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Acoustic bubble sizing, using active and passive techniques to compare ambient and entrained populations

by

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ABSTRACT

This report contains details of the progress into sizing bubbles actively by means of the two frequency insonation method, and outlines the success of examining the subharmonic sum-and-difference coupling. In addition, preliminary results are presented which relate to investigations into the variation of the subharmonic response with differing excitation amplitude and step size between successive interrogating signals, and examinations into the reproducibility of the response. Work has also been done on the passive sizing of bubbles upon entrainment with the Gabor transform technique, which gives a fast and accurate representation of the bubble's resonant frequency, of the time at which entrainment occurs and of the amplitude of the signal.

I. INTRODUCTION

The oceans provide a very large reservoir into which atmospheric gases dissolve[1]. The presence of bubbles introduces an important asymmetry into this flux of atmospheric gases, which can result in a 1-2% supersaturation of the lower solubility gases[2,3]. When a wave breaks at sea the air trapped in a wave crest or under a plunging breaker is entrained into the ocean as a cloud of bubbles, which are then dispersed through buoyancy, dissolution, turbulence and circulatory forces, and form an 'old age' background population[4]. Information on bubble dispersal and the associated gas flux can be obtained through comparison of the air entrained in the original wave breaking process and that contained in the 'old age' population.

Acoustic techniques are very suitable for this[5], as the pulsation of a bubble approximates a lightly damped single degree of freedom system, and as such it has a well-defined resonance. For air bubbles in water at atmospheric pressure, the radius of the bubble (R_o) and the resonant frequency (υ_r) can be related by:

$$\upsilon_r R_o \approx 3 \quad Hz\ m \tag{1}$$

Passive bubble sizing techniques make use of the sound emitted from a bubble when mechanically excited, for example upon entrainment, as this 'ring' occurs at their resonant frequency. Thus these emissions from a bubble cloud under a breaking wave or waterfall can be used to size and count the population entrained[6]. The work on passive sizing related to this project involves examining the acoustic nature of these signals, and developing a fast, accurate and automated method of interpreting these signals.

The active technique used to size the old age population relies on examining the nonlinear coupling of two sound fields incident on the bubble[7]. If the bubble is insonated with two frequencies, one a high fixed frequency ω_i (the *imaging* frequency), and another lower frequency ω_p tuned to the resonant frequency of the bubble (the *pump* frequency), the nonlinear response will give rise to frequencies at $\omega_i+\omega_p$ and $\omega_i-\omega_p$. Recent work[8] has shown that a *subharmonic* signal at $\omega_p/2$ can also be stimulated at resonance and will similarly undergo sum-and-difference coupling with the imaging frequency to give emissions at $\omega_i \pm \omega_p/2$. These have been shown to be much more accurate indicators of the bubble resonance frequency[9].

The aims and methodology of the project, as proposed to the NERC, are 'to develop bubble sizing technology capable of characterising bubble populations both upon entrainment and in ambience. The two-year project will enable proof of concept and development, to enable, but not actually undertake, construction of an in situ device. A system to characterise the bubble population on entrainment will be constructed. An active detector will also be developed to characterise the ambient population. Having completed proof of concept using frequency analysis of the complete signal, heterodyning techniques will be introduced to enable the rapid signal processing that would be required in a field device.'

The progress made in the first year using active techniques is considerable. The nonlinear frequency coupling method has been successfully applied, and has been shown to be an extremely accurate indicator of the bubble resonant frequency. The research has involved an investigation into the parameters employed when using such a system, namely the necessary amplitude of excitation for the subharmonic response, the appropriate frequency increment between two successive projector outputs, and an examination into the reproducibility of the signal. The heterodyning system has been simulated, designed and built, and is in the process of being incorporated into the measurement technique.

In addition, considerable progress has also been made into the passive sizing of bubbles upon entrainment. The work has used a specialist windowing function called the Gabor transform[10] to examine the time history of entrainment noise. This window returns a three dimensional function which gives details on the bubble resonant frequency, the time of entrainment and the amplitude of the response. This has been used to examine laboratory data, and has also been used to size the bubbles at the bottom of a small waterfall. Sea trials using this method took place in September 1993.

II. METHODS AND TECHNIQUES

Both the active and the passive laboratory experiments were performed in a 6' x 4' x 4' glass reinforced plastic tank, which is vibration isolated by four 1400 x 300 mm Tico pads.

Passive Tests:

Bubbles are entrained when a continuous liquid jet impacts the water surface. The resulting acoustic emissions are detected using a Bruel and Kjaer 8104 underwater hydrophone connected to a Bruel and Kjaer type 2635 pre-amplifier. The signals are recorded onto a portable Aiwa DAT recorder, and later analysed via a MATLAB data acquisition toolbox.

