Published in final edited form as:

Ultrasonics. 2008 July ; 48(3): 209–219. doi:10.1016/j.ultras.2008.01.002.

Investigating the absolute phase information in acoustic wave resonance scattering

F.G. Mitri^{a,*}, J.F. Greenleaf^a, Z.E.A. Fellah^b, and M. Fatemi^a

^aMayo Clinic College of Medicine, Department of Physiology and Biomedical Engineering, Ultrasound Research Laboratory, 200 First Street SW, Rochester MN 55905, USA

^bLaboratoire de Mécanique et d'Acoustique, CNRS-UPR 7051, 31 chemin Joseph Aiguier, Marseille, 13009, France

Abstract

The aim of this work is to investigate the absolute phase information in resonance acoustic scattering by spheres and cylinders and place this work in the broader context of scattering in which the properties of the magnitude and (processed) phase have been examined in a more general way than in the classical Resonance Scattering Theory (RST). Here, comparisons are made between the classical and modified RST formalisms of acoustic resonance scattering. Experimental and theoretical backscattering form functions are obtained and discussed. It is shown that the magnitude and processed (unwrapped) phase can be correctly obtained through the classical RST, suggesting that the modified RST formalism offers little new practical advantage. Furthermore, the absolute phase is shown to be very sensitive to object's resonances, suggesting that the unwrapped phase may be considered as an efficient tool, along with the magnitude information, to carry out remote (active) classification of targets in underwater acoustics applications. The combination of absolute phase information with the magnitude data offers a complementary advantage in the identification of resonances from cylinders and spheres.

Keywords

Acoustic scattering

Introduction

The Resonance Scattering Theory (RST) in acoustics [1–4] explains scattering problems by decomposing the backscattering echoes into a “rigid”, “intermediate [5–7] (mid-way)” or “soft” background part and a resonance part. The resonance part contains the material's “features” such as its mechanical properties composition and shape. So, subtracting the background component from the total backscattered signal defines how to obtain the resonance component [8]. RST has been actively studied in the aim of identifying targets from resonances in their echoes [9]. A number of models have been developed which gave accurate determination of the magnitude of the backscattered signals [1, 10–16]. Another quantity of equal interest is the phase of the backscattered signals since, in some situations,

© 2008 Elsevier B.V. All rights reserved

*Corresponding author: F.G. Mitri, mitri@ieee.org, mitri.farid@mayo.edu Fax: +001-507-266-0361.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

many of the important features of an echo signal are preserved only if the phase is retained. Moreover, under a variety of conditions, such as when a signal is of finite length, phase information alone is sufficient to completely reconstruct a signal to within a scale factor [17]. Although the phase information has been investigated in earlier studies [3, 4, 18], it has been reported in the literature [19] that the classical formalism of the RST gave non-conclusive phase spectra; the phase wrapping leads to artificial phase jumps (wraps) not related to resonances. However, the artificial wrapping was not removed from the total and resonance backscattering form function signals presented in Ref. [19], raising the question as to whether the corresponding results can be considered conclusive and reliable for any specific application.

In many applications, the measured nonlinear phase does provide useful information, however its values are known only modulo 2π . Therefore, the measured phase should be processed (unwrapped) prior to use as comprehensible data. The resulting unwrapped phase, known as the “absolute phase”, relates to resonances and some of the mechanical properties of scatterers [20]. The crux of the phase unwrapping problem is to obtain an estimate for the absolute phase from the measured wrapped phase. Thus, the wrapped value must be unwrapped through some method to estimate the absolute phase which, in this case, is the quantity relating to the resonances of the scatterers.

The aim of this work is to investigate the absolute phase information both theoretically and experimentally, and validate/compare the magnitude and the unwrapped phase results obtained from the classical [1] and modified [19] RST models with experimental data. The short-pulse [18, 21–24] method associated with the Fast Fourier Technique (FFT) is used to excite a 440C stainless steel cylinder and sphere immersed in water, and detect the backscattered signals. Though the sample test objects are cylinder and sphere, the relevant technique and analysis can be also applied on solid cylinders and spheres coated with a viscoelastic layer of material [25–29], circular cylindrical or spherical shells, and ellipsoids [30, 31]. After FFT processing of the temporal backscattered signals, it is shown how the experimental isolated resonance information from both magnitude and absolute phase signals can be obtained. The results are compared and discussed, and conclusions are presented.

