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Characterisation of the oceanic bubble population using a combination frequency technique

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There are great benefits to sizing bubbles using a two frequency technique, which examines the appearance of sum-and-difference signals generated by the coupling of a resonant bubble pulsation to a much higher frequency imaging beam. This paper presents the results from using the technique to size bubbles in the ocean, and outlines the lengthy calibration procedure necessary to be able to relate the height of the bubble scattered signal to the number of resonant bubbles of that size. It also shows how ambiguities and inaccuracies which affected earlier oceanic tests using the same method can be identified in the returned signal and removed from the estimate during the data processing.

1. INTRODUCTION

There are many practical applications where a knowledge of the size and distribution of a bubble population would be of benefit [1-3], and the strong backscattering properties due to the liquid / air impedance mismatch makes acoustic measurements particularly amenable to the task. When excited by sound, a bubble pulsates volumetrically as a one degree of freedom system with a well defined resonance frequency, and as the driving amplitude is increased the scattering behaviour of the bubble becomes increasingly nonlinear. Earlier workers have attempted to measure the resonance frequencies of bubbles directly by exploiting these linear and nonlinear backscattering properties, but such estimates are limited in their accuracy, afford poor spatial resolution, and provide ambiguous data [4].

These limitations have been overcome through use of a two frequency technique, where a bubble population is simultaneously insonified with a high frequency fixed *imaging* signal ω_i as well as the lower variable frequency *pump* signal ω_p, intended to excite the individual bubbles at their resonant frequencies [5]. The strength of the imaging signal scattered from the bubble varies with the oscillating target cross-section, and the modulation of the imaging signal by a pulsating bubble generates sum-and-difference signals at $\omega_i \pm \omega_p$. These components will occur whenever the bubble pulsates, and so can be detected far from resonance. However, when the pump sound field becomes coincident with a bubble resonance and the wall pulsations are large, the $\omega_i \pm \omega_p$ signals reach a maximum amplitude. The spatial resolution is determined by the volume of fluid in the intersection of the high frequency projector beam and the high frequency receiver, and is therefore considerably more localised than the measurements of the direct backscattered signals.

This particular indicator of the bubble resonance has been investigated by earlier workers for laboratory populations employing increasingly more sophisticated signal processing techniques [5-7], and once on an oceanic population [8]. The oceanic data was taken using a chirped signal between 2.5 and 6 kHz with an imaging frequency of 450 kHz, and suffered in that no attempt was made to distinguish between the bubble mediated coupling and that caused by turbulence, or to allow for the significant off-resonance contribution which is characteristic of the $\omega_i \pm \omega_p$ signal. This paper describes the results of a work undertaken to build a more robust and accurate bubble population estimator, and describes preliminary results taken from oceanic measurements, which used four spot frequencies at 28 kHz, 50 kHz, 60 kHz and 88 kHz. The choice of three of these frequencies allows comparison of the returned data with earlier bubble population estimates taken exploiting the resonant backscatter effect [9]. The paper shows how turbulent effects are differentiated from the bubble signals, and makes allowances for the broad nature of the $\omega_i \pm \omega_p$ signal. As individual tones were employed, the variable frequency response of the source transducer could be removed enabling constant bubble insonification conditions to be chosen. The paper first describes briefly the calibration of the equipment and returned signals, and then outlines the experimental oceanic set-up. Lastly, results and preliminary conclusions are presented from the data collected on site.

2. EXPERIMENTAL APPARATUS

2.1 Calibration in the laboratory.

The laboratory tests were performed in a 1.8 m × 1.2 m × 1.2 m deep glass reinforced plastic tank which is vibration isolated from the floor, and is filled with tap water to 1 m depth. The equipment schematic is shown in figure 1, and a detail of the transducer arrangement is included in figure 2.

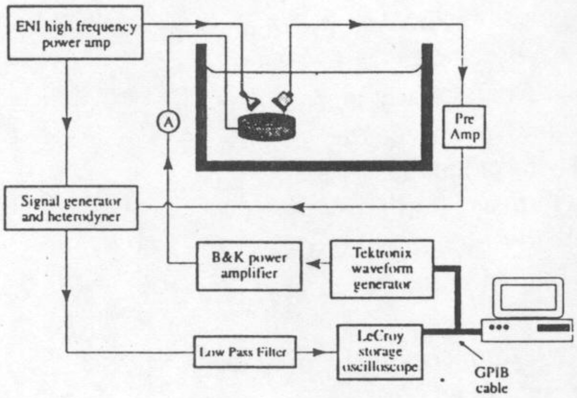

Figure 1: Schematic of the equipment used in the laboratory tests.

