Middeck Glovebox (MGBX)

/0 P.

Bubble and Drop Nonlinear Dynamics (BDND)

Glovebox Investigator:

Dr. L. Gary Leal
University of California, Santa Barbara
Santa Barbara, California

BUBBLE AND DROP NONLINEAR DYNAMICS (BDND)

E.H. Trinh [1] , L.G. Leal [2] , D.A. Thomas [3], and R.K. Crouch [4]
[1] Jet Propulsion Laboratory, California Institute of Technology
[2] Department of Chemical Engineering, University of California, Santa Barbara
[3] Astronaut Office, Johnson Space Center
[4] NASA Headquarters, Washington DC

ABSTRACT

Free drops and bubbles are weakly nonlinear mechanical systems that are relatively simple to characterize experimentally in 1-G as well as in microgravity. The understanding of the details of their motion contributes to the fundamental study of nonlinear phenomena and to the measurement of the thermophysical properties of freely levitated melts. The goal of this Glovebox-based experimental investigation is the low-gravity assessment of the capabilities of a modular apparatus based on ultrasonic resonators and on the pseudo-extinction optical method. The required experimental task is the accurate measurements of the large-amplitude dynamics of free drops and bubbles in the absence of large biasing influences such as gravity and levitation fields. A single-axis levitator used for the positioning of drops in air, and an ultrasonic water-filled resonator for the trapping of air bubbles have been evaluated in low-gravity and in 1-G. The basic feasibility of drop positioning and shape oscillations measurements has been verified by using a laptop-interfaced automated data acquisition and the optical extinction technique. The major purpose of the investigation was to identify the salient technical issues associated with the development of a full-scale Microgravity experiment on single drop and bubble dynamics.

1. BACKGROUND

The principal difficulty in the analysis of experimental results of measurements of the nonlinear dynamics of levitated single drops and bubbles on Earth arises from the interference of the levitation fields. Because of the high intensity required to overcome gravity, secondary effects such as shape distortion, strong restraining force, internal flows, and field-induced onset of instability must be separated from the strictly nonlinear effects under scrutiny. This is also important in the context when a specific material property of the liquid is to be inferred from the measured fluid particle motion. For example, a well-established method for the non-contact measurement of surface tension is the determination of the resonance frequencies of drop or bubble shape oscillations [1,2]. Unfortunately, these resonance frequencies are also dependent on the mechanical state of the particle such as the static equilibrium shape, the magnitude of internal flows, the rotational state, and the magnitude of the restraining force of the levitation field. In addition, because of nonlinearity, these resonant frequencies are also dependent on the shape oscillation amplitude [3]. For Earth-based investigations, one or several of these effects can be present during any particular measurement, and their impact must be taken into account in order to arrive at an accurate value for the surface tension.

The judicious combination of different levitation methods having mutually synergistic effects can mitigate these problems. Such an instance would be provided by the combination of electrostatic and ultrasonic levitation methods where the uncontrolled flows and rotation associated with ultrasonic fields are reduced at the expense of the addition of surface charges and a high electric field. A much more rigorous approach, however, would be to carry out the measurements in low-gravity where the field effects can be drastically reduced or even virtually eliminated. Under these circumstances, measurements of the thermophysical properties in Microgravity, or the calibration of the various theoretical analyses dealing with the field effects would both be productive research tasks. The BDND investigation addresses the problem of developing a compact and low-cost modular approach for the direct measurement of the nonlinear dynamics of both drops and bubbles at ambient temperature and in Microgravity. The emphasis has been placed on using the *same instrumentation* as that would be found in an Earth-based laboratory, and on keeping as much of *the same empirical experimental methodology* as allowable.

2. EXPERIMENTAL OBJECTIVES

State-of-the-arts techniques for the levitation of drops and trapping of gas and vapor bubbles have already been successfully implemented in Earth-based laboratories to obtain quantitative information on the nonlinear characteristics of oscillating drops and the rheological properties of gas bubbles [4,5]. Adapting such methods to the Microgravity environment is the principal motivation of this Glovebox investigation. The specific objectives were thus defined as:

1. The testing of the on-orbit performance of a single-axis ultrasonic levitator in combination with a photodetector-based optical pseudo-extinction method for the precise measurement of drop shape oscillation frequency and relative amplitude. The measurement of the relative change in the *free-decay* fundamental resonance frequency for drop shape oscillations with increasing amplitude *at zero acoustic field intensity*.
2. The measurements of the *driven* resonance frequencies of the first three modes and of the change in the fundamental resonance frequency as a function of the trapping acoustic pressure amplitude.
3. The evaluation of a closed resonant liquid chamber for the stable trapping of single air bubbles in water.
4. The excitation and measurement of large-amplitude bubble shape oscillations and the measurement of the amplitude dependence of the fundamental resonance frequency.

