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Reprints of the publications supported by this grant may be requested from the principal investigator P. L. Marston. Phone/Fax: 509-335-5343/7816, email: marston@wsu.edu

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**13. ABSTRACT** *(Maximum 200 words)*

The shape oscillations of acoustically levitated bubbles were used to probe the interfacial rheology of bubbles in clean water and in sea water and in water containing surfactants. Clean water conditions produced agreement with an improved theoretical analysis while bubbles in sea water displayed an excess damping. A new method was demonstrated for injecting a known amount of insoluble surfactant onto an acoustically levitated bubble. The method was used to test an analysis of the increase in damping and the shift oscillation in frequency resulting from the modification of the interfacial rheology. Analysis of CCD images of pendant bubbles was used to monitor the evolution of the surface tension resulting from surfactants injected onto a pendant bubble.

**14. SUBJECT TERMS**
Bubbles in Water, Bubbly Flows, Surfactants, Surface Tension, Acoustic Levitation, Ship Wakes

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# I. Research Summary

## A. Project Goals:

We wished to understand aspects of the dynamics and evolution of small bubbles in water. The emphasis was on the measurement of shape oscillations as a probe of the bubble's surface in distilled water and in sea water. The oscillations are influenced by surface active materials present (or injected into) the water samples. Monitoring the frequency and decay rate of shape modes over an extended period of time (along with the size of the bubble) allows the evolution of the surface properties to be inferred. The measurements are also relevant to understanding the nonlinear dynamics of bubbles. The evolution of surface properties was also inferred by monitoring the shape of pendant bubbles.

## B. Results:

The most significant results pertain to the influence of surfactants on the dynamics of bubbles in clean (fresh or salt) water and in sea water. Bubbles acoustically levitated in purified fresh and salt water had a decay rate and frequency for shape modes in agreement with a theory that took into account the viscous dissipation in the outer fluid (water) and in the inner fluid (air) for the case of an ideal interface. Bubbles in natural sea water always displayed significant excess damping and a shift in frequency from the predicted results for pure sea water. It should be noted however, that only a few sea water samples were studied and these all came from the same location in Puget Sound. The excess damping can be attributed to the presence of natural surfactants in the sea water as evident from the controlled experiments with surfactants on bubbles in fresh water summarized below.

The surfactants of interest can be roughly put into either two categories according to their solubility: (i) surfactants which are sufficiently insoluble that there is negligible loss or gain of surfactant molecules from the surface of a bubble under normal conditions and (ii) surfactants that are sufficiently soluble for significant diffusion to or from the surrounding water. While both (i) and (ii) clearly gave excess damping in sufficient concentrations, the best comparisons with theory were possible for insoluble surfactants since a novel method was developed for injecting a controlled amount onto the surface of an acoustically levitated bubble. As gas dissolved, the surface area of the levitated bubble decreased, producing a known increase in surface concentration. The resulting evolution of the shape oscillation damping rate and frequency was in agreement with a model of the interfacial rheology when interfacial parameters were adjusted to be within physically reasonable values. Analysis of CCD images of pendant bubbles was used for case (i) to monitor the evolution of the surface tension or spreading pressure.

*Supporting research* includes experiments performed on the Space Shuttle in 1992 which clarified the proper size range for studying bubble dynamics on the earth, quantitative studies of the effects of acoustic radiation pressure on bubble dynamics, and novel optical methods for detecting bubble oscillations.

## II. Students supported or partially supported by this grant:

A. Thomas J. Asaki (M.S. completed: 1991, Ph.D. completed: 1995)

M.S. Report title: Studies of Acoustically Levitated Air Bubbles in a Water Filled Rectangular Chamber

Ph.D. Thesis title: Shape Oscillations of Bubbles in Water Driven by Modulated Ultrasonic Radiation Pressure and Applications to Interfacial Dynamics

B. Other graduate students partially supported with this grant:
(a) John S. Stroud (M.S. completed: 1991, Ph.D. completed: 1995)
(b) Scot F. Morse (M.S. completed: 1994, Ph.D. thesis work in progress)
(c) Mark J. Marr-Lyon (M.S. completed: 1995, Ph.D. thesis work in progress)

