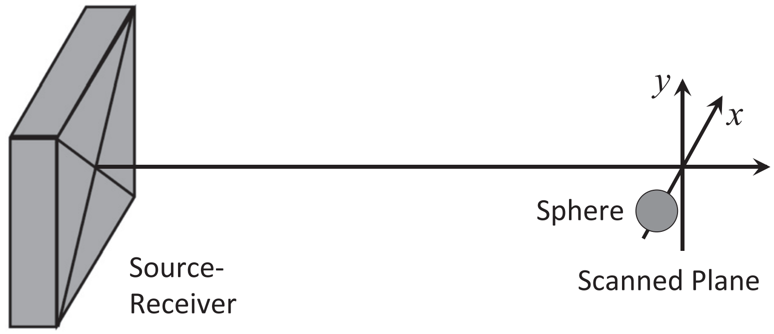

Fig. 7: Idealized experimental configuration in which a first-order vortex beam in water illuminates a sphere that is scanned in the xy-plane. Ideally the source plane is parallel to the scanned plane. The actual scanned plane is slightly tilted and offset. The drawing is not to scale: the length of each side of the square boundary of the source is 10.16 cm, the distance to the xy-plane is 1.67 m, and the sphere diameter is 25.4 mm. Figs. 7 & 8 are from our publication (J. Acoust. Soc. Am. August 2021) giving additional information.

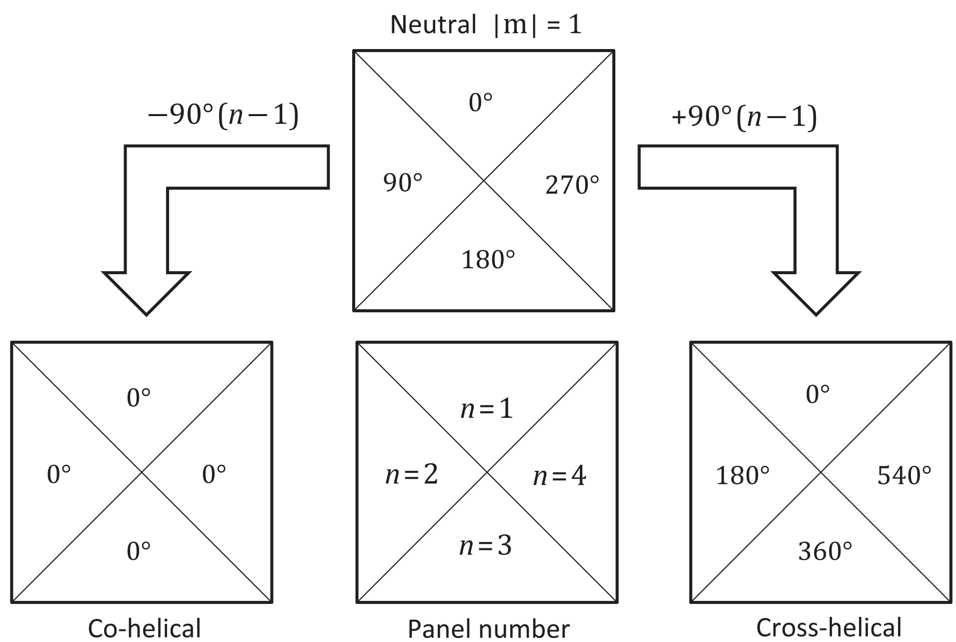

Fig. 8: Signal processing diagram for helical projection processing. The transducer panels are indexed by *n* in the lower-middle diagram. The upper middle diagram represents the idealized evolution of the phase of the scattering detected by the *n*th panel for an axially aligned sphere. For neutral projection processing, the receiver signals are added. On the lower left and right are shown inserted phase shifts for co-helical and cross-helical projection processing. This processing facilitates precise alignment of the sphere on the axis of the vortex beam.

N000141912039 : Acoustic Scattering Experiments and Models

Reporting Period: JUN 16, 2021 to SEP 30, 2022

Date Received:

Submitter: Philip Marston

Distribution Statement: Approved for public release; distribution is unlimited.