3. EXPERIMENTAL METHOD

An approach using a common optical mounting assembly for both drop levitator and bubble resonant cell has been chosen. The same laser-based illumination and silicon photodetector are used to monitor the dynamics of either single drops and bubbles depending upon the nature of the levitation module placed on the optical assembly. A collimated and expanded beam from a battery-powered 670 nm diode laser is aligned to project an image of a drop (bubble) shadow at a pinhole in focal plane of a focusing lens. A silicon photodetector is placed behind the pinhole to detect the light scattered due to the fluid particle shape oscillations [6,7]. The output of the photodetector is sent to a PCMCIA card in the Shuttle Laptop computer and the analog data is digitized and processed by the Labview software to display the time series and Fourier spectrum of the shape oscillations optical signal.

The drop levitator is the same device used for IFFD (Internal Flows in Free Drops), a related Glovebox investigation, and uses a 23 kHz transducer to generate a standing wave. Spherical drops with diameter between 0.1 and 0.6 cm can be stably positioned in the Shuttle environment with relatively low acoustic power. The electrical drive is supplied by a manually-operated Electronic Control Unit which is capable of generating 15 Volts rms at the input of the piezoelectric transducer. A third-harmonic signal can also be generated, and a variable-frequency (5 to 150 Hz) amplitude modulation of either or both signals is available. This amplitude modulation function is used to excite the various resonant modes of drop and bubble shape oscillations.

The bubble trapping resonator is a water-filled square cross-section cell used to generate a 23 kHz standing wave as well as its third harmonic. Using the 23 kHz wave, such a device is capable of trapping air bubbles with diameter up to 1 cm at positions along the cell axis and in an Earth-based laboratory. Experimental evidence suggests that gravity plays an important role in the determination of the trapping positions of gas bubbles within the standing wave: An equilibrium bubble position near the cell center may not be available under Microgravity conditions. On the other hand, the third- harmonic standing wave has been shown to be effective at trapping gas bubbles with diameter up to 1 cm in low- gravity [8]. An appropriate combination of the fundamental and third-harmonic resonant pressure distribution should allow trapping of a gas bubble towards the center of the cell and away from the walls. Amplitude modulation of either waves also allows the excitation of bubble resonant shape oscillation modes. **Figure 1a** is a photograph of the BDND flight experiment apparatus with the liquid cell installed on the optical support assembly. **Figure 1b** shows video images of a levitated water drop in air and of an air bubble in water.

4. MSL-1 FLIGHT EXPERIMENTAL RESULTS

4.1 Performance of the apparatus and resonance nonlinearity measurement

The accuracy of the pseudo-extinction optical technique for shape oscillation frequency measurement is roughly independent of the position of the drop or bubble as long as the fluid particle resides within the central portion of the 1.1 cm diameter illuminating laser beam. When ambient transient acceleration impulses within the Space Shuttle-Spacelab environment perturb the sample from its equilibrium position, however, translational oscillations will be excited and the recorded waveform will be a superposition of the translational oscillation frequency upon the shape-dependent signal. The results of an FFT operation will yield the two separate frequencies within the available resolution limit.

