NOVEL SENSORS FOR MONITORING THE OCCURRENCE OF ACOUSTIC CAVITATION

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1 INTRODUCTION

The phenomenon of cavitation, which may be described simply as the oscillation, growth and collapse of small, stabilised gas or vapour bubbles within a fluid medium, is well known, and can occur as a result of both hydrodynamic and acoustic effects[1]. Its occurrence ranges from being an unwanted effect (e.g. causing erosive damage to surfaces), to that of a process requirement (e.g. ultrasonic cleaning, sonochemistry), and yet reliable cavitation detection and measurement techniques are not generally available. In a recent worldwide survey of equipment manufacturers and users, a strong requirement for such techniques was identified[2]. Furthermore, establishing reliable and validated cavitation sensors was seen as essential in underpinning the development of such measurement methods, and their current absence was identified as a fundamental limitation to the exploitation of high power ultrasound in a scientific manner.

Methods that have been applied to monitor cavitation usually involve measuring its direct effects, such as light emission, free-radical generation and erosion[3]. It is also well documented that in response to a forcing acoustic field, bubbles act as secondary acoustic sources whose emission spectra contain distinct features intimately related to the dynamics of bubble motion and collapse[4]. One feature is the broadband continuum noise, whose appearance is often associated with the onset of violent inertial cavitation[3]. This paper describes a new type of passive acoustic sensor, designed to monitor high frequency acoustic signals generated by cavitation*.

2 SENSOR CONCEPT

A number of desirable features of a cavitation sensor can be defined. It should:

- be as unperturbing as possible to the driving acoustic field;
- possess a wide measurement bandwidth, extending into the MHz region, enabling it to detect the broadband acoustic energy generated by bubble collapse;
- provide spatial resolution which can be achieved using a focussed receiver concept, so that the acoustic energy monitored from the bubble collapse can be associated with a specific volume of the fluid.

* The novel sensors described are covered a UK Patent Priority Application No. 9921982.6, and are currently patent-pending in the UK, Germany, USA and Japan.

3 SENSOR REALISATION

A schematic representation and photograph of the developed cavitation sensor is shown in Figure 1. It consists of a hollow cylinder of internal diameter 30 mm, made from an inner strip of piezoelectric polymer film, acting as a passive acoustic receiver. The film thickness of 110 µm has a theoretical resonance at 9 MHz, providing it with a readily usable response at the MHz frequencies of interest. The piezoelectric film is encapsulated in a 4 mm thick layer of a polyurethane material, which will hereafter be referred to as the cavitation shield. A special moulding tool has been developed to enable the one-piece cavitation shield material to be deposited on the outside of the piezoelectric film. Electrical contacts are either partially or totally embedded within the cavitation shield material. The measured capacitance of the sensors is typically 2.2 nF, close to the predicted theoretical value.

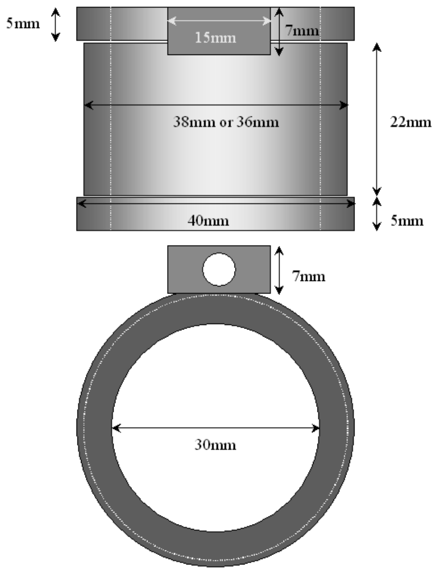

Figure 1: Left - schematic representation of the cavitation sensor, based on a hollow cylinder of inside diameter 30 mm and height 32 mm, which is shrouded in a 4 mm thick layer of the cavitation shield material. The 15 mm x 7 mm x 7 mm lug on the side of the cylinder is provided for mounting purposes. Right - photograph of the sensor, with a 20 p coin shown for scale.

