The Physics of Sound Scattering From, and Attenuation Through, Compliant Bubbly Mixtures

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LONG-TERM GOALS

The goal of this research is to acquire a quantitative understanding, leading to predictive models, of the broader aspects of linear and nonlinear sound scattering, transmission and coherency in oceanic bubbly mixtures pertinent to the shallow-water acoustics. This includes a conceptual understanding of the role played by damping and stabilization mechanisms in bubble dynamics and longevity. Of particular interest is the delineation of different regimes of behavior as a function of frequency, size distribution, flow and volume fraction.

OBJECTIVES

An objective specific to this project is the extension of the theory of sound transmission and coherency in bubbly liquids to derive attenuation characteristics for both small amplitude (linear response) and large amplitude (nonlinear response) forcing, ultimately incorporating the effects of contaminating surface-active solutes. A second objective is the development of a unique laboratory capability for the precise and accurate measurement of the frequency-dependent complex acoustic impedance of, scattering from, and the coherency of propagation through well-characterized bubble ensembles *for frequencies spanning the individual bubble resonance frequencies*. Characterization implies the precise knowledge of the space- and time-dependent bubble density and size distribution.

APPROACH

The approach involves a balance between theory, analytical modeling and experiments to predict and measure propagation, scattering, and coherency characteristics. The dynamics of a single bubble for both small and large amplitude forcing and is treated numerically using the Keller formulation for bubble dynamics. Attributes of bubble behavior (mainly damping and resonance response) can be quantified and incorporated into a comprehensive description of sound propagation, scattering and coherency by extending the Wood-Foldy-Morse theories. The final step is to incorporate the effect of surface active materials by adapting numerical models developed by Church [1995] and Allen & Roy [2000a&b], among others.

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Laboratory experiments cover two fronts of activity. FY00 efforts focused on the measurement of the complex impedance of bubble distributions terminating a sound-hard impedance tube over frequencies ranging from well below to well above bubble resonance. The bubbly medium can be characterized optically using a stereo microscope and electrically by way of conductivity measurements to determine void fraction. A variant of the dual-sensor impedance tube technique is employed. From this, the frequency-dependent phase velocity and attenuation of the bubbly medium is obtained.

The second experimental thrust for FY00 is the conduct of tank experiments to measure backscatter from, and transmission through, bubble-filled test sections. Both spherical and cylindrical geometries are employed. Experiments are conducted at frequencies higher than 4 kHz and are to supplement thin walled tube experiments at frequencies between 15 and 30 kHz. The targets employ bubbly media for which the characteristics are known and boundary conditions that are rigorously defined. These experiments are also a precursor to the FY02 field experiments.

Modeling is currently focused on the development of a comprehensive and self contained formalism for describing the acoustics properties of bubbly liquids, drawing from the classical efforts of Wood, Foldy, Morse and others. This is supplemented by a parallel effort aimed at developing 1st-order correction terms that account for the surface elasticity and dilatational viscosity of surface-active layers similar to those that can coat oceanic bubbles.

WORK COMPLETED

A central thrust of these activities is to complete the development of experimental techniques suitable for use in field test planned during the FY02. During FY00, an ONR "Focused Acoustics Bubble Workshop" was held at Boston Univ. to determine the research issues of oceanic bubbles in shallow water and their influence on propagation. On behalf of the ONR, we invited experts in this field to determine the scope of these issues and to develop a research plan that provides for their resolution. Workshop participants discussed the major theoretical and experimental issues as well as the type of shallow water experiments to be conducted in coordination with the High Frequency Acoustics Communication program during FY02.

In FY00, preliminary laboratory experiments were conducted to explore sound scattering from well-defined assemblages of bubbly fluid. To date, two primary advances have been made. First, a bubble generation system has been developed to produce large amounts of appropriately sized bubbly fluid, from which to make the experimental targets. Second, an initial round of scattering experiments has been conducted using targets made with this new bubble generator. Targets also included voided polyurethane spheres and thin-walled polyurethane & polyethylene spheres filled with bubbly gel.