Major Goals

The main objective of this project is to improve methods for acquiring acoustical signatures of targets in water and to improve models for understanding such signatures and methods of extracting, displaying, and using signatures. One of our approaches concerns aspects of low-frequency target responses to modulated acoustic radiation forces (MARF) of focused sound beams. These include methods for identifying the shape as well as the frequency of a mode of a particular target in the presence of other objects. This component involves laboratory experiments and development of underlying theory (which includes radiation force and focused beam theory as well as issues related to target response). Double sideband suppressed carrier modulation (DSB-SCM) of the acoustic illumination results in a MARF that oscillates at a single low frequency. Low-frequency (LF) signatures become detectable using only high-frequency (HF) illumination. In some cases, it may be helpful to use time-dependent electromagnetic Maxwell stresses (instead of MARF) to excite a given target mode to be acoustically detected. Other components of the research concern complications resulting from target proximity to interfaces or target placement in waveguides. Aspects of the research involve elastic responses of targets at high frequencies and associated signature contributions and ray theory. In the case of man-made shells, the responses reveal material composition and shell thickness. Related computational investigations include a better understanding of how shell thickness affects the target echoes. Related aspects concern the transmission of sound through the walls of targets and associated contributions to signatures and acoustical images. These include laboratory-based tests. The HF elastic contributions of interest are relevant to the development of ATR algorithms.

This research should aid in discriminating between natural acoustic clutter and man-made objects of interest. Thus, the research is relevant to improving the use of acoustic scattering for object identification and improving naval capabilities. Low-frequency modes of a target should reveal information about the contents of the target.

Some additional background information is available in: (a) the prior Annual Reports for this grant submitted by June 2019, June 2020, and June 2021, and (b) the Final Technical Report for the expired prior grant N000141512603 (DTIC Report AD1093528 by P. L. Marston): https://apps.dtic.mil/sti/pdfs/AD1093528.pdf

The reports for June 2020 and June 2021 note on the impact of Covid-19 research protocols. The research approach for the period summarized builds on the prior research in a way consistent with relaxed protocols, which were still significant.

The emphasis of the “Accomplishments” summary is on developments and publications not covered in the prior Annual Report (submitted in early June 2021). Some of these accomplishments are illustrated in the Figures “Upload” Section of this report.

Given the educational component of this research, for ease of reading and evaluation, the students and former students involved in the research or publications listed (during this report period) are noted here: WSU Graduate Students: Auberry R. Fortuner, Bernard R. Hall, Chris Powers; WSU Undergraduate Student now a WSU Graduate Student: Sterling M. Smith; WSU Undergraduate Students: Laina M. Wyrick.

Accomplishments Under Goals

[A] TARGET RESPONSE TO MODULATED ACOUSTIC RADIATION FORCE (MARF) EXPERIMENTS: In the 2020 report, Fortuner excited low-frequency deformation modes of a spherical shell tethered in the 12-foot diameter water tank a short focal length WSU fabricated ultrasonic source. That research and his related research using that source is archived in his July 2021 Ph. D. Thesis [1]. In addition, in spring 2020 a larger diameter 1-meter focal length focused ultrasonic source was fabricated using funds from the grant reported here, delivered late in June 2021. (Fortuner had previously, with support from this grant, carried out a preliminary computation of the focal pattern, however that was not included in his Thesis. See Fig. 5(d) of the 2021 Report. A preliminary design of this source had been carried out by Marston prior to the Covid-19 pandemic.) Smith began testing the new source with support from this grant, but for the period from July 1, 2021-early December 2021 he was supported by a subcontract on a related STTR-ONR project [2]. When funds were unavailable from that project, Smith continued tests with support from the grant reported here until about mid-June 2022, at which time sub-contract funds became available from the Option-Period of the STTR-ONR project [2]. Because of the shifting nature of the funding, most of the results may be credited to both funding sources without a complete delineation. The beam pattern was measured by scanning a small ultrasonic hydrophone, the sensitivity of which was known by comparison with a larger hydrophone having a known sensitivity. The beam power was computed by integration of the beam pattern and by comparison electrical measurements extrapolated to give the electrical power delivered to the source. Low frequency modes (LFM) of various cylindrical metal targets in water were excited at a distance of 1-meter from the source with DSB-SCM used to supply the oscillating radiation pressure of the focused beam. The low-frequency (LF) acoustic signature was detected with a hydrophone adjacent to the target in a small tank. Figure 1 shows some of the results. (An early demonstration of LFM excitation of liquid drops using ultrasonic DSB-SCM is documented in [3].)