C. Undergraduate student partially supported: Nathaniel Hicks (B.S. in Physics in progress)

D. Postdoctoral Assistant partially supported: David B. Thiessen

## III. Publications and Reports

A. Peer Reviewed Publications:

1. Asaki, T. J., Marston, P. L., and Trinh, E. H., Shape oscillations of bubbles in water driven by modulated ultrasonic radiation pressure: Observations and detection with scattered laser light, J. Acoust. Soc. Am. **93**, 706-713 (1993).*

2. Stroud, J. S., and Marston, P. L., Optical detection of transient bubble oscillations associated with the underwater noise of rain, J. Acoust. Soc. Am. **94**, 2788-2792 (1993).**

3. Asaki, T. J. and Marston, P. L., Acoustic radiation force on a bubble driven above resonance, J. Acoust. Soc. Am. **96**, 3096-3099 (1994).

4. Marston, P. L., Trinh, E. H., Depew, J., and Asaki, T. J., Response of bubbles to ultrasonic radiation pressure: Dynamics in low gravity and shape oscillations, in *Bubble Dynamics and Interface Phenomena,* edited by J. R. Blake et al. (Kluwer Academic Publishers, Netherlands, 1994), pp. 343-353.*

5. Stroud, J. S. and Marston, P. L., Transient bubble oscillations associated with the underwater noise of rain detected optically and some properties of light scattered by bubbles, in *Bubble Dynamics and Interface Phenomena,* edited by J. R. Blake et al. (Kluwer Academic Publishers, Netherlands, 1994), pp. 161-169.**

6. Asaki, T. J. and Marston, P. L., Equilibrium shape of an acoustically levitated bubble driven above resonance, J. Acoust. Soc. Am., **97**, 2138-2143 (1995).

7. Asaki, T. J., Thiessen, D. B., Marston, P. L., Effect of an insoluble surfactant on capillary oscillations of bubbles in water: Observation of a maximum in the damping, Physical Review Letters **75**, 2686-2689 (1995); printer's erratum **75**, 4336 (1995).

8. Asaki, T. J. and Marston, P. L., Free decay of shape oscillations of bubbles acoustically trapped in water and sea water, Journal of Fluid Mechanics **300**, 149-167 (1995).

B. Other Publications in Preparation:

1. Man, K. F. and Thiessen, D. B., section on "Surface Tension" for *The Measurement, Instrumentation and Sensors Handbook (In the Electrical Engineering Handbook Series)*, CRC Press.* + **
2. Asaki, T. J. and Marston, P. L., The effects of a soluble surfactant on quadrupole shape oscillations and dissolution of air bubbles in water.

C. Conference Publications

1. Marston, P. L., Asaki, T. J., Stroud, J. S., and Trinh, E. H., "Oscillations of bubbles driven by modulated ultrasonic radiation pressure, their optical detection, and the optical detection of transient bubble oscillations associated with rain noise," in *Proceedings of the 14th International Congress on Acoustics*, edited by Li Peizi (Beijing, 1992), pp. C-2-5.1, 2.* + **

2. Asaki, T. J., Marston, P. L., and Trinh, E. H., Shape oscillations of bubbles in water driven by modulated ultrasonic radiation pressure, in *Advances in Nonlinear Acoustics,* Proceedings of the 13th International Symposium on Nonlinear Acoustics, edited by H. Hobeak (World Scientific, Singapore, 1993), pp. 424-429.*

3. Marston, P. L., Trinh, E. H., Depew, J., and Asaki, T. J., Oscillatory dynamics of single bubbles and agglomeration in a sound field in microgravity, in *Joint Launch + One Year Science Review of USML-1 and USMP-1 with the Microgravity Measurement Group,* edited by N. Ramachandran, D. O. Frazier, S. L. Lehoczky, and C. R. Baugher (NASA Conference Publication 3272, Marshall Space Flight Center, AL, 1994) Vol. 2, pp. 673-690.*

4. Marston, P. L., Drops and Bubbles: Experimental Aspects, in *Proceeding of the 1994 Physical Acoustics Summer School,* (National Center for Physical Acoustics, 1995), Vol. 1 (pp. 48-104) and Vol. 2 (146 pages).* + **

D. Other Conference Presentations (Note: Annual presentations at the ONR Dynamics of Bubbly Flows Meetings or Workshops for 1991, 1992, 1993, 1995, and 1996 are not listed).