1. Exact form functions for cylinders and spheres

The steady-state scattered pressure in the far field from a cylinder [32] placed in a plane wave acoustic field has the following form:

$$P_{sc} = P_{inc} \sqrt{\frac{a}{2r}} f_{\infty}^{(c)}(ka, \theta) e^{ikr}, \quad (1)$$

and the steady-state scattered pressure in the far field from a sphere [33, 34] has the following form:

$$P_{sc} = P_{inc} \frac{a}{2r} f_{\infty}^{(s)}(ka, \theta) e^{ikr}, \quad (2)$$

where P_{inc} is the pressure amplitude of the incident acoustic wave, a is the cylinder or sphere radius, r is the distance from the center of the cylinder (or sphere) to some distance observation point, $k = \omega/c$ is defined as the wave vector of the incident plane wave, ω is the angular frequency, c is the speed of sound in the fluid medium, and θ is the angle between the forward direction of the incident beam and a straight line connecting the scattering point and the detector. The (complex) form functions (known also as Rayleigh series) for a

cylinder $f_{\infty}^{(c)}(ka, \theta)$ and a sphere $f_{\infty}^{(s)}(ka, \theta)$, respectively, are expressed by the exact partial wave series as

$$f_{\infty}^{(c)}(ka, \theta) = \frac{2}{\sqrt{i\pi ka}} \sum_{n=0}^{\infty} \varepsilon_n C_n(ka) \cos(n\theta), \quad (3)$$

$$f_{\infty}^{(s)}(ka, \theta) = \frac{2}{ika} \sum_{n=0}^{\infty} (2n+1) S_n(ka) P_n(\cos\theta). \quad (4)$$

The parameter in ε_n Eq.(3) is the Neumann factor and is defined as: $\varepsilon_0 = 1$, $\varepsilon_{n>1} = 2$. The functions $C_n(ka)$ and $S_n(ka)$ are the scattering coefficients determined by applying the following boundary conditions at the interface fluid-structure: (1) the pressure in the fluid equals the normal component of stress in the solid at the interface, (2) the normal (radial) component of displacement (or velocity, respectively) of the fluid must be equal to the normal component of displacement (or velocity, respectively) of the solid at the interface, (3) the tangential components of shearing stress must vanish at the surface of the solid (since the exterior fluid medium is considered to be non-viscous). These functions depend on the cylinder or sphere's material parameters such as the longitudinal sound speed c_L , the shear or transverse sound speed c_T , and the mass densities of both the fluid ρ_f and the structure ρ_s . These scattering coefficients are given in standard texts [2].

2. Resonance form functions for cylinders and spheres

Using the standard formalism of the RST [1], the resonance form functions were obtained by subtracting the proper background term (rigid, soft or intermediate) from the total form functions that represent the total scattered pressure field. The resonance form functions for a cylinder and sphere, respectively, using the classical RST [1] are expressed as

$$f_{\infty}^{(c)res}(ka, \theta) = \sum_{n=0}^{\infty} f_n^{(c)res}(ka, \theta) = \frac{2}{\sqrt{i\pi ka}} \sum_{n=0}^{\infty} \varepsilon_n [C_n(ka) - C_n^r(ka)] \cos(n\theta), \quad (5)$$

$$f_{\infty}^{(s)res}(ka, \theta) = \sum_{n=0}^{\infty} f_n^{(s)res}(ka, \theta) = \frac{2}{ika} \sum_{n=0}^{\infty} (2n+1) [S_n(ka) - S_n^r(ka)] P_n(\cos\theta), \quad (6)$$

where $C_n^r(ka)$ and $S_n^r(ka)$ are the scattering coefficients for a rigid immovable cylinder or sphere, respectively, given in Ref. [19].