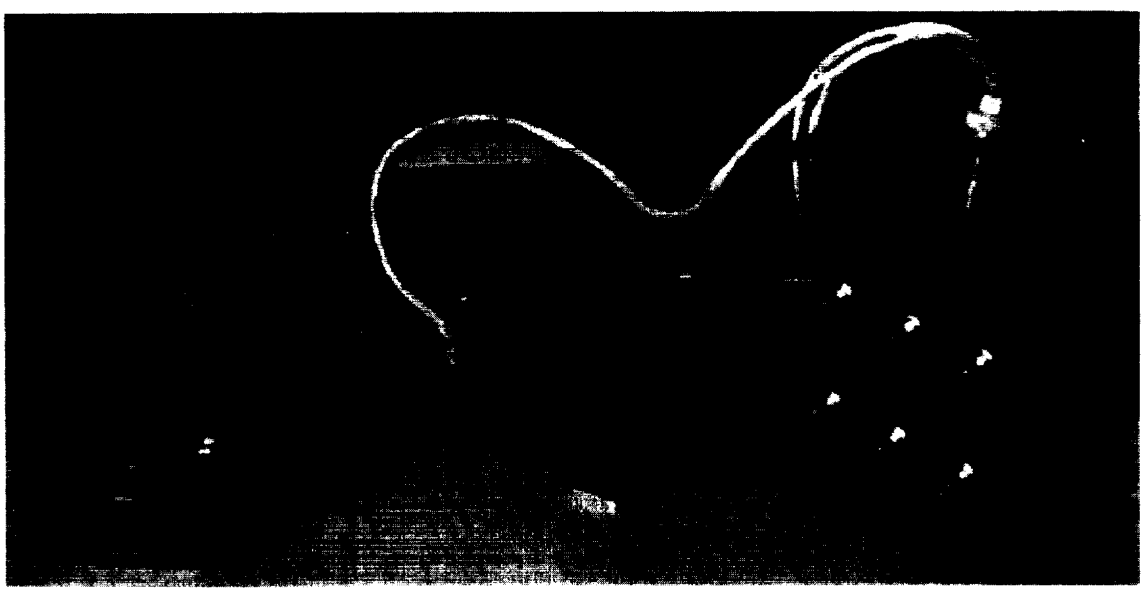

Figure 1a. **BDND flight investigation apparatus with Bubble trapping cell.**

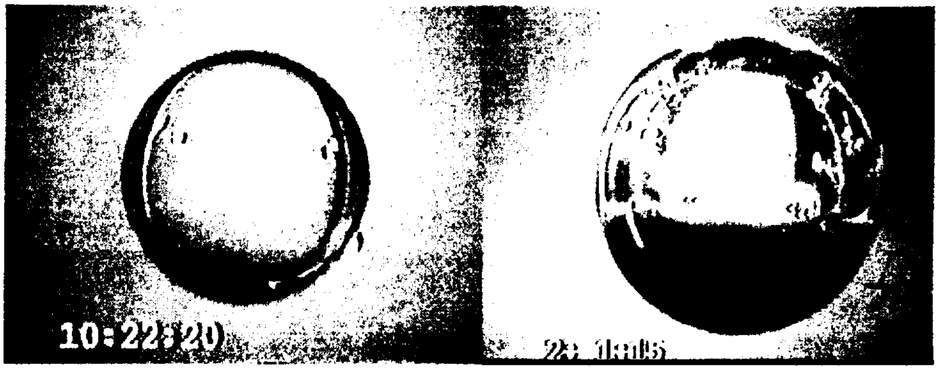

Figure 1b: Single video frames of a 5 mm diameter water drop in air (left) and a 5.5 mm air bubble in water (right). Both were trapped in Microgravity by ultrasonic fields.

The optical detection technique is fundamentally nonlinear, and the measurement of large-amplitude drop or bubble oscillations invariably results in the appearance of higher harmonics of the oscillation frequency. The approach is therefore not appropriate for the quantitative analysis of the frequency spectrum of large amplitude oscillations. The measured value of the *fundamental* oscillation frequency, however, has been verified to be accurate to within 0.2 %. It is thus possible to obtain a near instantaneous measurement of the oscillatory response of a drop or bubble to acoustic excitation both in the continuously driven or free-decay modes.