4 CAVITATION SHIELD PROPERTIES

The main function of the cavitation shield layer is to ensure that high frequency acoustic signals contributing to the electrical output signal of the sensor originate from the fluid contained within the sensor volume. As such, desirable properties of the material are that its attenuation coefficient must be exceedingly high at MHz frequencies, and kept to a minimum at the typical driving frequencies utilised by cleaning vessels, for example 40 kHz.

The composition of the cavitation shield material, which was devised under a specialist development programme, is proprietary. It is based on a polyurethane rubber, whose properties of attenuation coefficient and acoustic impedance have been optimised for the application. In particular, the acoustic impedance at 40 kHz has been adjusted to match that of water. Above 1.5 MHz, the transmission loss of the material is 65 dB cm^{-1} MHz^{-1}. Therefore, for frequencies above 1.5 MHz, the 4 mm layer of shield material will attenuate signals originating outside the cylinder by at least 40 dB, relative to those occurring within the sensor volume. This degree of attenuation increases very rapidly with frequency. The cavitation shield material also gives the cylindrical sensors a significant degree of rigidity.

5 EXPERIMENTAL SYSTEMS

5.1 ULTRASONIC CLEANING VESSEL

The main performance evaluation of the new cavitation sensors was carried out using a Branson Ultrasonics 6465-126-12CB cleaning vessel, operating at a frequency of 40 kHz, in conjunction with a B8040-12 generator. The generator had been modified to allow the electrical drive to be precisely and reproducibly varied over the range 5% to 100% of the full rated power of the cleaning vessel (900 W). In common with most commercial systems, the generator operated the vessel by means of an amplitude-modulated signal (100% modulation, 100 Hz rate).

5.2 SINGLE TRANSDUCER RIG

A second system was employed to investigate the response of the sensor. This consisted of a single 40 kHz Branson cleaning vessel transducer, mounted in a Perspex tank of internal diameter 220 mm and height 220 mm. The transducer was driven continuously by a Hewlett-Packard HP8165A function generator, operating through an ENI 240L RF power amplifier. Peak-to-peak transducer drive voltages of up to 210 V were used.

5.3 WATER PREPARATION

A water management system was used to prepare media of a specified purity (5 µm filter) and dissolved oxygen content (<0.5 ppm) to be used in the two test systems.

5.4 SPECTRUM ANALYSER

The spectral content of the sensor output signals was determined using a Hewlett Packard HP3589A Spectrum Analyser. Although various set-up conditions were used for the measurements shown in Section 6, they were typically characterised by between 5 and 50 averages of the frequency sweep.

6 EXPERIMENTAL RESULTS

6.1 ULTRASONIC CLEANING VESSEL

Prior to the design and development of the mould tool for fabricating the sensor, feasibility studies were carried out on the basic sensor concept. This involved comparing acoustic spectra generated from the ‘bare’ piezoelectric film with those spectra obtained when using the same piece of film shrouded in a cylinder of the cavitation shield material. The results below have been derived using the cleaning vessel filled with air saturated tap-water at room temperature (20 °C).

Figure 2 shows a comparison of the acoustic spectra up to a frequency of 400 kHz, with the cleaning vessel operating at 20% of maximum power. The vertical scale has been greatly expanded to show those frequency components occurring between the well-defined harmonics, which occur at multiples of the fundamental drive frequency of the vessel. Of interest within the current paper is the fact that at progressively lower frequencies, the two spectra are virtually indistinguishable. This indicates that the cavitation shield material is indeed reasonably non-perturbing below 50 kHz. At progressively higher frequencies, the signal levels generated by the film when placed in the cavitation shield cylinder are significantly lower, due to the increasing absorption coefficient of the shield material.