[B] WIDE-BANDWIDTH SCATTERING MEASUREMENTS, RAY-THEORY AND/OR CALCULATIONS FOR SHELLS: As noted in the 2020 and 2021 Reports, Hall computationally investigated complex guided-wave roots for cylindrical metal shells in water. Relevant scattering properties were examined using ray-theory approaches developed in Marston’s WSU program in the 1990s [4]. It was evident that there was a significant gap in ray-theory based understanding for shells between the thick and thin cases previously investigated at WSU. To facilitate scattering measurements in an available tank, scaled small shells were fabricated at WSU in July 2020. The emphasis during this period was in improving the measurements of new backscattering enhancements for tilted shells displayed in the (tilt-angle) – (frequency) domain giving results plotted in Fig. 2. The theoretical coupling arc in Fig. 2(c) lower-row, is for the ideal far field case and is based on a simplified calculation of the a0 wave coupling locus [4]. Large distinctive enhancements of this type, and others observed, are relevant to the development and understanding of ATR algorithms. These and other results are archived in Hall’s Thesis [5] and in a paper submitted for publication.

[C] OTHER TARGET PHYSICS FOR TARGETS ADJACENT TO FLAT SURFACES & MULTIPLE SCATTERING: An example of Fortuner’s results on this topic is shown in the 2021 Report. Other examples are archived in his Thesis [1]. These include observable subsonic surface guided wave (SGW) contributions for his spherical target adjacent to a flat surface.

[D] MODULATED ACOUSTIC RADIATION FORCE (MARF) THEORY: The following results support the relevance of a specular reflection approximation when modeling target responses to MARF (see [A]): (a) In the 2021 Report, specular high frequency (HF) reflection was extended to MARF calculation for cylinders and was published in J. Acoust. Soc. Am. in May 2021. Subsequently that analysis was extended to spheres and published in July 2021 [6]. Fig. 3 shows the simplest case of reflection from a rigid sphere. The normalized magnitude of the dynamic force computed this way agrees with the result found using an idealized partial wave series (PWS) approach. (b) In related work, to better understand situations associated with focused beam illumination, the specular reflection approximation of radiation pressure was extended to circular cylinders in two slanted plane waves, results published in September 2022 [7]. See Fig 4.

[E] TARGET RESPONSE TO MODULATED MAXWELL STRESSES (MMS) & MODE DISSIPATION: In conventional & MARF excitation of resonances, the detected signal strength depends on mode dissipation. To better understand dissipation, Powers has begun a systematic investigation of the MMS excited mode dissipation of metal targets. This started in summer 2021 with the testing of a new ferrite excitation electric coil with assistance by Smith. Experiments in July 2022 examined the effects of different mounts of metal cylinders including polymer foam contact to partially simulate sand. This has been followed by demonstration of significantly increased mode dissipation for targets proud on sand. In late summer 2022 support had to be shifted to the new grant N000142212599 and results will be summarized there. [F] MODIFYING LOW FREQUENCY VIBRATIONS USING OPTICALLY DETECTED FEEDBACK: As part of the undergraduate STEM component of this grant, a modification of our prior experiment was carried out in summer 2021 and 2022 by Wyrick, with assistance from Smith and Powers. In the new experiment optically detected feedback was used to modify the frequency and damping of LF vibrations.

[G] MODELING CAUSTICS IN HIGH-FREQUENCY SCATTERING: This phenomenon is sometimes more easily studied optically and was the topic of prior ONR support. Prior results were submitted and published in memory of a co-researcher [8]. REFERENCES & SELECTED PUBLICATIONS:

[1] A. R. Fortuner (ARF), Ph. D. Thesis (Washington State University, July 2021), abstracted & archived: https://doi.org/10.7273/000002462 [2] ONR-STTR Phase I Contract N6833521C0377 “The use of modulated radiation pressure in target detection and classification,” Ahmad T. Abawi, PI, Heat, Light, and Sound Research, Inc., San Diego, CA 92130. Ultrasonic source development, modeling, and testing, and some supporting aspects of the theory, are carried out at WSU by Marston and co-researchers partially with ONR grant support. [3] PL Marston & RE Apfel, J. Acoust. Soc. Am. 67, 27-37 (1980). [4] SF Morse, PL Marston, & 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). [5] BR Hall, Ph. D. Thesis (Washington State University, May 2022): https://rex.libraries.wsu.edu/esploro/outputs/doctoral/EXPLORING-HIGH-AND-MID-FREQUENCY-ELASTIC-MECHANISMS/99900883238901842 [6] PL Marston, TD Daniel, & AR Fortuner, “Specular reflection contributions to dynamic radiation forces on highly reflecting spheres (L),” J. Acoust. Soc. Am. 150, 25-28 (2021). [7] PL Marston & AR Fortuner, “Radiation forces on highly reflecting circular cylinders in two slanted plane waves: specular-reflection contributions,” J. Acoust. Soc. Am. 152, 1337–1344 (2022). [8] PL Marston & MI Mishchenko, “Scattering by relatively small oblate spheroidal drops of water in the rainbow region: T-matrix results and geometric interpretation,” Journal of Quantitative Spectroscopy & Radiative Transfer 283, 108142 (2022).