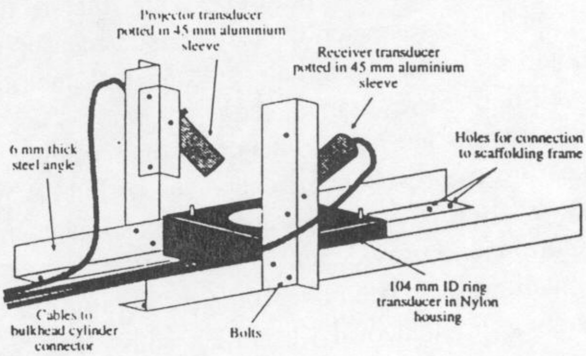

Figure 2: Close-up of the transducer arrangement used in both the laboratory tests and in the oceanic measurements.

The pump frequency signal generation was achieved using a Tektronix 2005 arbitrary waveform generator passed through a Bruel and Kjaer 2713 power amplifier. The pump transducer comprised a 104 mm inside diameter piezoceramic ring set into a polyurethane foam and encased in a nylon housing. The imaging signal was generated by a 1 MHz crystal oscillator constructed by the in-house electronics workshop amplified with an ENI 240L RF power amplifier. This signal was passed to the transducer from a Therasonic 1030 ultrasonic therapy unit, as manufactured by Electro Medical Supplies, which was potted inside a 45 mm diameter aluminium cylinder to protect it when later used in the open sea. This gave an imaging signal amplitude of 120 kPa. The returned signal from the bubble was picked up from a 1 MHz Panametrics V302 transducer, similarly potted in a 45 mm diameter sleeve, and conditioned using a Panametrics 5670 preamplifier. This signal was then heterodyned with a dummy signal from the crystal oscillator: this results in the useful information contained just above and below the imaging frequency being reproduced at just above dc, enabling much lower sampling rates and data storage. This low frequency information was filtered to prevent aliasing and acquired on a LeCroy 9314L storage oscilloscope. For the laboratory tests the data was sampled at 50 kHz and 10,000 points taken. The beam patterns of the two high frequency transducers were modelled, and showed that the active insonification volume, defined by where the sensitivity fell off to 3 dB of its peak value, was 0.20 cm^3.

The calibration of the apparatus was performed to ensure that it is possible to relate the absolute height of the returned signal from the oceanic tests to the signal strength associated with one resonant bubble. This was achieved by repeatedly insonifying a steady stream of bubbles of known natural frequency, and examining the strength of the returned signal. The bubble stream was generated by passing compressed air through a constricted syringe, resulting in a steady population of resonant frequency 5400 Hz, which was allowed to rise through the transducer focus where it was insonified at a pump signal amplitude of 200 Pa. The scope was set up to trigger each time with one bubble signal filling the centre of the display to allow a direct comparison of the results. The heights of the heterodyned $\omega_i+\omega_p$ signals were measured each time, and then averaged. They were found to be repeatable to within 15 %.

The second stage of the calibration involved modelling the bubble mediated sound pressure at the receiver transducer due to the two insonifying sound fields. This used an implementation of the Gilmore model, which is described elsewhere [10,11], and has been shown to accurately model volumetric bubble pulsations. The same bubble size and insonification conditions as employed in the laboratory experiments were simulated, such that a comparison of the results with the experimentally estimated values would allow the sensitivity of the receiver transducer, preamplifier and heterodyner combination to be evaluated. Using this estimate, the behaviour of resonant bubbles at the four pump frequencies used in the oceanic tests could also be modelled and, applying the same sensitivity correction, could be used to provide an estimate of the signal levels expected from a resonant bubble *in situ*.