At low frequencies, bubble clouds can be modeled, to first order, as acoustically compact compressible spheres. An effective medium approximation [Wood,1930] is used to infer the bubble cloud's compressibility based on the void fraction. This was demonstrated at Lake Seneca [Roy *et al.,* 1992] using artificially generated, freely rising bubble clouds. Present experiments are being conducted in an indoor tank using smaller bubbles with higher resonance frequencies in order to span the effective medium, resonance, and the sonic velocimeter regions. Several liters of bubbly fluid are necessary to construct the desired scattering targets and, until now, there has been no way to generate these types of fluids. Shown in Fig. 1 is a schematic of a new high-volume bubble-generation device. Water is pumped through a porous ceramic pipe is impregnated by compressed air forced through the wall of the pipe, resulting in a nearly mono-disperse distribution of bubble sizes. The sizes are inversely proportional to the liquid velocity; hence a degree of control is available. Recirculation is utilized to increase the void fraction. Samples are tapped from the main processing system, pass through the scattering test section (not shown) and returned to the holding tank. The flow rate through this secondary circuit is low enough to be considered static on the time scale of a single acoustic pulse.

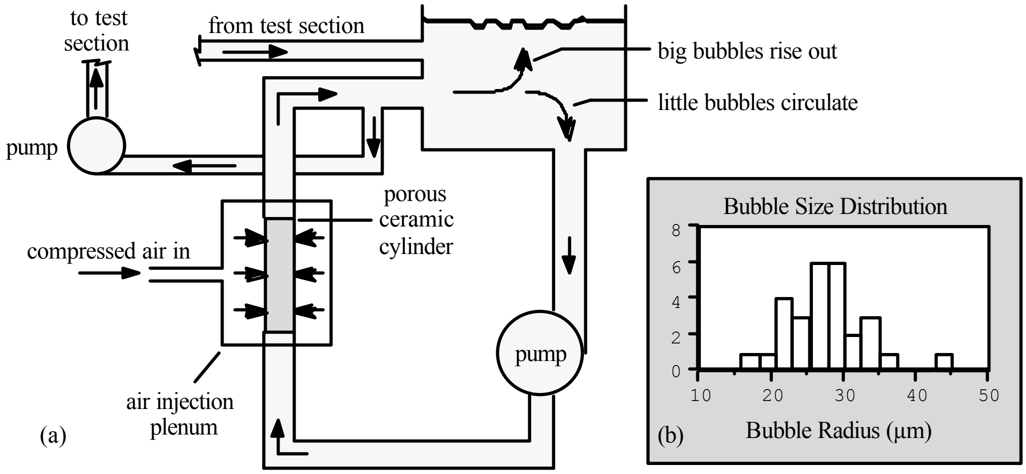

Figure 1: (a) Schematic of the bubble generation system. (b)Typical bubble size distribution produced by the system. The sample was taken from a test section at STP.

Initial scattering experiments were conducted at the NUWC Acoustic Test Facility using voided polyurethane spheres, bubbly-gel filled spheres, and a 10-m test section of thin walled latex tubing through which bubbly fluid flows. For the initial analysis, the targets were modeled as uniform, wall-less compressible spheres and cylinders (infinite length, see [Stanton,1988]). Independent void fraction determination is not yet available, so VF was fit as the only adjustable model parameter. Scattering results from cylinders with three different void fractions are shown in Fig. 2. A good quantitative fit is obtained between theory and measurement for the two lowest void fractions, but there is a 6 dB difference for the highest VF case. Although our initial analysis does not account for this discrepancy, there nonetheless am intriguing qualitative match. The resolution of this discrepancy calls for further experimentation/analysis however, the initial results are most encouraging.

