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THE EFFECT OF WATER QUALITY ON THE DAMPING OF BUBBLES

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A knowledge of the quality factors of gas bubbles in liquids is key to predicting the acoustic effect of the introduction of a given bubble population, including prediction of acoustic attenuation and measurement of that population. A recent experimental study has suggested that the quality factor of bubbles is far more strongly dependent on salinity than is predicted by. If confirmed, this would have implications for current models of the acoustics of bubble populations, and for the interpretation of historical acoustical measurements of oceanic bubble populations. Whilst the previous study examined the passive emissions from injected bubbles having radii of millimetre order, the current study examined a wider range of bubble sizes, driven with broadband signals. Bubbles in a range of water types were studied, including fresh water and sea water. The measurements do not concur with the previous observations.

1. INTRODUCTION

In 1959 Devin [1] produced his pioneering analysis of the mechanisms by which the pulsations of a gas bubble in a liquid are damped. He characterised the damping when the bubble pulsates at its natural frequency by a dimensionless damping coefficient, δ_{tot}. This parameter equals the sum of three dimensionless damping coefficients, corresponding to the damping due to viscous losses (δ_{vis}), thermal losses (δ_{th}), and the acoustic radiation from the bubble itself (δ_{rad}). For linear systems δ_{tot} represents the reciprocal of the quality factor, Q. Later studies extend the theory to formulate the off-resonance characteristics of these damping parameters [2-6].

Knowledge of the bubble damping is important for a wide range of practical applications. One example is in the response of bubble clouds to short acoustic pulses. The scattering of sound by bubbles is a local maximum at resonance [7] if sound of a given frequency is incident upon a bubble column strong scattering can occur from both resonant bubbles, and also from larger off-resonant bubbles which, though they do not pulsate significantly and so do not dynamically couple with the sound field to a significant extent, nevertheless represent large 'inert' targets. It may be possible to enhance sonar detection in bubbly environments by exploiting the time required for a resonant bubble to 'ring-up' to steady-state pulsation when it is insonified, and so reduce that component of scattering which is associated with bubbles at resonance. Since bubbles in the ocean characteristically have a broad size range from 10's to 100's of micrometers [8] corresponding to resonance frequencies in the region of 5 kHz to 300 kHz, it is not feasible to simply 'avoid' those frequencies at which bubbles resonate. The problem is compounded when considering the range of suitable frequencies available for search sonars. This is due to the constraints of attenuation in sea water at high frequencies [9], and that the bubble clouds themselves are known to scatter low-frequency sound in the region of 20 Hz - 2 kHz, dramatically increasing the ambient noise levels [10]. A reduction in acoustic scattering with decreased pulse length, was detected in the ocean by Akulichev *et al.* [11]. However two subsequent tank studies [12, 13] have failed to measure any reduction in scattering. Clearly, if the resonant and off-resonant contributions to scattering differed in the positive and negative trials, then this might be the source of the apparent discrepancy. It is of interest that the positive result was found in the ocean, and the negative ones in fresh water test tanks. If the tank studies contained an increased proportion of larger bubbles, the observed contradiction might be expected. A difference in the bubble size distributions which occur in the sea and test tanks might be expected unless the tank populations were specifically engineered to mimic the ocean. However the possibility of another key difference has suggested itself following the findings of Kolaini [14], who has suggested that the quality factor of bubbles in fresh water may differ greatly from bubbles of the same size and gas content in salt water. Such a possibility must be examined, not only because of its importance to the pulse-enhancement studies described above, but because if there were a dependence on salinity of the quality factor which theory did not predict, this would have serious implications for systems which use current models to determine the numbers of bubbles in the ocean. Kolaini's original suggestion, that quality factors could have a dependence on salinity at variance with theory, arose through attempts to explain variation in the acoustic emissions of breaking waves in fresh and salt water [15]. The quality factor of large bubbles of order 1-2 mm radius was measured over a salinity range (using commercial salt) of 0–35 ‰ [14]. Bubbles were injected by a needle and the quality factor determined from the logarithmic decrement of the bubble response.

For accuracy, the injection method ideally requires that individual bubbles be excited, in an infinite or anechoic volume, by an impulse. Coalescence [16], multibubble production [17] and shape oscillations [6] may reduce the accuracy. For this reason an active technique is used here for comparison.