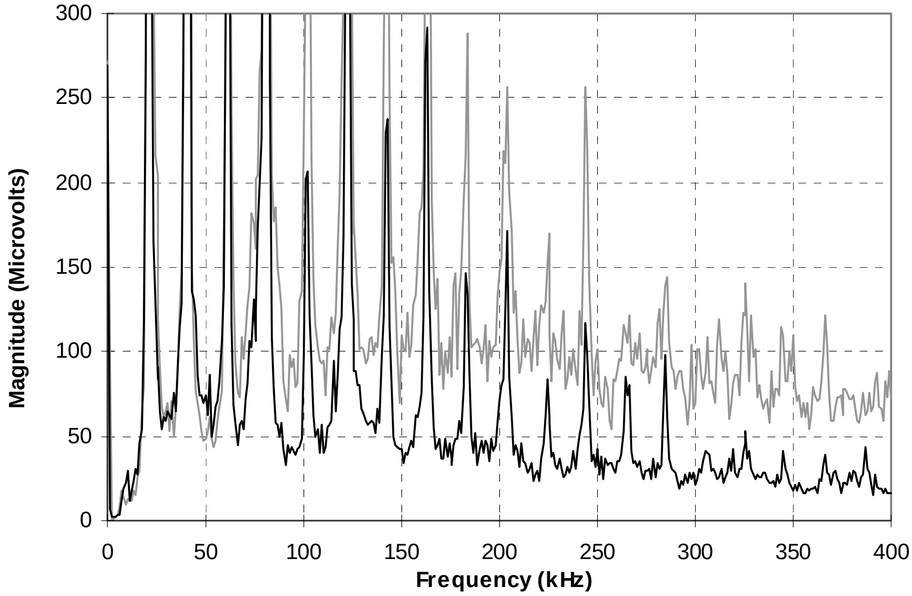

Figure 2: Comparison of sensor spectra derived from a) 'bare' piezoelectric film (grey plot) and b) the same film, placed in a 30 mm diameter hollow cylinder of the cavitation shield material (black plot). The two configurations have been positioned at nominally identical positions within the cleaning vessel which has been filled with air-saturated 'tap water'. The vessel was operating at 20% of its maximum output power.

Figure 3 examines the high frequency range, covering 1 MHz to 15 MHz (frequency resolution 35 kHz), where spectra are again compared for the two situations given above. It should be noted that the existence of acoustic signals at frequencies in excess of 10 MHz has been confirmed through measurements made using a wide-bandwidth GEC-Marconi bilaminar membrane hydrophone, and these results are given as a third curve in figure 3.

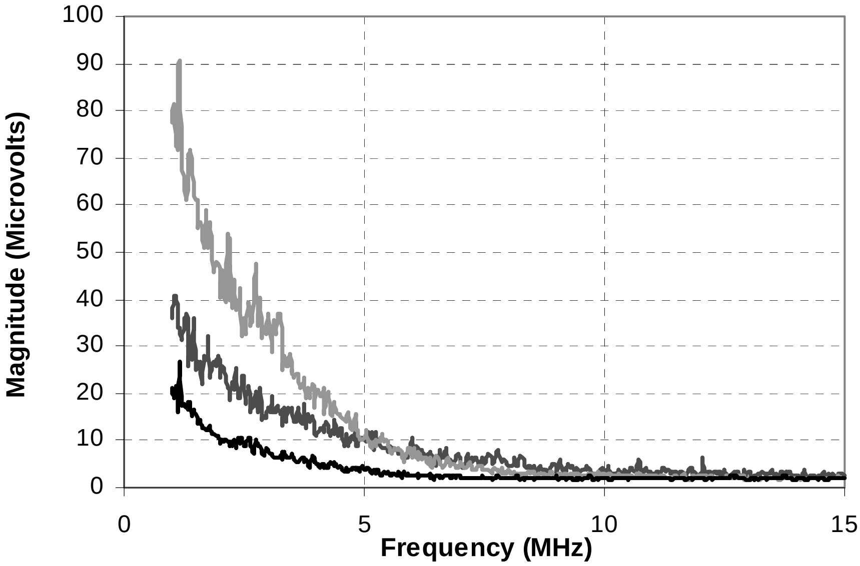

Figure 3: Comparison of sensor spectra derived from a) 'bare' piezoelectric film (grey) and b) the same film, placed in a 30 mm diameter hollow cylinder of the cavitation shield material (black). Also presented is the response generated by a wide bandwidth GEC-Marconi bilaminar membrane hydrophone (red). The experimental conditions are the same as those in figure 2.