It has been shown [19] that the classical RST formalism gave similar resonance magnitude information for *each* partial resonance mode (i.e. $n = 0, 1, 2 \dots$), however the magnitude of the resonance form function differs from the one obtained using the formalism developed in Ref. [19]. The resonance formalism developed in [19] requires isolating a constant term that hides resonances unless it is removed. Therefore, the resonance form functions in the far field for a cylinder and a sphere (involving the isolation of resonances from a *rigid* background), respectively, are expressed as [19]

$$f_{\infty}^{(c)res}(ka, \theta) = \sum_{n=0}^{\infty} f_n^{(c)res}(ka, \theta) = \frac{2}{\sqrt{i\pi ka}} \sum_{n=0}^{\infty} \varepsilon_n \left[\frac{C_n(ka) - C_n^r(ka)}{1 + 2C_n^r(ka)} \right] \cos(n\theta), \quad (7)$$

$$f_{\infty}^{(s)res}(ka, \theta) = \sum_{n=0}^n f_n^{(s)res}(ka, \theta) = \frac{2}{ika} \sum_{n=0}^{\infty} (2n+1) \left[\frac{S_n(ka) - S_n^r(ka)}{1 + 2S_n^r(ka)} \right] P_n(\cos\theta), \quad (8)$$

[A typeset error is noted in equations (19a), (19b), (28) and (29) in Ref.¹⁹ in which the argument of the Legendre polynomials $P_n(\cdot)$ should be “ Similarly, one can define the resonance form functions involving the isolation of resonances from a soft background (See Ref. [19]).

3. Experimental procedure

The targets 440C stainless steel cylinder and sphere were immersed in a tank of degassed water. A pulse generator periodically sent an electric pulse to a piston flat transducer for a duration of 100 ns. The broadband transducer acted as a transmitter-receiver. In the receiving mode, the backscattered signal ($\theta = \pi$) is digitized (after averaging to get rid of measurement noise) and displayed using an oscilloscope (Tektronix, TDS 3014), which performs waveform processing. The digital data were transmitted via an IEEE bus interface to a computer to perform a Fast Fourier Transform (FFT) with Matlab software. Extraction of the form function curves is based on the calibration technique for acoustic scattering measurements described explicitly in [21].

In the first experiment, a 440C stainless steel cylinder ($\rho_s = 7840 \text{ kg/m}^3$; $c_L = 5854 \text{ m/s}$; $c_T = 3150 \text{ m/s}$) of 6.4 mm-diameter was used. The cylinder, placed in the far field region at a distance of 12 cm, was insonified normally to its revolution axis by a wideband transducer (Panametrics, V306) operating at a central frequency of 2.25 MHz ($ka \approx 30.15$), and having a diameter of 14 mm. In the second experiment, a 440C stainless steel sphere of 3-mm diameter, suspended like a pendulum in the far field region at a distance of 15 cm, was insonified by a wideband transducer (Panametrics, V309) operating at a central frequency of 5 MHz ($ka \approx 31.4$), and having a diameter of 14 mm.

Isolating the resonances required temporal filtering of the backscattered signal in a way that the specularly reflected echo that corresponded to the rigid response of the target was eliminated. The resulting resonance spectra were obtained from the FFT of the remaining filtered signal. It was noticed that the resonance spectrum was composed of wide resonance peaks, which were related to strongly coupled waves at the interface stainless steel-water. It is important to note that the location and duration of the gated signal are critical parameters. If the length of the gate is too short, some resonances can be missed. For a given length of the gate, it is observed that the frequency spectrum is modified as the delay increases. When the gate is sufficiently delayed after a certain critical value, some resonances tend to disappear (those related to Rayleigh waves [22]), and the remainder became sharp resonance peaks that corresponded to ringing waves of lower reemission coefficient as a result of exciting the cylinder or sphere by the incident pulse. In our case, the resonances are isolated by FFT processing of the remaining signal after filtering out temporally the specularly reflected echo manifested as a high amplitude pulse at the beginning of the backscattered signal.

4. Results and discussion

This study aims to investigate experimentally the absolute phase information obtained from processing the backscattering signals from cylindrical and spherical structures, and compare it with the classical and modified RST results.