Plans Next Period

This Award terminated on September 30, 2022. Aspects of this research will be continued with support from a new Award (N000142212599), start date August 1, 2022. See the Report for that Award. Related research is planned for modulated radiation pressure target response field tests supported in part by a Phase II ONR-STTR subcontract through HLS, Res. Inc. (La Jolla, CA) in cooperation with the University of Washington Applied Physics Laboratory (Seattle WA).

Results Dissemination

A. Journal publications appearing during the period of this report in chronological order: [A1] PL Marston, TD Daniel, & AR Fortuner, “Specular reflection contributions to dynamic radiation forces on highly reflecting spheres (L),” J. Acoust. Soc. Am. 150, 25-28 (July, 2021). [A2] PL Marston & MI Mishchenko, “Scattering by relatively small oblate spheroidal drops of water in the rainbow region: T-matrix results and geometric interpretation,” Journal of Quantitative Spectroscopy & Radiative Transfer 283, 108142 (2022); 7 pages doi: 10.1016/j.jqsrt.2020.107226 [A3] PL Marston & AR Fortuner, “Radiation forces on highly reflecting circular cylinders in two slanted plane waves: specular-reflection contributions,” J. Acoust. Soc. Am. 152, 1337–1344 (2022). [A4] BR Hall & PL Marston, “Backscattering by a tilted intermediate thickness cylindrical metal empty shell in water,” JASA (J. Acoust. Soc. Am.) Express Letters (accepted 2022).

B. Professional Conference Presentations during this period: [B1] Invited: PL Marston, “Scattering by small oblate spheroidal drops of water in the rainbow region: T-matrix results and geometric interpretation,” The 19th Electromagnetic and Light Scattering Conference (ELS-XIX), virtual session July 14, 2021 (interactive via zoom) https://els2021.physics.itmo.ru/files/ELS2021_final_program.pdf https://www.youtube.com/watch?v=EqJGJhT3coo Presentation starts at 1:07:05 [B2] Invited: PL Marston, “Selected research in physical, structural, and underwater acoustics at WSU associated with Logan Hargrove’s ONR scientific program,” J. Acoust. Soc. Am. 150, A139 (2021); 181st ASA meeting; doi: 10.1121/10.0007901 [B3] BR Hall & PL Marston, “Backscattering by broadside and tilted intermediate thickness empty cylindrical metal shells in water: Experiments and theory,” J. Acoust. Soc. Am. 150, A197 (2021); 181st ASA meeting; doi: 10.1121/10.0008111 [B4] Invited: PL Marston, TD Daniel, AR Fortuner, IP Kirsteins, & AT Abawi, “Amplitude and time-dependence of ultrasonic radiation force on modulation frequency computed from specular reflection contributions,” J. Acoust. Soc. Am. 151, A89 (2022); 182nd ASA meeting; doi: 10.1121/10.0010749 [presented by AR Fortuner] [B5] AT Abawi, PL Marston, IP Kirsteins, AR Fortuner, SM Smith and TD Daniel, “Modeling the effects of modulated radiation pressure using a new acoustic lens,” J. Acoust. Soc. Am. 151, A89 (2022); 182nd ASA meeting; doi: 10.1121/10.0010750

C. Ph. D. Dissertations: [C1] Auberry Renaud Fortuner Title: I. Acoustic Line-Scan Imaging of Interface Scattering Effects II. Spectral Analysis of Scattering from Elastic Spherical Shells in Water III. Testing of Low-Frequency Elastic Modes (Washington State University, Pullman, July 2021) Link: https://doi.org/10.7273/000002462 Abstract: Aspects of acoustic scattering from simple underwater targets are considered in a variety of experimental and theoretical studies. Part I examines a lab experiment of line-scan imaging of the backscattering from a thin spherical shell for two cases: i) near a single flat interface, ii) within an ideal waveguide with an external source/receiver. Geometric ray models are used to describe the backscattering in the time, frequency, and holographic image domains. The holographic image focuses scattered echoes to distinct points in space and time identifiable by ray model, including multiple-scattering effects. Part II examines the theory of scattering from underwater elastic spherical shells, given by the exact solution Partial Wave Series form function. The form function of stainless-steel shells are examined in 2D domains: i) frequency vs. scattering angle domain, ii) frequency vs. thickness domain. The global structure observed in the 2D form functions are explained by ray models describing the interference between the distinct scattering mechanisms: the specular reflection and circumferential surface-guided Lamb waves. Part III examines tank experiments testing the low-frequency modes of a stainless-steel cylinder and a thin spherical shell, using modulated acoustic radiation pressure. The modulation allows a high-frequency focused wave to impart a low-frequency force on an object, driving the object at the resonance frequency of its lowest modes. A hydrophone measures the target response via acoustic radiation, providing a method of testing the elastic mode of the target by two types of scans: a frequency scan in modulation frequency, and a physical scan of the drive point along the object at a fixed modulation frequency.