It is clear from figure 3 that the signal levels above 1 MHz are greatly reduced when the piezoelectric sensor is in the shielded configuration. This arises due to the spatial resolution of the sensor, so that only bubble events occurring within the cylindrical volume contribute to the high frequency (above 1.5 MHz) sensor output. In contrast, in the un-shielded (or 'bare' configuration), events occurring throughout the cleaning vessel can potentially contribute to the sensor output.

To provide an indicator or 'measure' of the degree of inertial cavitation, the acquired acoustic spectra were analysed in terms of the broadband integrated energy, defined as:

$$\textit{Broadband integrated energy} = \int_{f_1}^{f_2} V_C(f)^2 \, df \qquad (1)$$

where $V_C(f)$ represents the frequency-dependent spectral magnitudes derived from the cavitation sensor spectrum. Figure 3 shows that beyond 5 MHz, the acquired signal levels from the shielded sensor are at a low level, and typically only a few dB above the noise floor, even for higher vessel drive levels. So, in the following figures, the integration limits f_1 and f_2 are taken as 1 MHz and 5 MHz respectively. This has been found to give a robust indicator of the cavitation activity, although it should be appreciated that there resides potentially significant energy at frequencies beyond 5 MHz.

It is clearly of interest to establish how the high frequency acoustic spectra generated by the sensor vary with the nominal electrical power delivered to the ultrasonic cleaning vessel. Figure 4 shows this dependence derived from one of a number of final encapsulated sensors fabricated for the purposes of performance evaluation.