The experimental total and resonance backscattering form function curves are obtained by FFT processing of the temporal backscattered signal from either the stainless steel cylinder

or sphere. The theoretical approach for obtaining the theoretical total backscattering form function curves is based on evaluating Eqs. 3 and 4, whereas the classical and modified RST form function curves are evaluated using Eqs. 5–8 for the cylinder and sphere respectively. The mechanical properties for the stainless steel material are $\rho_s = 7840 \text{ kg/m}^3$; $c_L = 5854 \text{ m/s}$; $c_T = 3150 \text{ m/s}$, and the surrounding fluid is water ($\rho_f = 1000 \text{ kg/m}^3$; $c_f = 1500 \text{ m/s}$). Computations of the total and resonance backscattering form functions are performed in a range of dimensionless frequency $ka = 45$ by intervals of 0.001. It is very important to choose a sufficiently small increment to capture the resonance magnitude peaks as well as the exact π -phase shift that are very sharp. One hundred fifty modal terms are kept in the backscattering form functions (i.e. Eqs. (3)–(8)) used to generate the curves to insure proper convergence of the series. This number was checked and chosen by numerical evaluation and analysis of its unchanging corresponding curve.

Figure 1 shows the total backscattered temporal signal from the stainless steel cylinder as received by the ultrasound transducer (Panametrics, V306). Figure 2 shows comparisons of experimental (obtained after FFT processing) and theoretical plots for the magnitude

$|f_\infty^{(c)}(ka, \pi)|$, phase $\angle f_\infty^{(c)}(ka, \pi)$, absolute (unwrapped) phase $^{UW}\{ \angle f_\infty^{(c)}(ka, \pi) \}$, and the derivative of the absolute phase $\Delta^{(c)}(ka, \pi) = d \left(^{UW}\{ \angle f_\infty^{(c)}(ka, \pi) \} \right) / d(ka)$ of the total backscattering form functions. The experimental magnitude signal is corrected by subtracting the backscattering signal from the natural frequency response of the transducer as measured by a needle hydrophone. The operator “ UW ” corresponds to the function “UNWRAP” [35] which is used to process the phase information after implementing the “ATAN2” [35] function. The “ UW ” operator corrects the radian phase angles to produce smoother phase plots based on a branch cut crossings algorithm [35, 36]. The function “DIFF” [35] is used to compute the derivative versus ka . One notices from the phase plots that the 2π jumps occur arbitrarily. These jumps are not related to resonances of the cylinder. After processing the wrapped phase with the “ UW ” operator, the absolute phase is obtained. At first sight, it may appear that the unwrapped phase is not a sensitive indication of resonances; this is due to the large scale on the graph. However, these variations will appear more clearly if a small ka -bandwidth is selected. To highlight the absolute phase sensitivity to the resonances of the cylinder, its derivative (i.e. $\Delta^{(c)}(ka, \pi)$) is evaluated. Dips and peaks in the magnitude form function curves are related to sharp variations in the $\Delta^{(c)}(ka, \pi)$ curves.

Figure 3 shows a comparison between experimental and theoretical backscattering *resonance* form function curves for the cylinder using the classical RST. The experimental resonance form function curves are obtained by FFT processing of the remaining signal ($4.83 \mu\text{s} \leq t \leq 100 \mu\text{s}$) after eliminating the specular echo as described in the experimental procedure in Sec. III. The simulated resonance backscattering form function curves are obtained from the classical RST by numerical evaluation of Eq.(5). Obtaining properly the phase from the *resonance* form function curves requires a particular arithmetic manipulation. It is important to note that eliminating the specular echo in time domain leaves the magnitude unchanged, but induces a linear phase shift denoted here by ϕ_{sh} . When analyzing the phase of the *resonance* form function curves (after subtraction of the specular echo), one should correct for this induced phase shift to obtain the proper phase information. This phase shift is defined as $\phi_{sh} = (ka)t_{sh}c/a$, where t_{sh} is the duration of the specular echo signal determined experimentally (i.e. $1.75 \mu\text{s}$ and $5.22 \mu\text{s}$ for the cylinder and sphere respectively). Therefore, the correct phase computation of the experimental *resonance* form function curves (for both cylinder and sphere) should be expressed as

$$\angle f_{\infty}^{(c,s)res}(ka, \pi) = \tan^{-1} \left(\frac{\mathcal{I} \left[f_{\infty}^{(c,s)res}(ka, \pi) \cdot \exp(-i\phi_{sh}) \right]}{\mathcal{R} \left[f_{\infty}^{(c,s)res}(ka, \pi) \cdot \exp(-i\phi_{sh}) \right]} \right), \quad (9)$$

where $\mathcal{I}[\cdot]$ and $\mathcal{R}[\cdot]$ correspond to the imaginary and real parts of a complex number.