[C2] Bernard Richard Hall Title: Exploring High and Mid-Frequency Elastic Mechanisms in Acoustically Illuminated Targets in Water (Washington State University, Pullman, May 2022) Link: https://rex.libraries.wsu.edu/esploro/outputs/doctoral/EXPLORING-HIGH-AND-MID-FREQUENCY-ELASTIC-MECHANISMS/99900883238901842 Abstract: We explore some intriguing instances of surface-elastic waves (SEW) on insonified cylindrical shells of different materials in water. These serve as a continuation of similar studies in the past–for example, on spherical shells of comparable materials. The waves in question are a generalization of Lamb Waves on flat plates. In this simpler case, noting an overall symmetric and antisymmetric class of wave, each exists as a unique root of Lamb’s Characteristic Equations. Similarly, such waves on curved surfaces, in particular that of a cylindrical or spherical shell, will be the root of the appropriate shell equation. This solution, in turn, serves as a mathematical description of the phenomena under discussion.

We focus on a few such roots, one of which is the (symmetric) s2b wave in the high frequency range, where we observe the unique case of a phase and group velocity moving in opposite directions. Though this wave has been noted in previous studies, we now explore the behavior with new targets and new materials.

In the mid-frequency range, we have the 0th symmetric and antisymmetric roots, and look at the behaviors of these in the case of a "semi-thin" cylindrical shell. This study complements similar experiments done to observe such phenomena with both "thick" and "thin" shells. Among other challenges, the a0 wave transitions from supersonic (relative to surrounding water) to subsonic at a "coincidence frequency" whose position depends on the shell. In this case, mathematical models that assume either subsonic or supersonic conditions must be modified to accommodate a transitional zone between the two.

Finally, we compare our semi-thin results to others previous using thick and thin shells. For the tilted semi-thin shell, prominent backscattering contributions are associated with guided helical subsonic waves, and with a meridional supersonic wave. Elastic waves also affect sonar images of the cylinder.

D. Other Reports [D1] PL Marston, Ad Hoc Report on MRP Target Response & Ultrasonic MRP Sources (November 2021) to Ahmad T. Abawi (HLS, Res. Inc., La Jolla, CA), partially supported by this grant & partially by ONR-STTR subcontract via HLS, Res. Inc.

Honors and Awards

Nothing to Report

Training Opportunities

Training Opportunities A. Graduate student research participants supported entirely or in part by this grant during this period include: (1) A. Fortuner (Ph. D completed July, 2021). Present address: Naval Undersea Warfare Center Division, Keyport, WA, 98345 (2) B. Hall (Ph. D completed May, 2022). Present address: Applied Physics Laboratory, Acoustics Department, University of Washington, Seattle, WA (3) C. Powers (4) S. Smith B. Undergraduate student research participants: L. Wyrick C. Discussion & Details: All of the students were & are mentored primarily by the PI (Marston). Wyrick, a physics major, took undergraduate science & math classes and contributed to experiments & related data processing.

Technology Transfer

(1) DoD research & engineering personnel associated with grant publications during the period of this report: (a) Timothy D. Daniel was with NSWC-PCD at the time the joint publication in J. Acoust. Soc. Am. (July 2021) was submitted and published. (b) Auberry R. Fortuner (Naval Undersea Warfare Center Division, Keyport, WA) contributed to the joint publication in J. Acoust. Soc. Am. (September 2022). He also contributed to the July 2021 publication while he was a WSU graduate student. (2) other DoD funded research personnel currently associated with this research during the period of this report: (a) Ahmad T. Abawi (HLS Research, Inc., La Jolla, CA), (b) Ivars P. Kirsteins (NUWC, Newport, RI) in cooperation with aspects associated an ONR-STTR Phase I contract to HLS Research, Inc. That aspect concerns producing high-intensity modulated ultrasonic focused beams in water and measuring and modelling target-physics and acoustics for target identification purposes. (3) Phase II of the aforementioned ONR-STTR contract to HLS Research, Inc will involve cooperation with the University of Washington Applied Physics Laboratory (Seattle WA) in modulated radiation pressure target response field tests. Brian Todd Hefner of UW-APL will be involved in those tests and will likely have significant involvement with WSU graduate students. Others at UW-APL may also become involved. (4) Bernard R. Hall, a former graduate student is currently a postdoctoral researcher at UW-APL involved in wide-bandwidth sonar.