Reliable results of the measurement of the *free-decay* frequency of drops have been obtained for four different samples. The data were obtained by first driving the drop oscillations through amplitude modulation of the acoustic field and subsequently shutting off the acoustic power and recording the optical signal onto the laptop computer. The use of a manual toggle switch on the levitator housing to suddenly null the acoustic force appears to cause an initial disturbance to the positioned drop for the free decay measurement. This introduces a non-constant baseline for the electrical signal from the photodetector monitoring the drop shape oscillations. This did not preclude, however, the measurement of the free-decay *frequency*. **Figure 2** is a sample 1-G data set obtained for a 4.5 mm diameter drop. The first display gives the time-series of the drop oscillations in real-time, the second is the FFT plot of the same time series data set. The number of total samples and the sample rate can be varied between 1,000 to 5,000. The third trace is the display of a previously captured data set plotted as a function of time, and shows a free-decay trace for a drop levitated in 1-G. The free-decay frequency is a more desirable measurement because of the absence of any acoustic restraining field. It provides the means for real-time measurement of the surface tension of the drop liquid if the density and drop diameter can be measured or are known. Using the MSL-1 flight results, it has been derived that the fundamental free-decay resonance frequency can be determined with a relative accuracy of +/- 0.5 %. In turn, the surface tension can be measured with a relative accuracy of +/-1 % since the drop diameter and the density can be determined to within +/- 0.1%. The decay rate also provides a measure of the liquid viscosity.