2. MEASUREMENT OF BUBBLE Q USING BROADBAND NOISE

It is possible to measure the quality factor in two discrete ways [18]. The first is by measurement of the logarithmic decrement of a freely decaying bubble oscillation by comparison of the amplitude of successive cycles in the acoustic emission used by Kolaini

[14]. The second method is by direct measurement of the bubble frequency response, since the quality factor equals the ratio of the resonance frequency to the half-power bandwidth in cases of very light damping. Note the injection technique monitors the natural frequency whereas the active technique utilises the resonance frequency. However the difference in these frequencies is very small, < 1 Hz at a resonance of 3 kHz and < 4 Hz at a resonance of 10 kHz for damping values given by Devin's theory.

The above ratio might be found by driving the bubble at varying frequencies close to resonance and measuring the bubble's response. Thus the second method of calculating the Q-factor is utilised. However since the bubble is now undergoing a forced oscillation the phase of the oscillation becomes important. If the bubble is oscillating below its resonance frequency, the bubble wall displacement is in phase with the driving signal acoustic pressure. However, above resonance it is in anti-phase. The amplitude of oscillation of the bubble wall increases as the frequency nears resonance, with a corresponding increase in the scattering signal, but the phase change at resonance results in destructive interference above the resonant frequency. In order to measure the Q-factor a method must be found to separate the response of the bubble from the driving signal. That is to say, it is first necessary to remove the component due to the pump signal from the output, so that only the scattering from the bubble remains. By using data collected without a bubble present it is possible to calculate the transfer function of the system by using:

$$S_{xy}(f) = H(f)S_{xx}(f)$$

where $S_{xy}(f)$ is the cross correlation of the input signal x and the output signal y; $S_{xx}(f)$ is the autocorrelation of the input signal; and $H(f)$ is the Fourier Transform.

$H(f)$ is an estimate of the system characteristics when no bubble is present, which can then be used to filter the input signal for the test when a bubble is present. Thus the response of the system to the new input signal is estimated. This is then subtracted in the time domain from the output signal to produce the response due to the bubble only. The power spectral density of the bubble response can then be calculated and the Quality factor measured as described below.

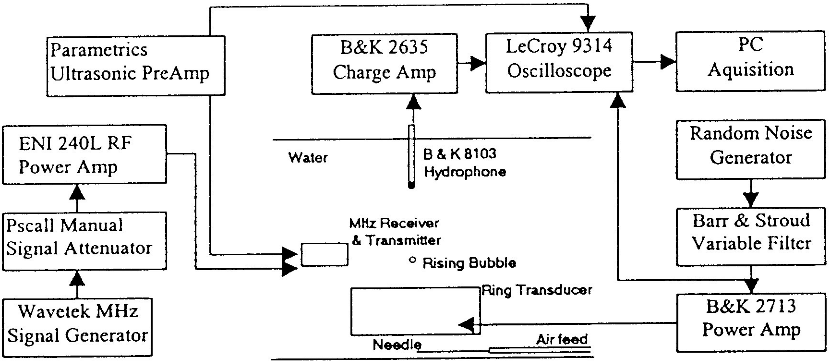

Figure 1. Experimental setup for the measurement of the Quality factor of free rising bubbles using broadband noise.

To determine the Q-factor accurately measurements were taken for a free-rising bubble injected by passing compressed air through a hypodermic needle. The experiments were performed in a 0.2 m x 0.6 m x 0.25 m glass tank, filled with water to a depth of approximately 0.65 m. The data acquisition was via National Instruments LabVIEW software and GPIB interface card. All signal processing was conducted using the MATLAB software package.

The experimental setup is shown in Figure 1. A driving signal consisting of band filtered white noise (1 – 25 kHz) was generated (using a Bruel and Kjaer Type 2032 dual channel signal analyser). In order to extract the bubble response from the output signal, which is subject to the phase change described above, it is necessary to repeat the experiment with and without a bubble. Since the input signal is random noise it will vary with time and it is therefore necessary to simultaneously acquire the input and output signals in order to calculate the bubble response using the technique described above.