2.2 Oceanic data collection

The equipment set up used in the sea trials was similar to that used in the laboratory experiments, and the schematic is shown in figure 3. The most important difference in the layout of the oceanic equipment is the provision of a remote equipment canister, which was placed in the sea and attached to the land based equipment via an underwater bulkhead connector and 200 m of waterproof cable, as manufactured by PDM. This comprised a 1000 mm long × 355 mm diameter watertight aluminium alloy cylinder, which was painted to minimise corrosion, and clamped to a rigid scaffold structure as shown in figure 4. This canister contained the high frequency power amplifier, the crystal oscillator and heterodyner equipment, the RF preamplifier, and a temperature sensor to ensure that the equipment did not overheat.

Additionally, a differential amplifier pair was added to the returned signal circuit to ensure that no signal corruption occurred when passed down the 200 m cable. Due to the higher pump frequencies involved, the data was sampled at 500 kHz, and 50,000 points were taken. To speed up the data collection and storage, the Tektronix output comprised all four frequencies in one signal, and the sampled data was triggered by markers from the generator to allow the individual sections to be identified in the returned waveform.

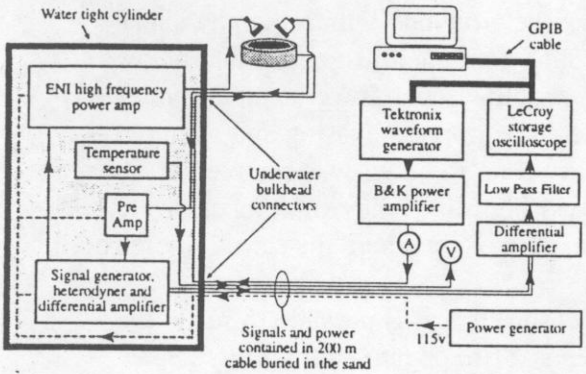

Figure 3: Schematic of the apparatus used in the oceanic measurements.

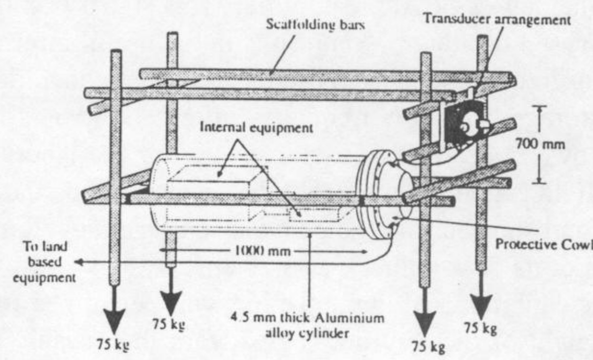

Figure 4: Deployment details of the watertight canister and scaffolding.

Preliminary calibration tests to prepare the apparatus were carried out in the department underground experimental tank, which measures 8m × 8m × 5m deep. The equipment was lowered into the tank until the transducer focus was 1.5 m underwater, the typical depth used in the sea trials, and the pump signal amplitude was measured at each of the four frequencies using a Bruel and Kjaer 8103 hydrophone when driven with a constant input signal level. This allowed the frequency response of the pump transducer to be inverted, and a calibrated pump signal amplitude to be employed.

The oceanic tests were performed in the North Sea between 26th and 30th November 1995, on a beach in Tunstall in East Yorkshire, and were carried out in tandem with a party from the Southampton Oceanography Department. The beach was chosen due to its slight gradient, which allowed the equipment to be set up at low tide and anchored to the sand, such that as the tide came in it would eventually cover the rig to enable measurements to be taken. The rig was weighed down with 75 kg metal weights at each corner which were buried in the sand. The data collection used a 3000 Pa pump signal amplitude, and 25 four frequency samples were taken over a 3.5 minute period every half hour that the transducers were immersed. As the signals were broadcast consecutively with no gap, each measurement lasted only 0.4 s.

3. RESULTS AND DISCUSSION

A typical spectrum from the sea trials is presented in figure 5, taken from a 28 kHz insonification. The particular data was collected at 22.30 on the 29th November 1995, when the wind speed 11 m/s, and the transducers were immersed at a depth of 1.5 m in water approximately 3 m deep. The data shows the heterodyned signal from the high frequency receiver, in which the imaging signal is visible at 1 kHz (not at dc due to the Doppler shift from the moving bubble targets). The sum frequency spectral information contained just above the imaging signal is also shown, at approximately 29 kHz, and the difference data shown at 27 kHz - these signals would overlap were the measured bubbles stationary. Between the two combination frequency peaks is a single spike at 28 kHz. This is caused by the nonlinear combination of the pump and imaging signals by turbulence in the detection zone, and can be therefore distinguished from the actual bubble mediated information.