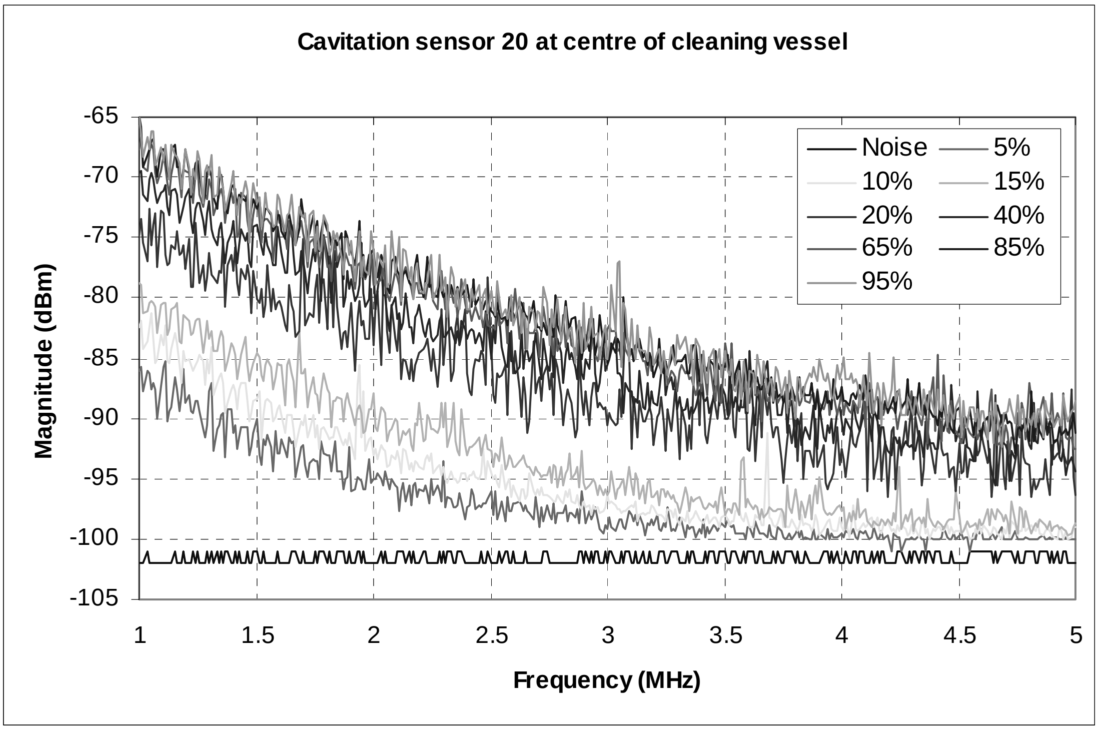

Figure 4: Frequency spectra generated at eight power settings of the BRANSON cleaning vessel, in addition to a measurement made of the background noise level.

The spectra shown in figure 4 were derived from measurements made in degassed-deionised water whose initial conditions were a dissolved oxygen content of 2.5 ppm and a temperature of 23.8 °C. The sensor was placed centrally within the cleaning vessel volume and spectral acquisitions carried out as the vessel power was gradually increased from the minimum level of 5% up to the 95% of the maximum output power of the vessel. The results shown in Figure 4 are for a single sensor, but they are typical of a number of measurement runs carried out using different sensors, as well as repeat measurements made using the same sensor placed at a nominally identical position within the cleaning vessel.

It is clear from figure 4 that there is a strong and systematic increase in the MHz frequency signal levels as the output power setting of the cleaning vessel is increased. The 1 MHz signal level increases by approximately 20 dB when the vessel output is increased from 5% to 95%. The spectra are characterised by energy progressively being transferred to higher frequencies as the vessel output power is increased. For the 95% case, for example, signals at 5 MHz are around 10 dB above the noise floor of the measurement system. This is the expected behaviour for a strongly nonlinear system such as a bubble cloud, driven at increasingly high forcing pressures[5].

The spectra shown in Figure 4 have been analysed according to equation (1), and the resulting broadband integrated energy values are plotted in Figure 5, as a function of vessel output level. The increase of the broadband energy as the vessel output level increases is initially slow, and then steepens up to the 20% level, before increasing at a slower rate up to the maximum level tested. There is a suggestion that the rate of increase flattens off at the higher levels, and this may be indicative of the broadband energy extending into higher frequencies, beyond the 5 MHz limit studied. Other phenomena, such as cavitation shielding, may also be responsible for the effect. Cavitation shielding involves bubble clouds forming close to the transducer output faces at high drive levels, which scatter the transmitted field and reduce the acoustic pressure levels, and hence cavitation activity, experienced deeper into the fluid