To determine the Q-factor, the resonance frequency and half-power bandwidth was extracted from the power spectral density of the response of the bubble. However owing to the nature of signal analysis in the frequency domain, there is a trade-off between bias due to averaging and variance at higher resolutions. In this case the latter is a particular problem since the input signal was random noise and the resulting response around resonance was undersampled. In order to overcome this the response was interpolated using zero padding.

3. RESULTS

Quality factor measurements where taken for bubbles having radii of 850±75 μm (Figure 2) and 300±15 μm (Figure 3) radius in tap water, distilled water and sea water of salinity 35.5 ‰. In addition, for bubbles of radius approximately 850±75 μm, Q values calculated from the logarithmic decrement are also shown. For comparison the theoretical damping value as determined by Devin's theory [1] are also indicated.

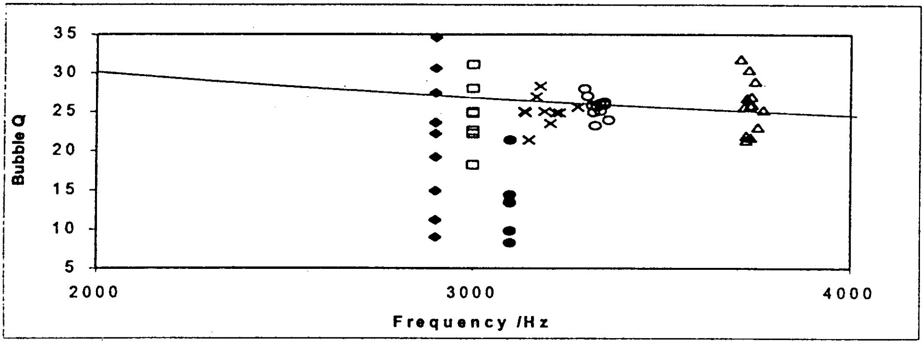

Figure 2. Data spread for 850±75 μm bubbles in tap water (×), distilled water (Δ) and sea water (O) of salinity 36 ‰. Also shown are damping measurements using the injection method for 850±75 μm radius bubbles in tap water (□), distilled water (♦) and salt water (•) which have natural frequencies of 3.25±0.25 kHz but have been offset on the frequency axis for clarity. The fresh and salt water quality factor as predicted by Devin's theory are also shown as a solid line for comparison (the plots are overlying on this scale).

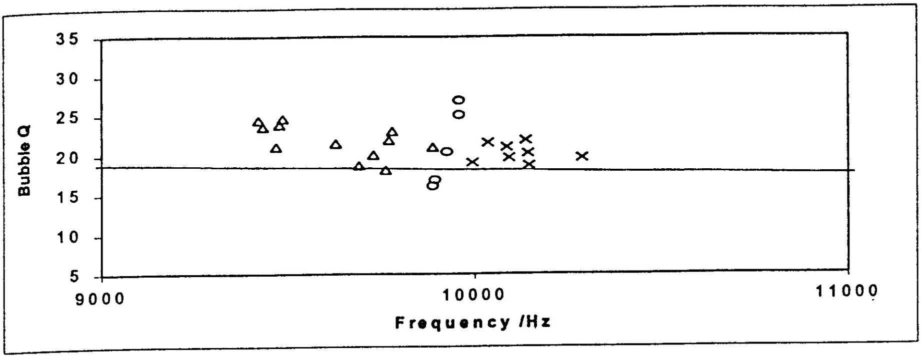

Figure 3. Data spread for 300±15 µm bubbles. Key as for Figure 2.

4. DISCUSSION

It is clear that the scatter of the data measured using the logarithmic decrement is much greater than that when measured using broadband excitation. The former does show a trend of decreasing Q with salinity, as did Kolaini. However this is not apparent when the broadband technique is used. This suggests the trend observed by Kolaini may be the result of the effect of salinity on bubble injection itself, rather than on the bubble damping. Averaging the data sets of figures 2 and 3 (see figure 4) shows that theoretical predictions of quality factor (indistinguishable on this scale for fresh and salt water) lie within the error of the broadband measurement, but not within that of the salt water injection data.