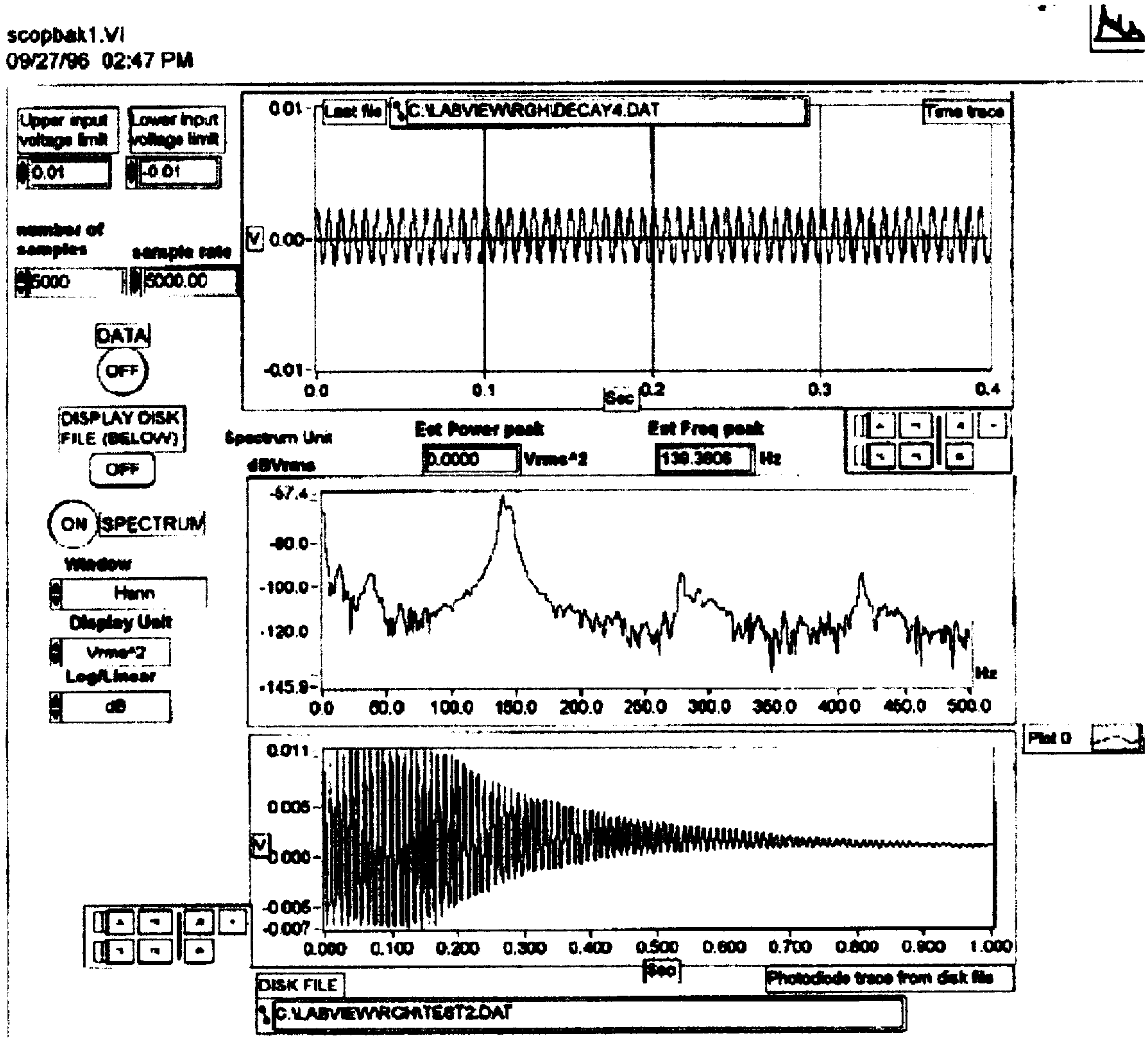

Figure 2. **Print-out of the BDND LabView data acquisition display page**

Figure 3 is a sample of the MSL-1 data sets obtained in Microgravity. The drop was *initially driven* at 34.8 Hz through amplitude modulation of the acoustic field. The power was then cut-off to the levitator, and the oscillations decay were recorded. The *free-decay* frequency was measured to be a *constant* and equal to 34.2 Hz (+/- 0.1 Hz). No soft-nonlinearity was therefore detected.

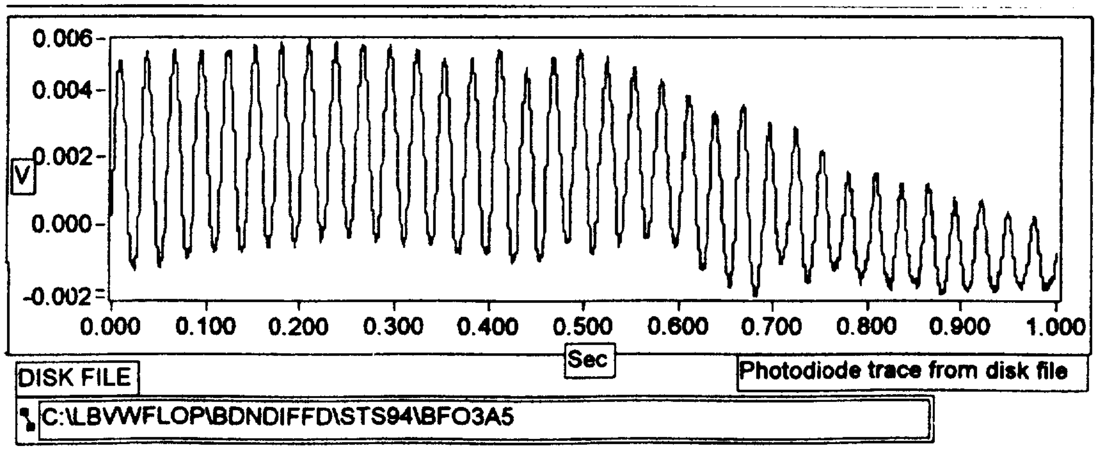

Figure3: Sample time series data set from the MSL-1 results.

4.2 Measurement of first resonance frequencies of drop shape oscillations

Manual measurement of the fundamental resonance frequency for drop and bubble shape oscillations was demonstrated in the driven as well as free-decay approaches. The manual procedure for resonance determination was the visual monitoring of the video image or measuring the amplitude of the time-series signal from the photodetector on the laptop LabView display as the modulation frequency was manually varied. The fundamental mode of shape oscillations was straightforward to excite through amplitude modulation of the acoustic pressure, and its frequency was also successfully measured in the continuously driven mode. The residual rotation of the drop was minimized, but the rotation axis was always nearly perpendicular to the z-axis along which the acoustic pressure was modulated. This residual rotation interfered with the clean excitation of large-amplitude oscillations and prevented the substantial driving of the next higher modes which are more heavily damped due to viscous effects.

4.3 Evaluation of a closed resonant chamber for bubble trapping

Contrarily to Earth-based experimental observations, the fundamental (23 kHz) standing wave did not allow the trapping of air bubbles in water at positions away from the cell walls in the Microgravity environment. Because large gas bubbles (with radii larger than 300 μm) are driven by radiation pressure to acoustic nodal regions, it becomes evident that the desirable bubble trapping positions are found in regions centered along the cell axis between the pressure nodal and anti-nodal planes. The observed capability for centered and long-duration trapping of air bubbles in 1-G is due to buoyancy which causes the equilibrium trapping position to shift to a position above the pressure nodal plane.

