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Sonic Pulse

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Ultrasonic Bubble Measurements In Pipes

Introduction

The Institute of Sound and Vibration Research has an expanding interest in Underwater Acoustics, with research currently underway on topics such as the measurement of the oceanic bubble population, ultrasonic cavitation, the ultrasonic characterisation of bone and of suspensions in water, and the propagation of sound in the ocean and in shallow water. This article describes the development and preliminary results of an acoustic system designed to detect and size gas bubbles in a liquid-filled pipe. This system exploits a variety of different bubble acoustic properties, from the basic geometric backscatter which any impedance mismatch will provide, through to the acoustic measurement of tiny surface ripples set up on the bubble wall. It is hoped that a comparison of these different responses will allow the drawbacks inherent in each technique (when used individually) to be minimised, as well as identifying which signals are not amenable to this particular application. Tests were performed on two different bubble populations, a single bubble attached to a wire in the transducers' focus (for calibration) and then a freely rising bubble stream.

The Acoustic Bubble

Being able to detect and size stable gas bubbles in a liquid is important to a range of industrial applications such as filling processes (in the glass and paint industries, for example) and the production of photographic material. In addition, stable micro-bubbles may need to be identified to assess the likelihood that they might seed inertial cavitation in a liquid. Many such applications would involve the detection of bubbles in pipes, ranging from the very large (e.g. in the petrochemical industry) to the very small (e.g. in blood vessels).

Acoustic techniques are very suitable for bubble sizing, as there is a large impedance mismatch at the gas-liquid interface. As well as this basic scattering property, the bubbles themselves can pulsate with a well defined resonance frequency, f_0. For air bubbles in water at atmospheric pressure, this can be expressed as $f_0 \approx 3.2/R_0$, where R_0 is the equilibrium bubble radius. Therefore, if it is possible to determine the acoustic resonance frequencies of a bubble population, their sizes can be easily calculated.

This article describes the results from preliminary tests designed to categorise the acoustic properties of a known bubble population in a fluid filled pipe. The tests were performed on two distributions - a single bubble attached to a wire in the focus of the transducers and a free rising stream of bubbles. For both of these populations a variety of acoustic signals were examined simultaneously, which arise from different characteristics in the bubbles' acoustic interaction. The experimental apparatus is outlined below in Fig 1, and the results from the attached bubble tests only are presented as a brief introduction to the research.

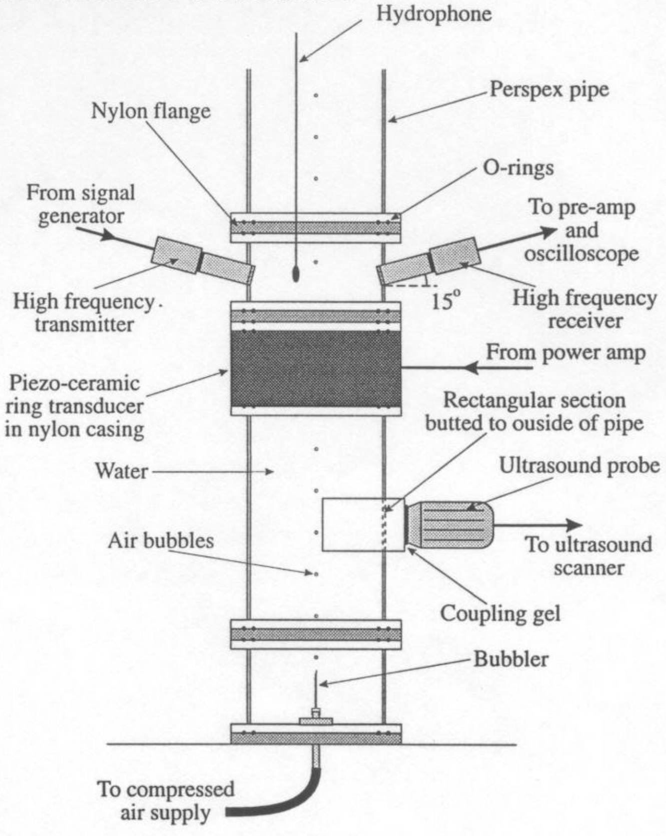

Fig 1: Apparatus used in the tests. The pipe internal diameter was 100 mm.

The most simple of the acoustic signals generated by the bubble is the geometric backscatter experienced when a sound wave encounters an impedance change, such as that at the bubble surface. This was monitored using a 3.5 MHz foetal-scan probe scanning the cross-section of the pipe, a frequency considerably higher than the resonance frequencies of any bubbles in the pipe. This signal provides some information on whether or not an inhomogeneity is present in the fluid, but it cannot provide any information on the size or number. If this technique were to be used on its own, it would also be difficult to distinguish a bubble from a solid particle. However, the probe can be set to run continuously and monitor the flow to provide a trigger for more sophisticated techniques, which can not only distinguish a bubble from a particle, but can also determine its size.

To do this, it is necessary to stimulate the bubbles at their resonance frequency. Fig. 2 illustrates the bubble 'amplification' taken by monitoring the strength of the backscatter when a range of discrete *pump* frequencies (ω_p) spanning the bubble resonance were broadcast using the ring transducer. The results show a peak at the frequency location of the bubble resonance: this can be distinguished from a solid particle as the scattering of the pump signal by a bubble is many orders of magnitude stronger than that from a solid body of similar size. However, such resonance estimates have poor spatial resolution, and provide ambiguous results, in that a bubble much larger than resonance may scatter more sound than a small resonant bubble.