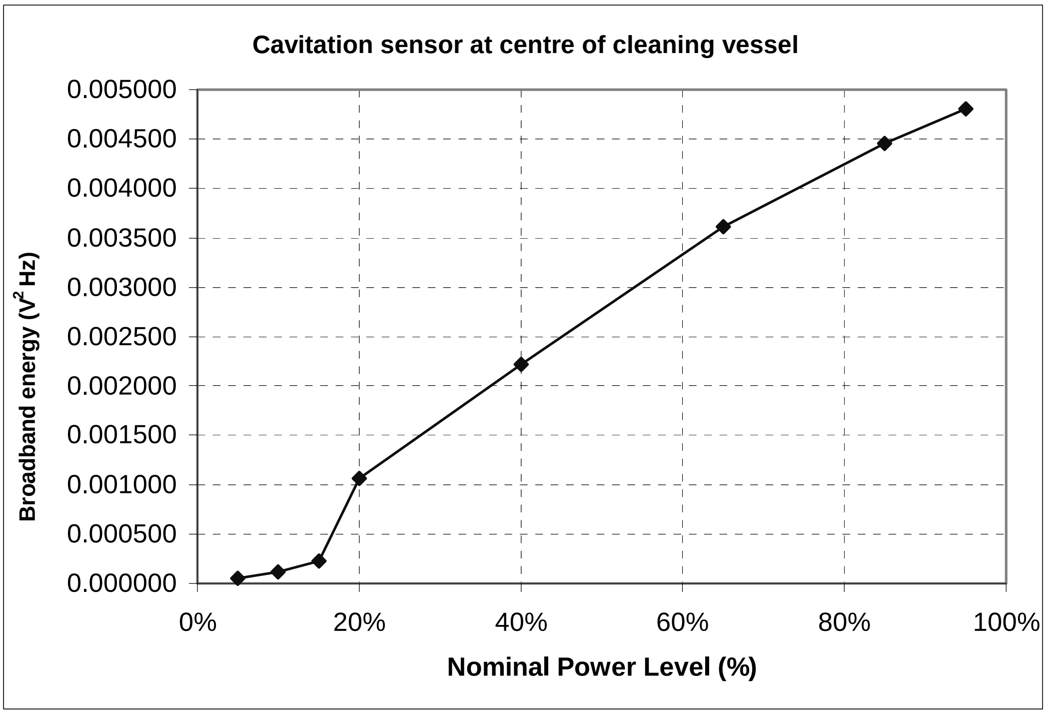

Figure 5: Variation of broadband integrated energy as a function of cleaning vessel output setting

6.2 SINGLE TRANSDUCER RIG

Following the studies carried out in the cleaning vessel, the final encapsulated sensor design was used with the single transducer rig system described previously, and depicted in Figure 6. The tank was filled with tap water.

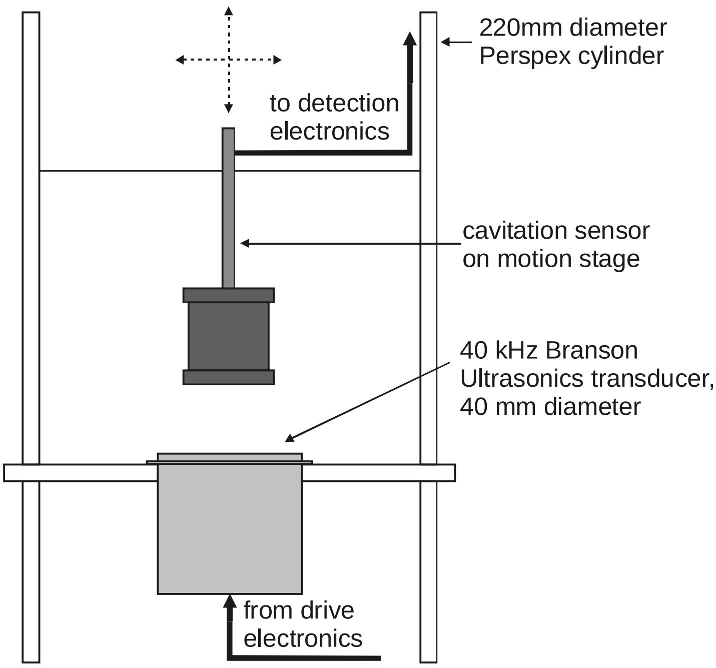

Figure 6: Schematic representation of single transducer facility

The transducer was driven at around 200 V peak-to-peak, at 40 kHz, continuous wave. The sensor was positioned over the transducer, at a vertical separation distance of 30 mm ± 0.5 mm (to the bottom of the sensor), and centralised horizontally, by eye, to within ± 2 mm. Keeping the drive constant, measurement spectra in the range 1 MHz to 5 MHz were acquired as a function of lateral position of the sensor relative to the transducer, and the data analysed according to equation 1 above. The broadband energy values at the respective lateral positions are plotted in figure 7.