Participants

Name	Role	Person Months
Fortuner, Auberry	Graduate Student (research assistant)	1
Hall, Bernard	Graduate Student (research assistant)	7
Powers, Chris	Graduate Student (research assistant)	2
Smith, Sterling	Graduate Student (research assistant)	6
Marston, Philip	PD/PI	4
Wyrick, Laina	Undergraduate Student	1

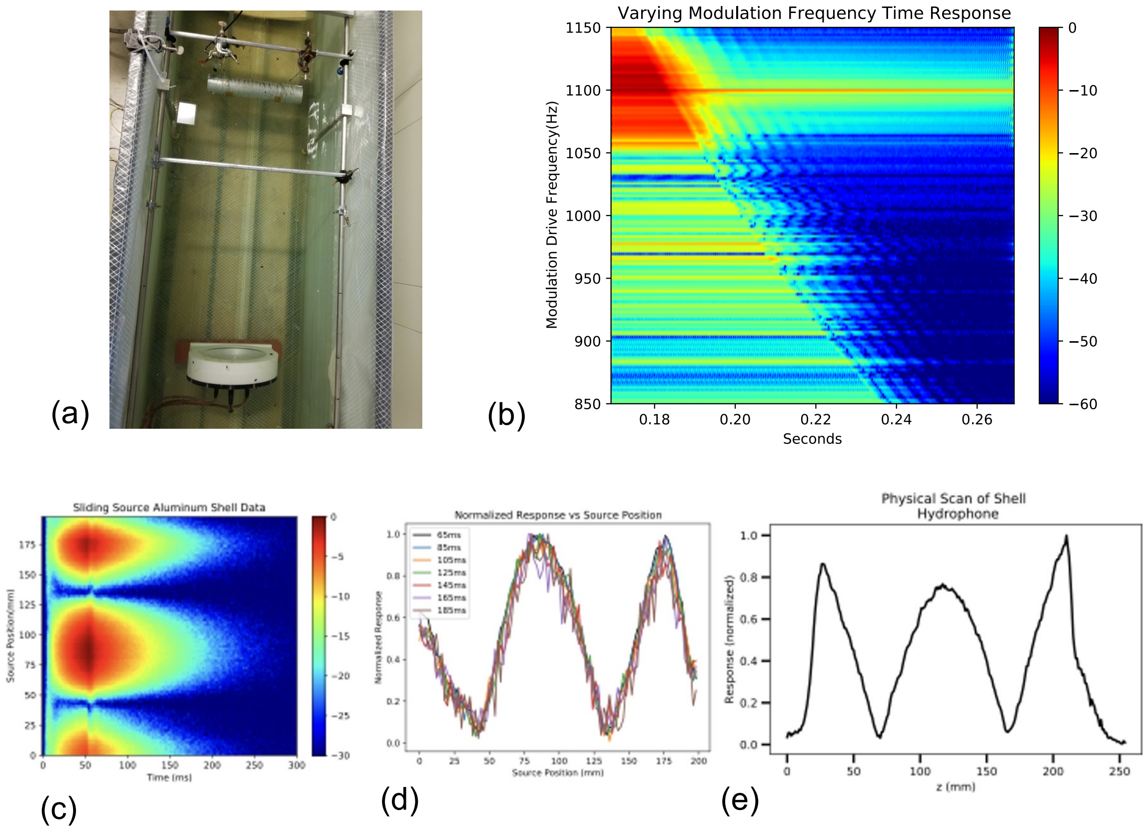

Fig. 1: Target response to modulated acoustic radiation force experiments: (a) 1-m focal length (FL) ultrasonic lens fabricated with support from this grant focused on a 2.75-inch-diameter X 13.75-inch-long aluminum cylinder. (b) Low-frequency hydrophone signal envelope as a function of modulation frequency (vertical) and time (horizontal). As predicted, the mode frequency is near 2 X 1.1 kHz = 2.2 kHz. (c) - (e) show mode shape measurements for an open-ended horizontal cylindrical shell hung in water. The measurements in (c) and (d) were made by scanning the 1 m FL lens in early 2022 where in (c) the lens scan position is on the vertical axis while time is horizontal. (d) and (e) display the inferred mode shapes where (e) was obtained by Timothy Daniel in 2019 at WSU using the modulated radiation pressure of a short focal length scanned source. All of the measurements shown here are based on low-frequency hydrophone data. (c) shows the magnitude of the mode shape given by plotting on a linear scale, slices of the envelope at different time during the decay of the mode. Each slice is normalized relative to the maximum value. As expected, the mode shape is independent of the time of each slice though the plots are noisier for the later slices when the signal is weakest. On the right is the mode shape obtained in the same way in Timothy Daniel's 2019 WSU