Active Tests:

The experimental set-up for the active experiments is shown in ***figure 1***.

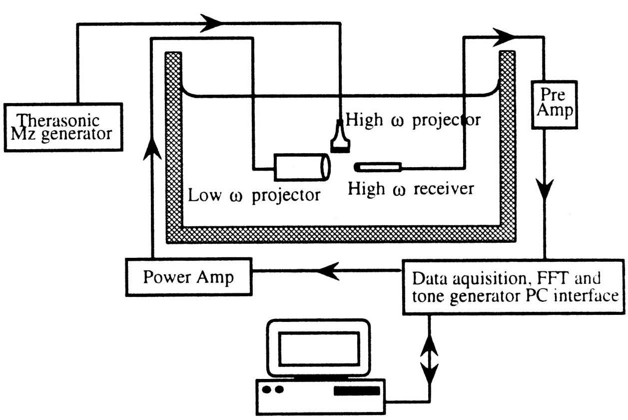

Figure 1. *The equipment and experimental arrangement used in the tests. The three transducers are drawn out of the horizontal for clarity.*

The high frequency imaging signal is provided by a Therasonic 1030 Ultrasound Generator working at 1 MHz, the low frequency projector is a Gearing and Watson UW60 underwater loudspeaker, and the high frequency receiver is an unfocused Panametrics V302 transducer. The low frequency projector and the high frequency receiver face each other to facilitate the calculation of the volume of water over which the transducers act. The three transducers are all clamped onto a rigid 205 mm x 140 mm x 400 mm high stainless steel cage to maintain their relative alignment. The signal to the low frequency projector is driven by a Bruel and Kjaer type 2713A power amplifier, and the received signal is conditioned by a Diagnostic Sonar 5670 battery powered preamplifier. The set-up is of rugged design to allow measurements in hostile environments, and is remote and non-invasive of the region of interrogation.

A single bubble is employed to characterise the system, since it is important to ensure that this sizing technique, unlike others currently in operation, is not capable of erroneous triggering. The bubble is attached to a thin wire coated in petroleum jelly, which is fixed horizontally 4 cm from the front face of the Gearing and Watson transducer to prevent bubbles being displaced by buoyant forces during the experiment.

The system designed for the collection of high frequency data and the associated signal processing is a Loughborough Sound Images custom built data acquisition board and P.C. Interface. The system works by reading a P.C. file which specifies the projector frequencies and corresponding amplitude multipliers. The unit then sends out a signal at the first frequency value, and simultaneously takes in data from the high frequency receiver. This data is then decimated and heterodyned, and a 8192 point FFT is taken around the imaging frequency with 5 Hz resolution. This is then saved onto the P.C., and the unit repeats the tests using the second input frequency, and so on.

III. RESULTS

Passive Tests:
The passive sizing of bubbles upon entrainment in the laboratory is demonstrated in **figure 2.** This shows the time history from a jet of water directed into the tank as measured by the hydrophone. The jet was released at 25 mm above the water surface at an angle of 70° to the horizontal from a pipe of inside diameter 5 mm, and with a flow rate of 4.5 litres/min. The characteristic decaying sinusoidal responses of bubbles being entrained are evident. The Gabor transform of this data is enclosed as **figure 3**. Each peak corresponds to the entrainment of a bubble, and its location in the mesh indicates its resonant frequency and the time at which it was formed. Current work on the passive sizing technique involves examining the potential for its automation to count and size a statistically significant number of bubbles. Waterfall trials and oceanic measurements have been made.