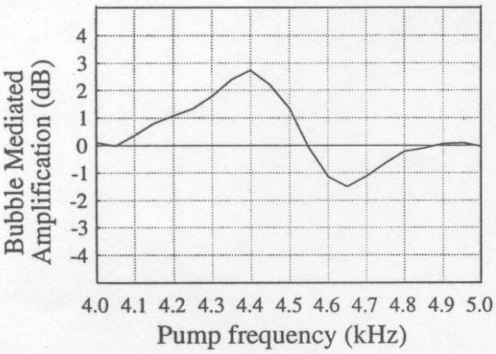

Fig. 2: Strength of the backscatter at ω_p from measurements of a stationary bubble tethered to a wire, insonified between 4 and 5 kHz in 50 Hz steps through its resonance at an amplitude of 120 Pa.

This ambiguity may by reduced by monitoring the nonlinear behaviour of a bubble, evident at large pulsation amplitudes (typically indicative of resonant behaviour). This results in the generation of harmonics of the driving signal frequency at $2\omega_p$, $3\omega_p$ etc. However, our tests showed that these were generally unsuitable, as the distortion in the equipment and nonlinear sound propagation in the fluid swamped the bubble signal.

Further nonlinearities can be excited in the form of non-integer harmonics of the sound field, the most prominent of which is a subharmonic at $\omega_p/2$, caused by the stimulation of Faraday waves on the bubble's surface. Although these are the least ambiguous signals as they can only be generated by a bubble driven very close to resonance, they do not propagate far into the fluid as they involve no bubble volume change, and could not therefore be monitored at the measurement hydrophone.

A further refinement on these backscatter techniques is to look at the response when the bubbles are driven simultaneously with a high frequency fixed *imaging* beam (at angular frequency ω_i) as well as the pump beam ω_p. This allows the resonant pulsations to be monitored as the high frequency scattered signal is modulated as the bubbles' acoustic cross-section changes over time: this will generate sum-and-difference frequencies in the returned spectra, with the strength of two of these signals shown in Fig. 3. The first is the signal at $\omega_i \pm \omega_p$ due to the resonant pulsation, and the second at $\omega_i \pm \omega_p/2$ due to the modulation caused by the Faraday surface waves. These have advantages in that they have excellent spatial resolution (defined by the intersection of the high frequency beams) and do not suffer the same ambiguities of the basic scatter techniques, in that they cannot be stimulated from bubbles far from resonance. In addition, with an imaging frequency ω_i in the MHz range, all the useful information about the bubble appears at these high frequencies, well away from sources of lower-frequency noise which can otherwise be problematic in an industrial environment. It is clear from Fig 3 (b) that the $\omega_i \pm \omega_p/2$ signal allows an excellent estimate of the bubble's resonance frequency of 4500 ± 50 Hz , corresponding to a bubble radius of 740 ± 8 μm. This was confirmed optically.

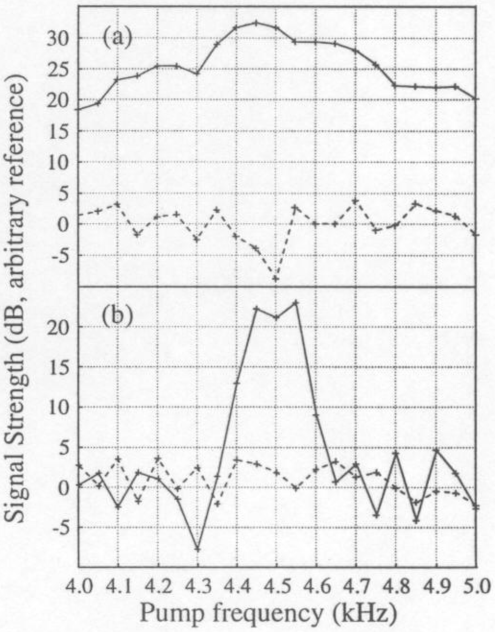

Fig 3: Strength of the backscatter at (a) $\omega_i \pm \omega_p$ and (b) $\omega_i \pm \omega_p/2$ from measurements of a stationary bubble tethered to a wire, insonified between 4 and 5 kHz in 50 Hz steps through its resonance at an amplitude of 120 Pa. The dashed line represents the signal strength in the absence of the bubble, and the unbroken line with the bubble present. All signal strength measurements are presented as dB relative to the average noise floor.

Discussion and future work

There are three signals from the wide range of acoustic responses taken simultaneously from the resonant bubbles which are useful for this particular application, specifically the signals at ω_p, $\omega_i \pm \omega_p$ and $\omega_i \pm \omega_p/2$. It is proposed in any future work that the first two of these signals (which essentially exploit the same bubble pulsation characteristic) be used to determine the spatially averaged and local distributions respectively, and the $\omega_i \pm \omega_p/2$ signal used to identify individual (larger) bubbles. Additionally, simple geometric scattering provides a useful monitor / trigger facility. The technique shows considerable promise for the particular application.

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