Thesis, using a short-FL source having a much higher ultrasonic frequency. The important result is that the nodes are nearly in the same place relative to the central antinode and the antinodes at each end. What is important about the results in (c) and (d) is that for the first time, the general mode shape has been measured with the source transducer at a range of 1 m. Subsequently a higher frequency 1-m FL focused ultrasonic source was fabricated.

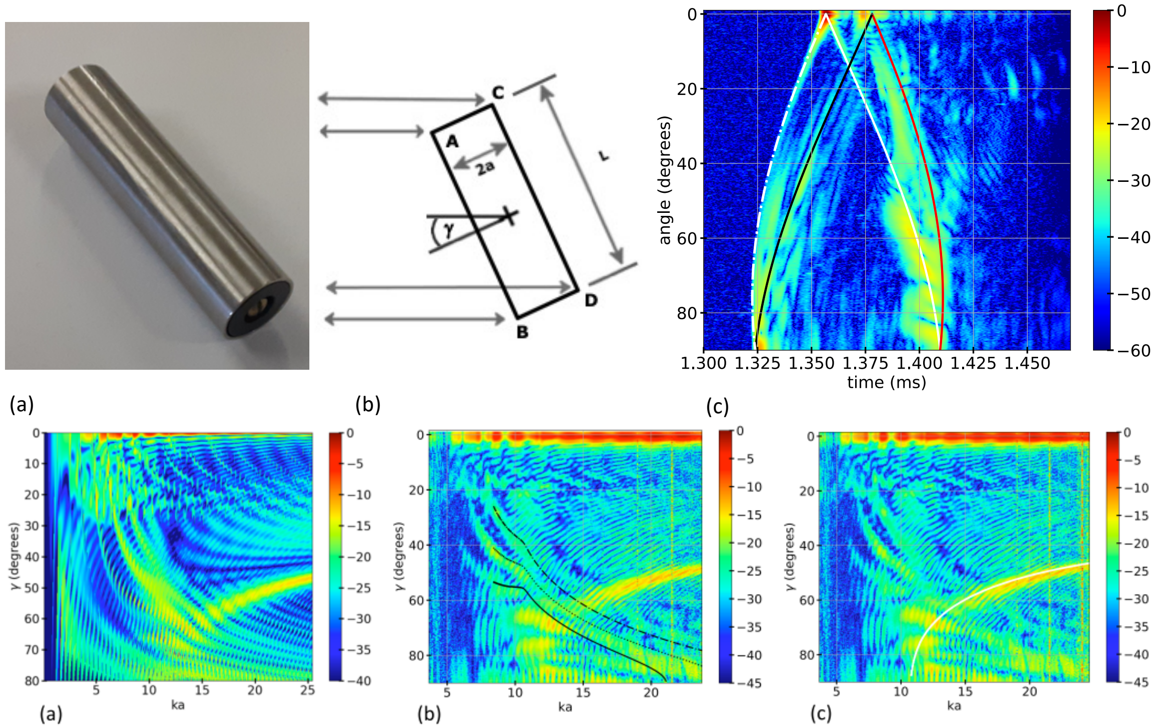

Fig. 2: From Bernard Hall's thesis and manuscript on the backscattering by an empty tilted stainless-steel cylinder in water. *Upper Row:* (a) Picture of the semi thin SS316 target. The target is air-filled with PVC endcaps. (b) The illustration depicts the target as seen from above. The "+" shows the cylinder's axis of rotation. The horizontal double arrows show the paths of incoming and outgoing sound, while each corner of the target is labeled A-D, respectively. The angle γ represents the average tilt angle of the cylinder relative to the incoming sound and to the source. L is the length of the cylinder, and *a* is its radius. (c) Time domain envelope magnitude in dB from 0-90 degrees, with calculated locations of return timings from the cylinder corners traced out. (Key: corner [A] white-dashed; [B] white; [C] black; [D] red.) *Lower Row:* (a) Calculated spectrum versus tilt angle where k*a* is the normalized frequency is the horizontal axis. Measurements are in (b) and (c). (b) Tracing of a_0− loci of M = 7 (solid), 8 (dotted), and 9 (dot-dash) for subsonic helical wave coupling where M is a circumnavigation index. (c) The white curve is the locus of a_0 meridional ray enhancement associated with a supersonic wave.