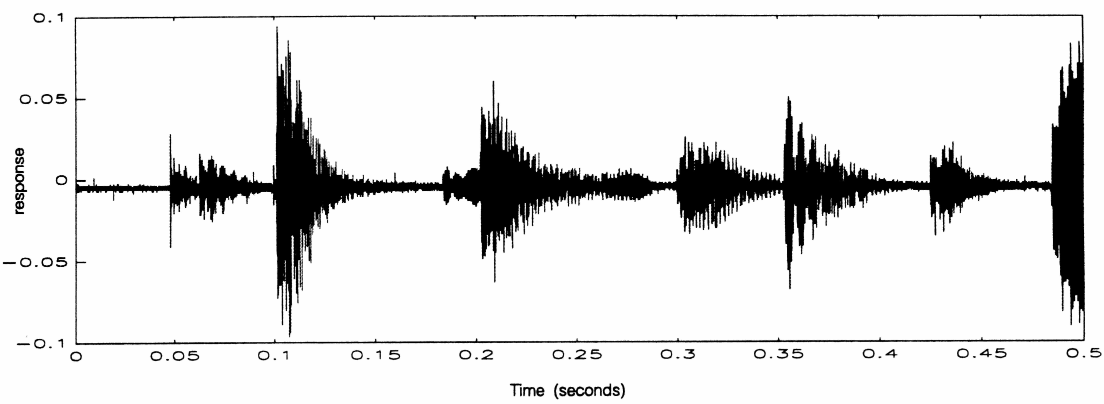

***Figure 2** Plot showing the bubble noise upon entrainment from a water jet.*

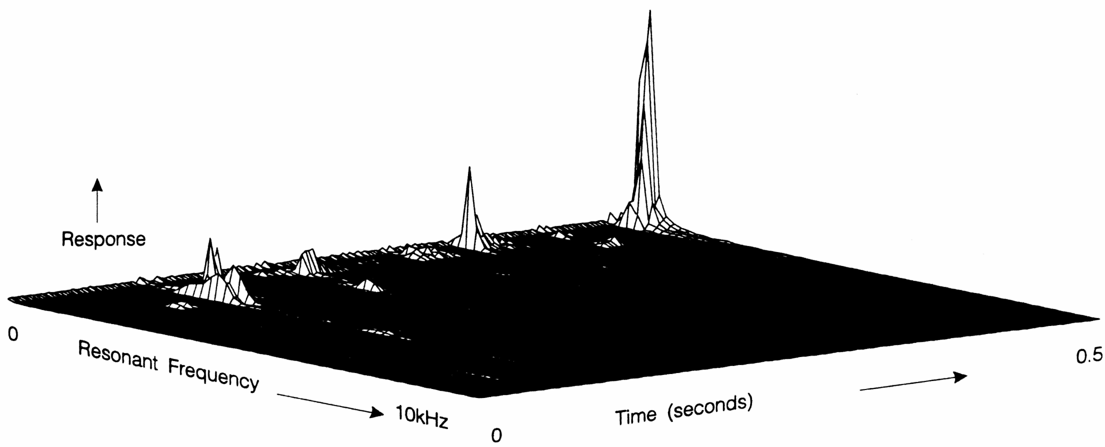

***Figure 3** Gabor transform of water jet data showing time at which entrainment occurs, resonant frequency and amplitude of response.*

Active Tests:

Tests performed using the active stimulation of bubbles have shown that the appearance of a subharmonic signal is a far better indicator of the resonant frequency of a bubble than by examination of the $\omega_i \pm \omega_p$ response. This is demonstrated in ***figure 4.*** The plot shows the data acquisition unit output over twenty different pumping frequencies, going from 1925 Hz to 2400 Hz in 25 Hz steps. The main ridge which is constant over the twenty tests is the imaging signal from the Therasonic frequency generator, with spurious side lobes either side of its centre peak. In front of this is a second broken ridge which similarly is present over all twenty pumping signals - this is the coupled response corresponding to $\omega_i + \omega_p$. Between the two bands is a single peak which occurs at a pumping frequency of 2275 Hz. This is due to the subharmonic emission from the bubble, and is located at $\omega_i + \omega_p/2$. The peak returned from the subharmonic is not only considerably narrower than that of the fundamental, but stands far higher above the noise floor than the $\omega_i + \omega_p$ signal. Further work has shown that the $\omega_i \pm \omega_p$ signal can arise from the direct coupling of the two interrogating sound fields in the absence of a bubble, although this stands 10-15 dB below the level caused by the nonlinear mixing action of a bubble. Therefore bubble sizing solely using the signal at $\omega_i \pm \omega_p$ would not provide an unambiguous indicator of the presence of a bubble.