Figure 4 shows the comparison between experimental and theoretical *resonance* form function curves as obtained using the modified RST via Eq.(7). By comparing the classical and modified RST results, one observes that both theories agree with the experimental data to some extent.

One also notices by comparing the $UW \left\{ \angle f_{\infty}^{(c)}(ka, \pi) \right\}$ curves in Fig. 2 to Figs. 3 and 4, the change from a decrease to an increase in the slope. The decrease in the slope (Fig. 3) is the result of a positive delay (shift to the right) as the wave propagates in its backscattering wave motion. When the specular echo is eliminated, which correspond to a negative delay (time domain shift to the left), there is an increase in the slope, and the unwrapped phase remains close to straight line. This property is summarized as follows: a shift in the time domain corresponds to changing the slope of the phase.

Figure 5 shows the total backscattered temporal signal from the 440C stainless steel sphere as received by the ultrasound transducer (Panametrics, V309). Figure 6 shows comparisons of experimental (obtained after FFT processing of the temporal signal (Fig. 5)) and

theoretical plots for the magnitude $\left| f_{\infty}^{(s)}(ka, \pi) \right|$, phase $\angle f_{\infty}^{(c)}(ka, \pi)$, absolute (unwrapped) phase $UW \left\{ \angle f_{\infty}^{(s)}(ka, \pi) \right\}$, and the derivative of the absolute phase

$\Delta^{(s)}(ka, \pi) = d \left(UW \left\{ \angle f_{\infty}^{(s)}(ka, \pi) \right\} \right) / d(ka)$ of the total backscattering form functions. As shown in Fig. 6, experimental results agree with the theoretical predictions, and the phase information (i.e. $\Delta(s)(ka\pi)$) is a sensitive indication of the resonances.

Figure 7 shows a comparison between experimental and theoretical backscattering *resonance* form function curves of the sphere as obtained via the classical RST. The experimental resonance form function curves are obtained by FFT processing of the remaining signal ($4.08 \mu s \leq t \leq 250 \mu s$) after eliminating the specular echo in the temporal signal (Fig. 5).

Figure 8 shows a comparison between experimental and theoretical backscattering *resonance* form function curves of the sphere as obtained through the modified RST. Comparing both the classical and modified RST results, one notices that the classical RST results are more satisfactory than the modified RST results regarding the magnitude amplitude and sensitivity to the resonance peaks positions.

Theoretical classical and modified acoustic resonance scattering of the fundamental ($n = 0$) partial wave, is analyzed in Figs. 9-(a)–(b) for an aluminum cylinder ($\rho_s = 2800 \text{ kg/m}^3$; $c_L = 6370 \text{ m/s}$; $c_T = 3070 \text{ m/s}$) immersed in water. The phase plot is obtained through Eq.(9) and unwrapped as described previously for proper analysis. By comparing the classical and modified RST results, one obviously notices that while the magnitudes are identical, the phases are different. The phase of the resonance form function $\angle f_{\infty}^{(c)res}(ka, \pi)$ shows artificial phase jumps not related to resonances. However, if unwrapped, the absolute phase $UW \left\{ \angle f_{\infty}^{(c)res}(ka, \pi) \right\}$ is shown to be sensitive to resonances.

Previous work [37] has shown that the total backscattering form function magnitude can be locally large or small depending on whether the interference between the specular and Rayleigh contributions to acoustic backscattering is constructive or destructive. It is anticipated that this effect influences the absolute phase. It would be therefore interesting to examine the contribution of the Rayleigh wave phase to the total absolute phase, which will be the subject of future investigations.