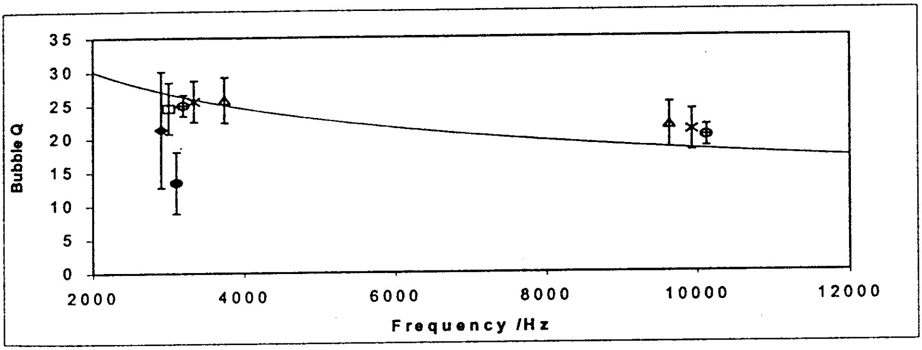

Figure 4. Results for 850±75 µm and 300±15 µm radius bubbles. Key as for Figure 2.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

[1] Devin, C. Jr, Survey of Thermal, Radiation, and Viscous Damping of Pulsating Air Bubbes in Water. *J. Acoust. Soc. Am.* **31**, 1654 (1959)

[2] Eller, A. I. Damping constants of pulsating bubbles. *J. Acoust. Soc. Am.* **47**, 1469-1470 (1970)

[3] Prosperetti, A. Thermal effects and damping mechanisms in the forced radial oscillations of gas bubbles in liquids. *J. Acoust. Soc. Am.* **61**, 17-27 (1977)

[4] Nigmatulin, R. I. Khabeev, N. S. Heat exchange between a gas bubble and a liquid. *Fluid Dyn.* **9**, 759-764 (1974)

[5] Miksis, M. J. Ting, L. Nonlinear radial oscillations of a gas bubble including thermal effects. *J. Acoust. Soc. Am.* **76**, 897-905 (1984)

[6] Longuet-Higgins, M. S. Nonlinear damping of bubble oscillations by resonant interaction. *J. Acoust. Soc. Am.* **91**, 1414-1422 (1992)

[7] Medwin, H. Counting bubbles acoustically: a review. *Ultrasonics* **15**, 7-14 (1977)

[8] Leighton, T. G. (editor). Natural physical processes associated with sea surface sound (University of Southampton 1997)

[9] Fisher, F. H. and Simmons, V. P. Sound absorption in sea water. *J. Acoust. Soc. Am.* **62** (3), 558 – 564 (1977)

[10] Roy, R. A. and Carey, W. M. Acoustic scattering from bubble clouds *In Natural Physical Processes Associated with Sea Surface Sound*, (T. G. Leighton, editor), 221-231 (1997)

[11] Akulichev, V. A. Bulanov, V. A. Klenin, S. A. Acoustic sensing of gas bubbles in the ocean medium, *Sov. Phys. Acoust.* **32**, 177-180 (1986)

[12] Suiter, H. R. Pulse length effects on the transmissivity of bubbly water, *J. Acoust. Soc. Am.* **91**, 1383-1387 (1992)

[13] Pace, N. G. Cowley, A. and Campbell, A. M. Short pulse acoustic excitation of microbubbles. *J. Acoust. Soc. Am.* **102** (3), 1474-1479 (1997)

[14] Kolaini, A. R. Effects of salt on bubble radiation, *Natural Physical Processes Associated with Sea Surface Sound,* (T. G. Leighton, editor), 240-249 (1997)

[15] Kolaini, A. R. Sound radiation by various types of laboratory breaking waves in fresh and salt water. *J. Acousr. Soc. Am.* **103** (1), 300-308 (1997)

[16] Leighton, T. G. Fagan, K. J. & Field, J. E. Acoustic and photographic studies of injected bubbles. *Eur. J. Phys.* **12**, 77-85 (1991)

[17] Medwin, H. Beaky, M. W. bubble sources of the Knudsen sea noise spectra. *J. Acoust. Soc. Am.* **25**, 1124-1130 (1953)

[18] French, A. P. Vibrations and Waves, Nelson, London, 96-102 (1971)