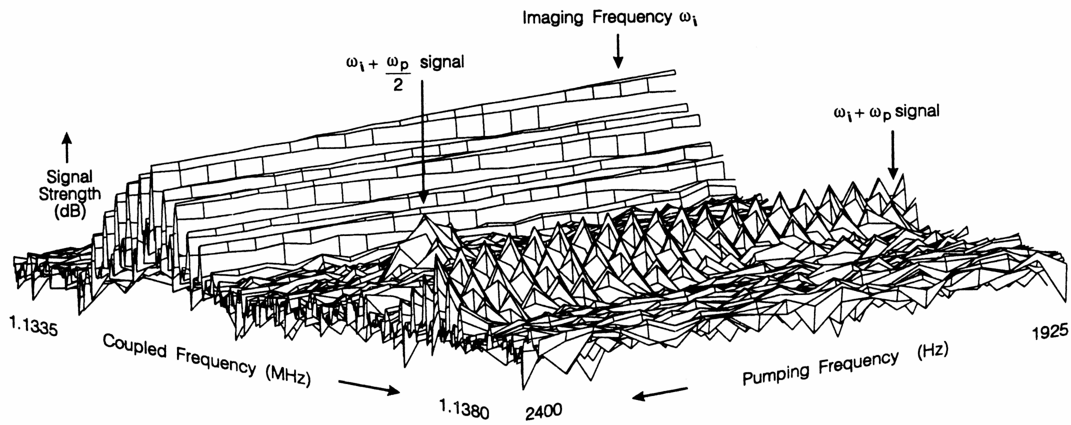

Figure 4 *Mesh plot of returned signal strength through a bubble's resonance. The bubble was insonated at 70 Pa and the pumping frequency was stepped in 25 Hz intervals.*

Tests have been performed to investigate the dependence of the output response on the level of the pumping signal. ***Figure 5*** shows the results of one such test. The bubble was insonated through its resonance at 40 discrete pumping frequencies in 5 Hz steps, and each run the pumping signal's strength was increased by 2.5 Pa. The plot shows four of these responses, which correspond to 60 Pa, 70 Pa, 75 Pa and 85 Pa. The response at 60 Pa shows that no subharmonic is present in the noise, and therefore that a definite excitation threshold exists. The subharmonic response at 70 Pa shows a peak in the signal with an unambiguous maximum - this can be used to very accurately determine the resonant frequency of the bubble to within ± 2.5 Hz. However, when the bubble is insonated at 75 Pa and above the response becomes overdriven, and there is an increase in the frequency range of the pumping signal over which a subharmonic can be exacted. Therefore the exact location of the bubble's resonant frequency is less obvious. Such results indicate that the choice of pumping amplitude is critical for bubble sizing[11].

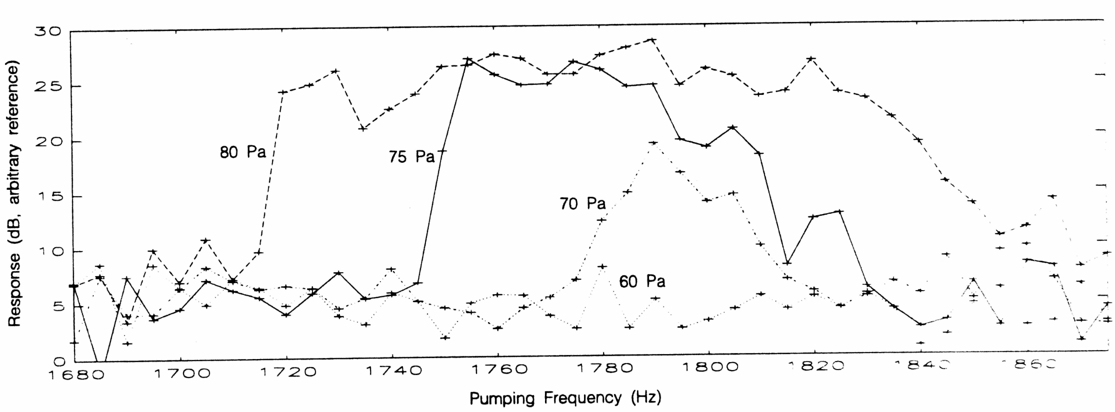

Figure 5 *Plot showing the variation in sum-and-difference subharmonic height through resonance as the strength of the pumping frequency is altered. The frequency step size is 5 Hz, and the lines correspond to pressure amplitudes of : 60 Pa (dotted), 70 Pa (dash-dot), 75 Pa (unbroken) and 85 Pa (dashed).*

The reproducibility of the subharmonic signals were tested by repeating an identical run five times, and looking for the maximum value of the fundamental and subharmonic sum-and-difference responses[11]. This was performed for various sizes of bubbles and data was collected corresponding to insonation at the threshold of subharmonic excitation, and again when the bubble was being overdriven. The results show a considerably larger amplitude spread for the subharmonic signal than for the fundamental sum-and-difference signal. This may mean that it is more favourable to use the subharmonic signal to locate the bubbles, and the height of the fundamental signal to count the number occurring in that frequency band[11].

IV. ADDITIONAL COMMENTS

Future work on the active system will involve a more thorough investigation into the amplitude excitation thresholds and reproducibility after the returned signal has been heterodyned. It will also investigate bubbles whose resonant frequency falls over the full range of the projector, as the results described above have all been obtained from bubbles resonant between 1700 and 2500 Hz.

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