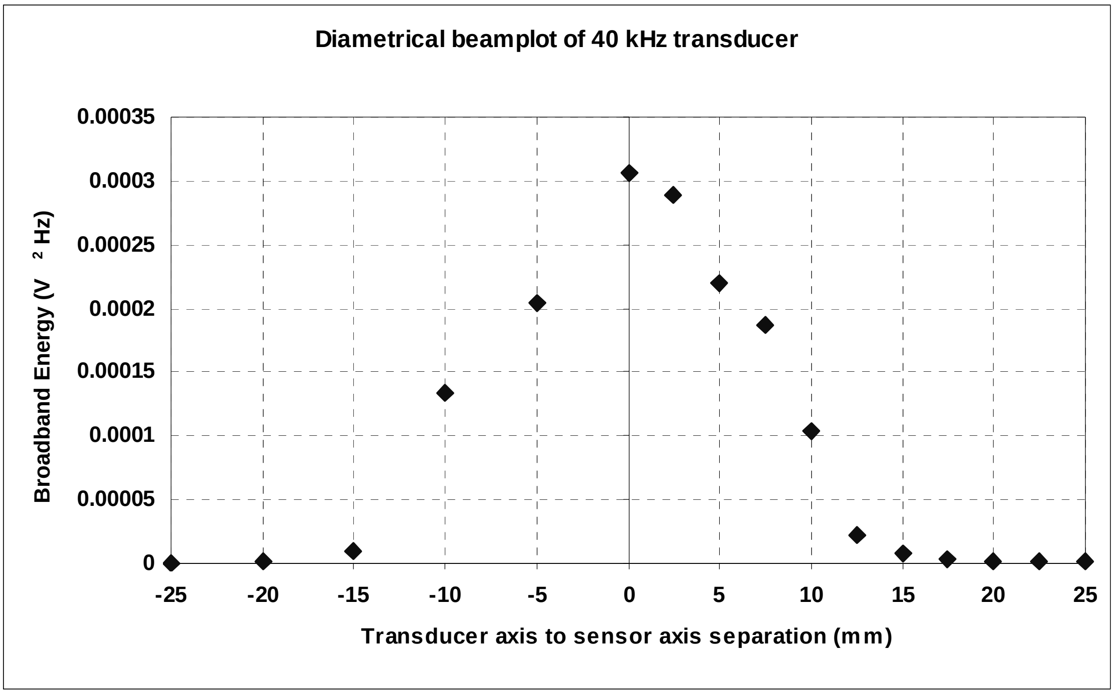

Figure 7: Spatial variation of broadband cavitation activity across a 40 kHz transducer

Figure 7 shows a significant degree of spatial variation in cavitation activity in the vessel, which the sensor is able to resolve. The sensor measures in effect a ‘cavitation beam width’, which is approximately 25 mm at the –6 dB level – this compares with the face diameter of around 40 mm. This result, which was repeatable, suggests that although the direct acoustic field produced by the 40 kHz transducer would be expected to be strongly diverging, the resulting cavitation activity produced is more localised. This may have implications for the uniformity of the cavitation activity in small ultrasonic cleaning vessels.

7 SUMMARY

This paper has introduced a new type of passive acoustic sensor designed to monitor the broadband emissions generated by acoustic cavitation.

The characteristics of the sensor are as follows:

- the usable measurement bandwidth of the sensor is in excess of 10 MHz, enabling the MHz frequency signals generated by violent inertial cavitation to be monitored;

- a cavitation shield resident on the outside of the hollow cylindrical sensors ensures that contributing MHz signals originate from within the sensor itself, providing the sensors with spatial resolution.

Early tests to establish the ‘proof-of-concept’ have been encouraging and it is anticipated that the major potential application area for the sensor is as a monitoring tool for assessing cavitation activity occurring with ultrasonic cleaning vessels. Ultimately, devising a relationship between measured cavitation activity and its effects is likely to be of significant utility.

8 ACKNOWLEDGEMENTS

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