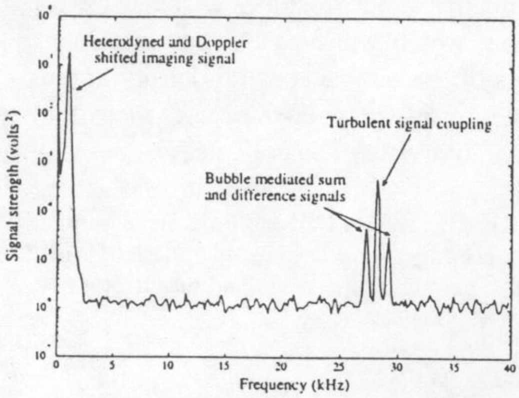

Figure 5: Typical results from the oceanic tests, showing the heterodyned frequency content for a 28 kHz insonification signal.

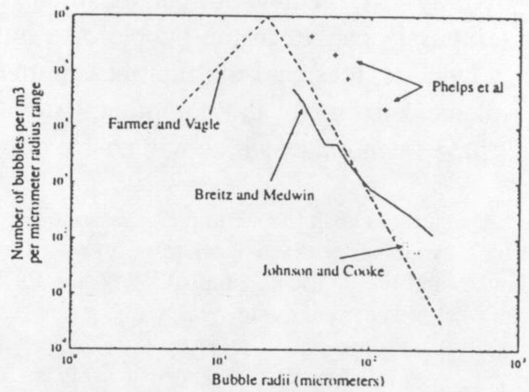

Figure 6: Comparison of preliminary time averaged oceanic data with earlier estimates, taken from Farmer and Vagle [9], Breitz and Medwin [12] and Johnson and Cook [13]

The data collected over these 25 time intervals was analysed to get the individual heights of the heterodyned sum signals, and time averaged so that comparisons with existing bubble data is possible. This data was taken from Farmer and Vagel [9], Breitz and Medwin [12] and Johnson and Cooke [13] who have all previously applied different bubble estimators to oceanic distributions. The preferred method of presenting the data is in numbers of bubbles per m^3 per micrometer radius range, and figure 6 shows the three sets of data superposed with the time averaged population measured using the two frequency technique. The radius range over which these signals existed was numerically calculated from linear theory of the behaviour of a range of bubble radii to the four frequencies employed [4], defined again by where the individual contributory sound pressure level was 3 dB down on the maximum resonant level.

The data shown in Figure 6 shows that the bubble population measured using the two frequency technique exceeds the other estimates over the whole radius range. This is to be expected as the data was collected in the surf zone where because of the continual wave action a high concentration of bubbles is created. Farmer and Vagle collected their data in a 12-14 m/s wind speed from bubble scatter in a 4 km deep channel using upwards facing sonar designed to monitor the linear backscatter from the bubble population. Johnson and Cooke used photographic estimates in 20-30 m deep water, of which the population estimate at 0.7 m depth and 11-13 m/s wind speed is included. Breitz and Medwin collected their oceanic data with a flat plate resonator, which again exploits the linear resonance of bubbles. They measured in water 120 m deep in 12-15 m/s wind speeds and at a depth of 25 cm. Thus, although the environmental measurement conditions were similar over the four sets of collected data, the local sea dynamics were very different for the Tunstall measurements due to the presence of surging breakers.

4. CONCLUSIONS

The paper has described the design and implementation of an oceanic bubble measurement device capable of sampling a small but well defined volume. Unlike previous oceanic measurements, the technique employed here provides an unambiguous and potentially more accurate estimate of the local bubble population. Additionally, as the device collects data over a period of only 0.4 seconds for all the four frequencies, the results can be used to investigate the temporal changes in the bubble distribution, which will be published in a later paper. To our knowledge, these are the first measurements of the bubble spectral density in the surf zone. It is planned to mount the equipment from a buoy in the deeper ocean where the historical studies have been made, which will enable comparative data to be collected.

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