In this work, the direct acoustic backscattering problem, which involves determining the backscattered field that arises when an incident field impinges on the solid material with known physical properties is considered. However, in many applications such as in NDT and NDE, the physical or mechanical properties of the tested objects are not well known *a priori*. It is therefore of some importance to work out new experimental methods and efficient tools for estimation of those properties and this process is known as inverse acoustic scattering. The basic inverse problem associated with the acoustic backscattering signals is to find the values of the medium's parameters by correlating experimental and theoretical data. Although some experimental techniques for the inversion of acoustic scattering signals appeared in the literature (page 281 in Ref.[2]), [38–43], they were mainly focused on processing the magnitude information only. The results obtained here show that phase is sensitive to object's resonances. It is therefore anticipated that the phase signals may be of valuable information to determine materials mechanical properties and shape from acoustic backscattering signals by inverse problem.

5. Conclusion

In this work, the absolute phase information extracted from experimental acoustic backscattering signals of a 440C stainless steel cylinder and sphere is investigated. It is also shown that the classical RST phase information, if correctly processed (unwrapped), is exact and provide useful information related to object's resonances. It is also shown to some extent that the classical RST gives more satisfactory results than the modified RST when compared to experimental data, suggesting that the modified RST formalism offers little new practical advantage. Moreover, the experimental phase of the *resonance* form functions is corrected (i.e. Eq. 9) to take into account the phase shift that occurred when eliminating the specular echo in time domain, which is in agreement to some extent with theoretical unwrapped phase results. It is shown that a shift in the time domain corresponds to changing the slope of the phase. It is therefore suggested that the unwrapped phase obtained from resonance form functions may be considered as an efficient tool, along with the magnitude information, to carry out remote (active) classification of targets in underwater acoustics applications. The combination of absolute phase information with the magnitude data offers a complementary advantage in the identification of resonances from cylinders and spheres.

Acknowledgments

The first author is grateful to Dr. M.W. Urban for the help in signal processing and discussion. The authors thank R.R. Kinnick for technical and laboratory support. This work was supported by Grant No. EB 00535-04 from the National Institute of Health.

References

- [1]. Flax L, Dragonette LR, Uberall H. Theory of elastic resonance excitation by sound scattering. *Journal of the Acoustical Society of America*. 1978; 63:723–731.
- [2]. Flax, L.; Gaunaurd, GC.; Uberall, H. Theory of Resonance Scattering. In: Thurston, RN.; Pierce, AD., editors. *Physical Acoustics*. Vol. Chap. 3. Academic Press; San Diego: 1981. p. 191-294.
- [3]. Gaunaurd GC. Elastic and acoustic resonance wave scattering. *Applied Mechanics Reviews*. 1989; 42:143–192.