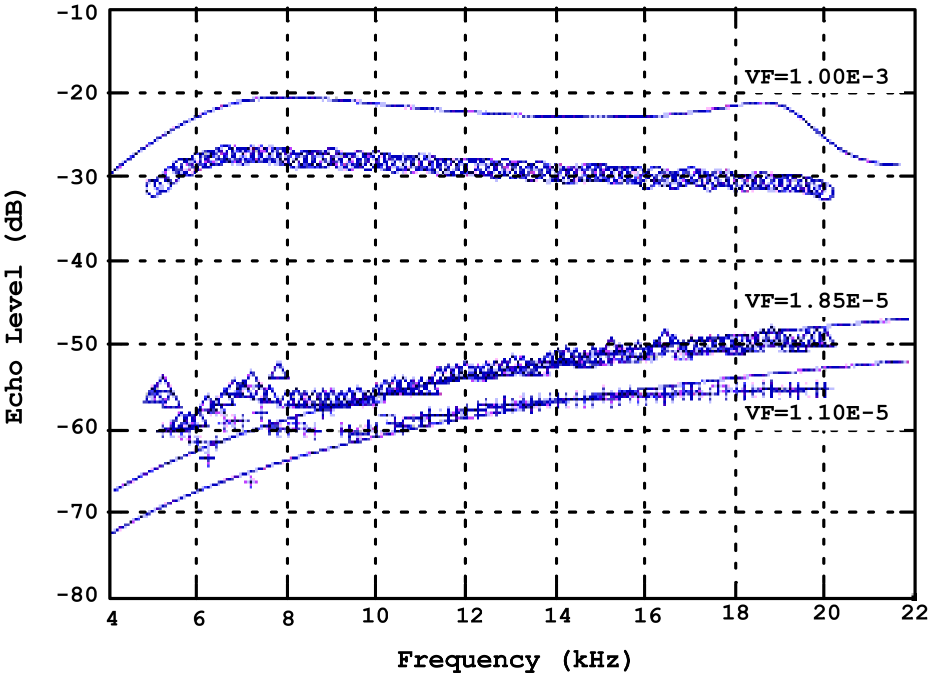

Figure 2: Measured and predicted values of scattering from a bubbly-fluid-filled latex tube with 1.27-cm id. Solid lines represent model predictions using void fraction to fit the measurements. Below 8 kHz, the scatter in the two lowest VF cases may be caused by poor signal-to-noise ratio.

The impedance tube apparatus was developed (see Fig. 3) to characterize the bubbly liquids and initial measurements were reported last year. Results agree with model calculations in all respects except for frequency-dependent damping. During FY00 we have formulated a damping model with accurately accounts for radiation damping and will be incorporated into the propagation models for both the thick-walled impedance tube and the thin-walled pulse tube. Impedance tube results were also obtained using a bubble-free polymer termination and a water termination (i.e. an open ended tube). In both cases the data agreed with theoretical predictions, however artifacts were observed in the data that suggest that a more accurate sensor phase calibration is required when probing samples with low intrinsic attenuation. An improved calibration scheme is nearing completion.

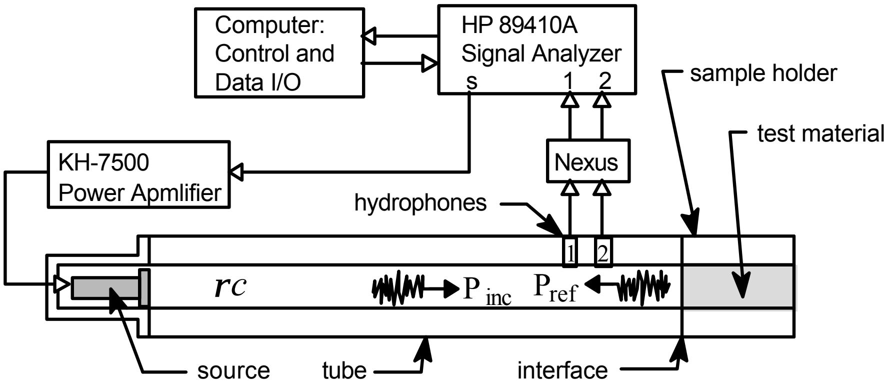

Figure 3. Impedance tube apparatus used to characterize bubbly fluids.

There were two other techniques employed for generating bubbles for laboratory scattering and propagation experiments. Freely rising micro-bubbles were generated using a rotating porous cylinder though which air is forced [Chiba & Takahashi, 1998]. Bubbly distributions were also created by suspending micro-bubbles in a 1% solution of Xanthan gum. The advantage of the latter technique is the bubble distributions in both size and space are stationary in time and easy to characterize. The disadvantage is that the impact of the viscoelastic suspending gel is not known. To address this latter point, we intend to measure the acoustic response of a single bubble suspended in the polymer gel. The frequency-dependent response of the bubble will be measured using laser Mie scattering and compared with model predictions of bubble dynamics in Newtonian and viscoelastic media.