The results from the MSL-1 runs confirmed previous observations obtained during the STS-50 flight during which a similar cell was used in the third-harmonic mode to trap single air bubbles [7]. A few stable trapping positions could be empirically found at various locations within the bulk of the liquid. The positioning stability at each of these locations is bubble volume dependent, and varies significantly with the chamber frequency tuning.

4.4 Large-amplitude bubble shape oscillations

Bubbles were trapped near the bottom of the cell using the third harmonic mode, and were also successfully driven into significant amplitude shape oscillations. The fundamental mode of shape oscillations was measured manually by maximizing the oscillation amplitude through the variation of the amplitude modulation frequency. Because the bubbles are trapped at a local pressure minimum in Microgravity (as opposed to above the pressure nodal plane in 1-G), the morphology of the oscillatory shapes is symmetrical with respect to the bubble equator. **Figure 4** shows the strobed configuration of a bubble oscillating in the fundamental mode in Micrograviy and in 1-G. The asymmetry of the prolate shape in 1-G is quite pronounced, and reveals a larger excursion of the lower pole during the maximum prolate deformation of the oscillatory cycle.

1-G Low-G

Figure 4: Comparison of the shape at maximum prolate deformation for a bubble oscillating at 1-G and in low-G.

SUMMARY

The results of the MSL-1 experiment runs have provided the hard experimental data required for the *evaluation* of the current experimental approach, and new definite directions for redesign have been obtained. *The method for the measurement of the fundamental free-decay frequency has been validated*, and consequently, a *real-time technique for the measurement of the surface tension of low-viscosity liquids* has been developed. The controlled investigation of large-amplitude shape oscillations dynamics requires the complete elimination of all residual drop rotation, or the capability to excite drop oscillations in the direction of the rotation axis. Although mechanical adjustments of the levitator were allowed, they were not found to be completely effective at eliminating all residual rotation. No new data for large-amplitude bubble shape oscillations were obtained, but conclusive information on the effect of gravity on the trapping capabilities of a resonant ultrasonic cell was derived. *The basic feasibility of the experimental approach has been confirmed*, and a redesign will allow the complete experimental study of the nonlinear dynamics of single bubbles in Microgravity. The ultimate objectives of the Glovebox investigation were to test and to refine the experimental approach. We believe that these objectives were achieved.

ACKNOWLEDGMENTS

This research was sponsored by the NASA Microgravity Research Division. We would like to thank the invaluable support of the Glovebox Project Office, of the MSL-1 mission team, and of the Marshall Space Flight Center POCC team.

REFERENCES

1. E.H. Trinh, P.L. Marston, J.L. Robey, "Acoustic Measurement of the Surface Tension of Levitated Drops," J. of Colloid and Interf. Science **124**, 9S, (1988)..
2. T. J. Asaki, P.L. Marston. and E.H. Trinh, "Shape oscillations of bubbles in water driven by modulated ultrasonic radiation pressure: observation and detection with scattered laser light", J. Acoust. Soc. Am. **93**, 706 (1993)
3. E.H. Trinh, R.G. Holt, and D.B. Thiessen, " The dynamics of levitated drops in an electric field", Phys. Fluids **8**, 43 (1996)
4. E.H. Trinh, D.B. Thiessen, and R.G. Holt, " Oscillations of bubbles and drops immersed in a liquid", J. Fluid Mech., (1998) at press)
5. T. Asaki, P.L. Marston, D.B. Thiessen, " Effect of an insoluble surfactant on capillary oscillations of bubbles in water: Observation of a maximum in damping", Phys. Rev. Lett. **75**, 2686-2689 (1995)
6. T. Asaki, P.L. Marston, "Free-decay of shape oscillations of bubbles acoustically trapped in water and sea water", J. Fluid Mech. **300**, 149-167 (1995)
7. P.L. Marston, E.H. Trinh, J. Depew, and T.J. Asaki, "Response of bubbles to ultrasonic radiation pressure: Dynamics in low gravity and shape oscillations", in Bubble Dynamics and Interface Phenomena, 343-353, J.R. Blake et al. (eds.) Kluwer Academic Publishers, the Netherlands 1994