1. Marston, P. L., Asaki, T. J., and Trinh, E. H., Shape oscillations of bubbles driven by modulated ultrasonic radiation pressure: Experiments (abstract), J. Acoust. Soc. Am. **89** 1885 (1991). [Invited presentation at the 121st meeting of the ASA.]*

2. Asaki, T. J., Marston, P. L., and Trinh, E. H., Experiments on the oscillations of bubbles driven by modulated ultrasonic radiation pressure (abstract), Bull. Am. Phys. Soc. **36** 2652 (1991). [Presentation at the 44th Annual Meeting of the APS Division of Fluid Dynamics.]*

3. Asaki, T. J., Marston, P. L., and Trinh, E. H., Shape oscillations of bubbles driven by modulated ultrasonic radiation pressure: The complex frequency response (abstract), J. Acoust. Soc. Am. **91** 2396 (1992). [Presented at the 123rd meeting of the ASA.]*

4. Stroud, J. S. and Marston, P. L., Optical detection of transient bubble oscillations associated with the underwater noise of rain (abstract), J. Acoust. Soc. Am. **91** 2429 (1992). [Presented at the 123rd meeting of the ASA.]**

5. Marston, P. L., Using acoustic levitation and radiation pressure to study the dynamics of drops and bubbles and optical diffraction catastrophes, International Workshop on Physical Acoustics, Nanjing, 1992 (Invited).* + **

6. Marston, P. L. and Trinh, E. H., Bubble dynamics in low gravity and related experiments on Earth (abstract), J. Acoust. Soc. Am. **93**, 2365 (1993). [Invited presentation at the 125th meeting of the Acoustical Society of America.]*

7. Asaki, T. J. and Marston, P. L., Experiments and analysis of shape oscillations of bubbles levitated in water on the Earth (abstract), J. Acoust. Soc. Am; **93**, 2365-66 (1993). [Presented at the 125th meeting of the Acoustical Society of America.]

8. Marston, P. L., Asaki, T. J., Trinh, E. H., and Depew, J., Bubble oscillations and coalescence in low gravity and related experiments on earth (abstract), Bull. Am. Phys. Soc. **38**, 2226 (1993); presented at the 46th APS Division of Fluid Dynamics meeting.*

9. Asaki, T. J. and Marston, P. L., Radiation force, equilibrium position, and shape for acoustically levitated bubbles driven above resonance, J. Acoust. Soc. Am. **96**, 3278 (1994); presented at the 128th meeting of the ASA.

10. Asaki, T. J. and Marston, P. L., Evolution of surface properties of acoustically levitated bubbles in aqueous solutions and seawater and sources of anomalous damping (abstract), J. Acoust. Soc. Am. **96**, 3278 (1994); presented at the 128th meeting of the ASA.

11. Marston, P. L., Acoustical and Optical Levitation and Scattering: Fundamentals and Applications (abstract), AAPT Announcer **25** (2), 68

(1995). [Invited presentation at the American Association of Physics Teachers Summer Meeting.]* + **

12. Asaki, T. J., Thiessen, D. B., and Marston, P. L., Calming the capillary waves on the surface of bubble using an insoluble surfactant (abstract), J. Acoust. Soc. Am. **98**, 2981 (1995); presented at the 130th meeting of the ASA.

13. Asaki, T. J., Thiessen, D. B., and Marston, P. L., Calming the capillary waves on the surface of bubble using an insoluble surfactant (abstract),Bull. Am. Phys. Soc. **40**, 1977 (1995); presented at the 48th meeting of the APS Division of Fluid Dynamics.

14. Thiessen, D. B., Marston, P. L., and Asaki, T. J., Modification of bubble properties by direct injection of insoluble surfactants and other advances in bubble dynamics (abstract at press); to be presented at the 132nd meeting of the ASA.

E. Other Reports:

An Annual Report is published for each grant year in the ONR Ocean Engineering and Marine Systems Program (ONR 321) compilation of research abstracts.

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