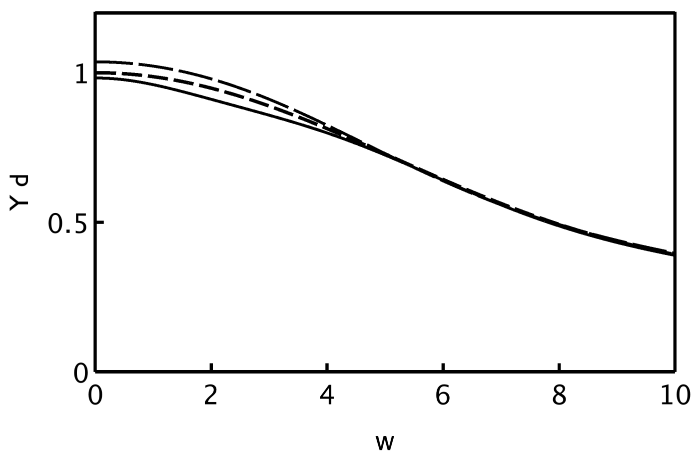

Fig. 3: The vertical axis is the normalized magnitude of dynamic radiation force function Y_d for double sideband suppressed carrier illumination. The curve with intermediate dashes is the specular contribution for a rigid sphere plotted as a function of w, the normalized dimensionless modulation frequency. The solid curve is the partial wave solution (PWS) computed here for a fixed rigid sphere with normalized carrier frequency $k_C a$ = 25. The agreement supports the relevance of the specular analysis. For applications related to target identification usually w will be small. The curve with long dashes is the PWS solution for a perfectly soft sphere with $k_C a$ = 25. Figure 3 is from our publication (J. Acoust. Soc. Am. July 2021) where additional information is given.

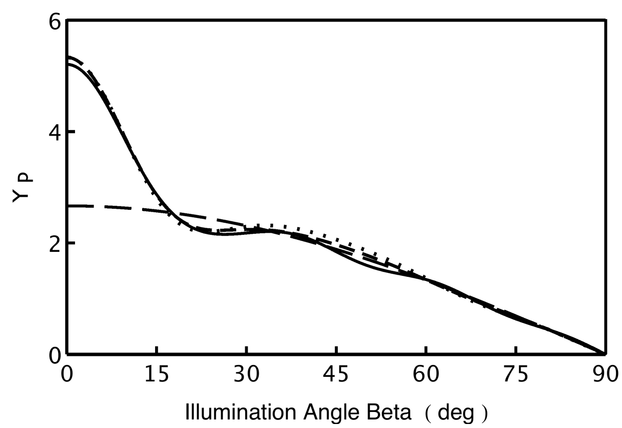

Fig. 4: The dimensionless radiation force function Y_P (normalized as for a single illuminating wave) is plotted as a function of the slant angle Beta for illumination by two slanted waves for a rigid cylinder. The smooth curve with long dashes is a specular model that neglects interference between waves. The remainder of the curves are for the normalized frequency k*a* = 7.5. The solid curve is a partial wave series (PWS) prediction. The curve with points is the full specular reflection approximation and the curve plotted as short dashes is without a small contribution. Figure 4 is from our publication (J. Acoust. Soc. Am. September 2022) where additional information is given. Figures 3 and 4 support using approximate radiation pressure expressions at ultrasonic frequencies for large objects.

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14. ABSTRACT
The purpose of this investigation was to improve the understanding of the way that sound in water interacts with various types of targets in situations similar to those encountered in underwater acoustics. Objectives of this project include improving methods for acquiring acoustical signatures of targets in water and models for understanding such signatures and methods of extracting, displaying, and using signatures. One of the approaches in the proposed research concerns aspects of target responses to acoustic radiation forces of focused sound beams. This component involves laboratory experiments and development of underlying theory. Other components of the research concern complications resulting from target proximity to interfaces or target placement in waveguides. Aspects of the research involve elastic responses of targets at high frequencies and associated signature contributions.

15. SUBJECT TERMS
Acoustical Scattering, Spheres, Cylinders, Acoustic Beams, Synthetic Aperture Sonar, Acoustic Holography, Acoustic Radiation Force, Modulated Radiation Force, Time-Frequency-Angle-Response, Acoustic Color

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