- [4]. Gaunaurd GC, Werby MF. Acoustic resonance scattering by submerged elastic shells. *Applied Mechanics Reviews*. 1990; 43:171–208.
- [5]. Murphy JD, Breitenbach ED, Uberall H. Resonance scattering of acoustic waves from cylindrical shells. *Journal of the Acoustical Society of America*. 1978; 64:677–683.
- [6]. Murphy JD, George J, Nagl A, Uberall H. Isolation of the resonant component in acoustic scattering from fluid-loaded elastic spherical shells. *Journal of the Acoustical Society of America*. 1979; 65:368–373.
- [7]. Murphy JD, George J, Uberall H. Isolation of the resonant component in acoustic scattering from fluid-loaded cylindrical shells. *Wave Motion*. 1979; 1:141–147.
- [8]. Werby MF. The acoustical background for a submerged elastic shell. *Journal of the Acoustical Society of America*. 1991; 90:3279–3287.
- [9]. Gaunaurd GC, Strifors HS. Transient resonance scattering and target identification. *Applied Mechanics Reviews*. 1997; 50:131–149.
- [10]. Gaunaurd GC, Uberall H. Numerical evaluation of modal resonances in the echoes of compressional waves scattered from fluid-filled spherical cavities in solids. *Journal of Applied Physics*. 1979; 50:4642–4660.
- [11]. Gaunaurd GC, Akay A. Isolation of the spectrograms and rosettes of insonified sets of submerged, concentric, thin shells. *Journal of Vibration and Acoustics - Transactions of the ASME*. 1994; 116:573–577.
- [12]. Marston PL, Sun NH. Backscattering near the coincidence frequency of a thin cylindrical-shell - surface-wave properties from elasticity theory and an approximate ray synthesis. *Journal of the Acoustical Society of America*. 1995; 97:777–783.
- [13]. Hefner BT, Marston PL. Backscattering enhancements associated with subsonic Rayleigh waves on polymer spheres in water: Observation and modeling for acrylic spheres. *Journal of the Acoustical Society of America*. 2000; 107:1930–1936. [PubMed: 10790018]
- [14]. Mitri FG, Fellah ZEA, Chapelon JY. Acoustic backscattering form function of absorbing cylinder targets (L). *Journal of the Acoustical Society of America*. 2004; 115:1411–1413.
- [15]. Pareige P, Maze G, Izbicki JL, Ripoche J, Rousselot JL. Internal acoustical excitation of shells: Scholte and whispering gallery-type waves. *Journal of Applied Physics*. 1989; 65:2636–2644.
- [16]. Brill D, Gaunaurd GC, Uberall H. The response surface in elastic wave scattering. *Journal of applied Physics*. 1981; 52:3205–3214.
- [17]. Oppenheim AV, Lim JS. The importance of phase in signals. *Proceedings of the IEEE*. 1981; 69:529–541.
- [18]. Maze G. Acoustic scattering from submerged cylinders. *MIIR Im/Re: Experimental and theoretical study*. *Journal of the Acoustical Society of America*. 1991; 89:2559–2566.
- [19]. Rhee H, Park Y. Novel acoustic wave resonance scattering formalism. *Journal of the Acoustical Society of America*. 1997; 102:3401–3412.
- [20]. Peters F, Petit L. A broad band spectroscopy method for ultrasound wave velocity and attenuation measurement in dispersive media. *Ultrasonics*. 2003; 41:357–363. [PubMed: 12788217]
- [21]. Dragonette LR, Numricha K, Frank LJ. Calibration technique for acoustic scattering measurements. *Journal of the Acoustical Society of America*. 1981; 69:1186–1189.
- [22]. de Billy M. Determination of the resonance spectrum of elastic bodies via the use of short pulses and Fourier transform theory. *Journal of the Acoustical Society of America*. 1986; 79:219–221.
- [23]. Ripoche J, Maze G, Izbicki JL. A new acoustic spectroscopy: Resonance spectroscopy by the MIIR. *Journal of Nondestructive Evaluation*. 1985; 5:69–79.
- [24]. Brill D, Gaunaurd GC, Uberall H. Acoustic spectroscopy. *Journal of the Acoustical Society of America*. 1982; 72:1067–1069.
- [25]. Gaunaurd GC, Kalnins A. Resonances in the sonar cross sections of coated spherical shells. *International Journal of Solids and Structures*. 1982; 18:1083–1102.
- [26]. Mitri FG. Acoustic radiation force due to incident plane-progressive waves on coated spheres immersed in ideal fluids. *European Physical Journal*. 2005; B 43:379–386.