Since the recognition that oceanic microbubbles have a dramatic influence on sound production, scattering and transmission, many articles have appeared in the acoustics literature concerning the properties of these bubbly mixtures. To extend this work to turbulent media we have examined the engineering literature on two-phase fluid flow. Relevant experimental results have been summarized and a unified theoretical treatment has been prepared to provide clarity to the community as well as a basis for our experimental work. This includes an extension to the Morse and Ingard treatment for the scattering and transmission of sound through turbulence containing bubbles. This treatment provides the basis for the calculation of signal coherency and it is our intent to test this theory in careful tank experiments. Moreover, we have made considerable progress in developing a model of sound propagation through bubbles coated with contaminating skins and layers. Correction terms that account for surface elasticity and dilatational viscosity have been incorporated into the force balance equation [Jankovsky *et al.,* 1999].

RESULTS

Multi-frequency backscattering experiments have been performed in a tank using a variety of bubbly targets of known geometries. Voided polyurethane sphere target strengths (2-20kHz) were measured for void fractions of 0%, 3.4%, and 6%; target strengths for the voided spheres where on the order of 40 dB (*re* 1m). The frequency response exhibited modal structure, with peaks shifting to lower frequencies for lower void fractions. No backscatter signal was detected for the solid polyurethane sphere. Target strength was also measured for a hollow polyurethane and polyethylene spheres containing a suspension of bubbles in polymer gel, and from a bubbly-fluid-filled latex tub. Results are consistent with an effective fluid scattering theory. These initial results are preliminary as independent void fraction determination measurements were not performed. However, qualitative agreement was found with reasonable estimates. The latex tube experiment used our new method to generate large volumes of mono-dispersed bubbly fluid samples.

Model calculations for surfactant coated bubbles show an increase in attenuation for frequencies far removed from the bubble resonance for radii less than 100 microns. There is *no* significant increase in attenuation for larger bubbles (order 1 mm). Interestingly, near resonance, the interfacial viscous case has a lower attenuation than the clean interface, most likely due to the reduced radiation damping associated with smaller radial excursions. Likewise, resonance effects on the phase speed dispersion curve are also significantly diminished due to the interfacial viscosity.

IMPACT/APPLICATIONS

The notion that bubbles can be driven to pulsate collective is important to any assessment of scattering and attenuation from oceanic bubble clouds and layers. The area of research is important to HF/SW noise and propagation, SW mine hunting sonars, high power acoustic arrays for MCM, and wake homing torpedoes. Furthermore, the acoustical measurement of bubble populations and circulation patterns may depend on the physics of multiple scattering and absorption in bubbly mixtures. Finally, the persistence of microbubbles in the shallow water column can also effect the resolution of sonars and these effects need to be quantified.

RELATED PROJECTS

1. A collaboration with NUWC/Newport (R. Costa) and CSS/Panama City (K. Commander) on an instrument designed for *in situ* measurement of oceanic bubble dissolution rates. The instrument was successfully deployed as part of a wake physics sea test at Nanoose in September, 1998 and the results were published in the Proceedings of Oceans '99 [Costa et al., 1999].

2. A collaboration with APL/UW (S. Kargl) on the physics of nonlinear beam forming. The issues of bubble-enhanced nonlinearity and dissipation in bubbly water are key to both projects. The goal of the beam forming project is to assess the viability of high-intensity sound beams for MCM.

3. A collaboration with Univ. Virginia (J. Allen) on developing new theories that describe the dynamics of bubbles in viscoelastic media. The PI was the research advisor for J. Allen, a UW Ph.D. student in Mechanical Engineering who completed his dissertation September '97.

4. A collabration with the NRL has been proposed. Meetings have been held with Dr. Franchii and his staff at NRL.

REFERENCES

J.S. Allen and R.A. Roy, 2000a, "Dynamics of gas bubbles in viscoelastic fluids I. Linear viscoelasticity," J. Acoust. Soc. Am. **107**(6), 3167-3178.

J.S. Allen and R.A. Roy, 2000b, "Dynamics of gas bubbles in nonlinear viscoelastic media," J. Acoust. Soc. Am., in press.

ASTM Standard, 1990. Standard Test Method for Impedance and Absorption of Acoustical Materials Using a Tube, Two Microphones, and a Digital Frequency Analysis System, American Society for Testing and Materials, Standard Number: E 1050-90.

N. Chiba and Y. Takahashi, 1998. "Generation of micro air bubbles of uniform size in water," Proceedings of the 3rd International Symposium on Cavitation, Grenoble, France, pp. 91-94.

C.C. Church. 1995, J. Acoust. Soc. Am. **97**, 1510-21.

R. Costa, R.A. Roy, and K.W. Commander. 1999, "A novel approach for obtaining bubble dissolution measurements at sea: Results," in Proceedings of Oceans '99, Seattle, WA, September.

J.C. Jankovsky, R.A. Roy and W.M. Carey, 1999, “The effects of interfacial viscosity on the attenuation and phase speed of acoustic waves in bubbly liquids,” J. Acoust. Soc. Am **107**(5 pt. 2), 2866.

L.D. Lafleur, F.D. Shields. 1995, Low-frequency propagation modes in a liquid-filled elastic tube waveguide, J. Acoust. Soc. Am. **97**, 1435-45.

R.A.Roy, *et al.*, 1992, Low-frequency scattering from submerged bubble clouds,” J. Acoust. Soc. Am. **92**(5): p. 2993–2996.

T.K.Stanton, 1988, “Sound scattering by cylinders of finite length. I. Fluid cylinders,” J. Acoust. Soc. Am. **83**(1): p. 55–63.

A.B.Wood, *A Text-Book of Sound*. 1st ed. 1930, New York: MacMillan.

PUBLICATIONS

J.S. Allen and R.A. Roy, “Dynamics of gas bubbles in viscoelastic fluids I. Linear viscoelasticity,” J. Acoust. Soc. Am. **107**(6), 3167-3178, 2000.

J.S. Allen and R.A. Roy, “Dynamics of gas bubbles in nonlinear viscoelastic media,” J. Acoust. Soc. Am., Accepted for publication.

R. Costa, R.A. Roy, and K.W. Commander, “A novel approach for obtaining bubble dissolution measurements at sea: Results,” in Proceedings of Oceans ’99, Seattle, WA, 1999.

I.M. Hallaj, R.O. Cleveland, P.E. Barbone, S.G. Kargl and R.A. Roy, “Amplitude degradation of time-reversed pulses in nonlinear absorbing thermoviscous fluids,” Ultrasonics **38**(9), 885-889, 2000.

R.A. Roy, P.W. Wilson and W.M. Carey, “Characterization of bubbly fluids using a sound-hard impedance tube and the transfer function technique,” in Proceedings of the European Congress on Underwater Acoustics, Lyon, France, July, 2000.

R. Evans and W. Carey, " Low-Frequency Array Response to Surface-Generated Noise" in Proceedings of the Fifth European Conference on Underwater Acoustics, ECUA 2000 Edited by P. Chevret and M.E. Zakharia, Lyon, France, 2000

W. Carey and P. Cable, " array signal gain measurements in shallow water", in proceedings of the fifth european conference on underwater acoustics,” in Proceedings of the European Congress on Underwater Acoustics, Lyon, France, July, 2000.

W. Carey, " Oceanic Low Frequency Ambient Noise" in Proceedings Of the MTS/IEEE Oceans 2000, 11-14 September, Providence RI, 2000.

W.M. Carey and R.A. Roy, “The low frequency radiation and scattering of sound from bubble clouds,” in Proceedings of Oceans 2000 Vol. 2, 1077-1084, 2000.

W. Carey, " Array Measurements and Characterizations with Relative Velocity as a Parameter" in Proceedings Of the MTS/IEEE Oceans 2000, 11-14 September, Providence RI, 2000.