- [27]. Mitri FG. Acoustic radiation force due to incident plane-progressive waves on coated cylindrical shells immersed in ideal compressible fluids. *Wave Motion*. 2006; 43:445–457.
- [28]. Mitri FG. Calculation of the acoustic radiation force on coated spherical shells in progressive and standing plane waves. *Ultrasonics*. 2006; 44:244–258. [PubMed: 16545414]
- [29]. Gaunaurd GC. Sonar cross section of a coated hollow cylinder in water. *Journal of the Acoustical Society of America*. 1977; 61:360–368.
- [30]. Wei W, Thiessen DB, Marston PL. Acoustic radiation force on a compressible cylinder in a standing wave. *Journal of the Acoustical Society of America*. 2004; 116:201–208.
- [31]. Leon F, Chati F, Conoir JM. Acoustic scattering by an elastic elliptic cylinder in water: numerical results and experiments. *Ultrasonics*. 2004; 42:297–300. [PubMed: 15047301]
- [32]. Dardy HD, Bucaro JA, Schuetz LS, Dragonette LR. Dynamic wide-bandwidth acoustic form-function determination. *Journal of the Acoustical Society of America*. 1977; 62:1373–1376.
- [33]. Neubauer WG, Vogt RH, Dragonette LR. Acoustic reflection from elastic spheres. I. Steady-state signals. *Journal of the Acoustical Society of America*. 1974; 55:1123–1129.
- [34]. Dragonette LR, Vogt RH, Flax L, Neubauer WG. Acoustic reflection from elastic spheres and rigid spheres and spheroids. II. Transient analysis. *Journal of the Acoustical Society of America*. 1974; 55:1130–1137.
- [35]. Matlab. <http://www.mathworks.com/>
- [36]. Ghiglia, DC.; Pritt, MD. Two-Dimensional Phase Unwrapping--Theory, Algorithms, and Software. Vol. Chap. 4. John Wiley & Sons; Canada: 1998. Path-following methods; p. 100-177.
- [37]. Williams KL, Marston PL. Synthesis of backscattering from an elastic sphere using the Sommerfeld-Watson transformation and giving a Fabry-Perot analysis of resonances. *Journal of the Acoustical Society of America*. 1986; 79:1702–1708.
- [38]. Brigham JC, Aquino W, Mitri FG, Greenleaf JF, Fatemi M. Inverse estimation of viscoelastic material properties immersed in fluids using vibroacoustic techniques. *Journal of Applied Physics*. 2007; 101:023509.
- [39]. Cohen-Tenoudji F, Tittmann BR, Quentin G. Technique for the inversion of backscattered elastic wave data to extract the geometrical parameters of defects with varying shape. *Applied Physics Letters*. 1982; 41:574–576.
- [40]. Gericke OR. Determination of the geometry of hidden defects by ultrasonic pulse analysis testing. *Journal of the Acoustical Society of America*. 1963; 35:364–368.
- [41]. Mitri FG. Inverse determination of porosity from object's resonances. *Journal of Applied Physics*. 2004; 96:5866–5869.
- [42]. Gaunaurd GC. Transient and steady state scattering of acoustic waves from elastic objects in fluids and of elastic waves from inclusions in solid media: direct and inverse scattering aspects. *Journal of Sound and Vibration*. 1992; 159:421–440.
- [43]. Fellah ZEA, Mitri FG, Depollier C, Berger S, Lauriks W, Chapelon JY. Characterization of porous materials with a rigid frame via reflected waves. *Journal of Applied Physics*. 2003; 94:7914–7922.

Fig. 1. Backscattered pressure pulse as received from a 440C stainless steel cylinder immersed in water.

Fig. 2.

Comparisons between experimental (solid line) and theoretical (dashed line) magnitudes

$|f_{\infty}^{(c)}(ka, \pi)|$, phases $\angle f_{\infty}^{(c)}(ka, \pi)$, absolute (unwrapped) phases $UW\{\angle f_{\infty}^{(c)}(ka, \pi)\}$, and derivatives of the absolute phase $\Delta^{(c)}(ka, \pi) = d(UW\{\angle f_{\infty}^{(c)}(ka, \pi)\})/d(ka)$ of the total backscattering form functions for the 440C stainless steel cylinder.

Fig. 3.

Comparisons between experimental (solid line) and theoretical (dashed line) resonance

magnitudes $|f_{\infty}^{(c)res}(ka, \pi)|$, phases $\angle f_{\infty}^{(c)res}(ka, \pi)$, absolute (unwrapped) phases

$UW \{ \angle f_{\infty}^{(c)res}(ka, \pi) \}$, derivatives of the absolute phase

$\Delta^{(c)res}(ka, \pi) = d \left(UW \{ \angle f_{\infty}^{(c)res}(ka, \pi) \} \right) / d(ka)$ of the resonance form functions for the 440C stainless steel cylinder as obtained through the classical RST formalism.

Fig. 4.

Comparisons between experimental (solid line) and theoretical (dashed line) resonance magnitudes and derivatives of the absolute phase of the resonance form functions for the 440C stainless steel cylinder as obtained through the modified RST formalism.

Fig. 5. Backscattered pressure pulse as received from a 440C stainless steel sphere immersed in water.

Fig. 6.
The same as in Fig. 2 but for a 440C stainless steel sphere.

Fig.7.

The same as in Fig. 3 but for a 440C stainless steel sphere.

Fig. 8.
The same as in Fig. 4 but for a 440C stainless steel sphere.

Fig. 9.

Comparisons of theoretical magnitudes, phases and unwrapped phases of isolated resonances using the classical (a) and the modified (b) RST for the monopole ($n=0$) resonance of an aluminum cylinder immersed in water.