A detector for monitoring the onset of cavitation during therapy-level measurements of ultrasonic power

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Abstract. Acoustic cavitation occurring in the water path between a transducer and the target of a radiation force balance can provide a significant source of error during measurements of ultrasonic power. These problems can be particularly acute at physiotherapy levels (> 1 W), and low frequencies (≤ 1 MHz). The cavitating bubbles can absorb and scatter incident ultrasound, leading to an underestimate in the measured power. For these reasons, International Specification standards demand the use of degassed water. This imposes requirements that may actually be difficult to meet, for example, in the case of hospitals. Also, initially degassed water will rapidly re-gas, increasing the likelihood of cavitation occurring. For these reasons, NPL has developed a device that monitors acoustic emissions generated by bubble activity, for detecting the onset of cavitation during power measurements. A commercially available needle hydrophone is used to detect these emissions. The acoustic signals are then monitored using a Cavitation Detector (CD) unit, comprising an analogue electrical filter that may be tuned to detect frequency components generated by cavitating bubbles, and which provides an indication of when the measured level exceeds a pre-defined threshold. This paper describes studies to establish a suitable detection scheme, the principles of operation of the CD unit, and the performance tests carried out with a range of propagation media.

1. Introduction
This paper describes work undertaken to develop a detector for monitoring the onset of acoustic cavitation during measurements of the output power of physiotherapy ultrasound machines. The work described forms part of a project which is supported financially by the European Community 5th Framework programme of GROWTH. The Cavitation Detector (CD) is designed to interface with a calibrated Portable Power Standard (PPS), and the aim of the two devices is to provide transfer standard devices for ensuring the accurate calibration of ultrasonic physical therapy machines in clinical use.

Physiotherapy ultrasound is commonly applied to treat soft tissue injuries, with an estimated 10,000 machines in UK, delivering 1,000,000 treatments per annum. However, recent surveys [1, 2] show that the majority of machines still do not comply with the relevant standard [3], stating that the actual output shall be within ±20% of the device indication.

A possible cause of this non-compliance may be in the use of gassy media when making measurements of output power using radiation force balances, leading to the occurrence of acoustic cavitation. Acoustically cavitating bubbles can absorb and scatter incident ultrasound or, through coalescence, can collect in front of the transducer under test: the majority of commercially available
radiation force balances operate in a vertical configuration. Such processes can lead to an underestimate in the measured power.

To minimise the likelihood of cavitation-related problems, International Specification standards stipulate the use of degassed water as the propagation medium in the radiation force balance tank, and state that the level of dissolved oxygen in the medium should be less than 4 mg/l. However, this places stringent demands on the capabilities of manufacturers, test-houses and hospitals that may be difficult to meet. Also, initially degassed water will rapidly re-gas, increasing the likelihood that cavitation will occur. For these reasons, there is a need to develop a simple diagnostic test for determining when cavitation has started to occur during power measurements.

During a previous collaborative European project [4], power measurement errors of up to 20% were identified as being potentially attributable to cavitation, and a method for the acoustic detection of cavitation was proposed, and investigated at the laboratory level. The work presented in this paper describes the extension of the initial work to the development of an instrument for determining the onset of cavitation during power measurements. One such instrument has been provided to each of the project partners: Commonwealth Scientific and Industrial Research Organisation (CSIRO, Australia), Physikalisch-Technische Bundesanstalt (PTB, Germany) and Netherlands Organization for Applied Scientific Research (TNO, The Netherlands).

2. Acoustic cavitation

Acoustic cavitation can be described in simple terms as the production of small vapour-containing bubbles or cavities in a liquid or tissue, under the influence of an ultrasound field [5]. Through pulsation and collapse, cavitating bubbles are secondary sources of sound, and by using a hydrophone, acoustic emissions from a cavitating environment can be detected readily. It is well established that the acoustic spectrum generated by cavitating bubbles is rich in a range of frequency components, and example of such a spectrum, detected by a ceramic needle hydrophone positioned directly beneath a 1.08 MHz physiotherapy source, is shown in Figure 1.

![Acoustic spectrum](image)

**Figure 1.** Acoustic spectrum measured from a physiotherapy source operating at 1.08 MHz, 11 W, into tap water.

The figure shows clearly sub-harmonics, ultra-harmonics, integer harmonics and the ‘white-noise’ background, all of which can be used to deduce information on the cavitation processes occurring. In particular, the occurrence of the subharmonic ($f_0/2$) and ultraharmonics (odd integer multiples thereof) have been considered as indicators of the threshold of inertial cavitation activity [6].
3. Detection technique – proof of principle

To identify the occurrence of cavitation in tap water at typical physiotherapy output levels, a 1.08 MHz physiotherapy transducer was driven by a Hewlett Packard HP3336c synthesiser/generator, using a ENI 240L power amplifier. The drive voltage applied to the transducer was measured using a Hewlett Packard HP3403c true rms voltmeter. The transducer was set up such that it was coupled to a radiation force balance with a reflecting target. A right-angled Dapco hydrophone with a PZT element diameter of 0.6 mm was positioned close to the transducer, such that its active element was orientated towards the geometric centre of the transmitting crystal. The hydrophone was connected directly to a Hewlett Packard HP3589A spectrum analyser, which was interfaced to a PC. In this way, acoustic emissions from cavitation could be detected on the spectrum analyser (and downloaded for post-processing) whilst measurements of acoustic power were carried out using the radiation force balance. A schematic of the experimental configuration is shown in Figure 2.

![Figure 2. Schematic representation of experimental configuration used in determining spectral features as a function of output power and medium type.](image)

Filtered degassed, and tap water samples were investigated, with measurements of ultrasonic power being made as a function of drive voltage. At each drive level, an acoustic spectrum (in the range 0.4-3 MHz, averaged over 10 sweeps) was acquired. The results are shown in Figure 3.

Figure 3 shows the results obtained on the two water samples. As the output level is increased, the measured power varies linearly with the square of the drive voltage up to around 15 W. Beyond this, the measured power for the tap water case deviates from the linear trend (itself derived from a fit to the first ten degassed water measurements), with the difference at 20 W being around 20%. At the highest drive levels, the degassed water run also shows some deviations from the linear case, of around 10%. These differences may partly be attributable to crystal heating, but cavitation is considered to be the primary factor responsible.

The two data sets plotted against the right-hand Y-axis show the evolution in the level of first subharmonic component \(f_0/2\) as the drive voltage is increased. It can be seen that in both media, cavitation occurs (represented by the detection of the subharmonic component), and also, that the first appearance of the component precedes the deviation of the measured power from the linear case. As would be expected, cavitation is established in the tap water case at a lower power level than the degassed water case. From this, it is possible to define a threshold level for the subharmonic level, beyond which cavitation sufficient to affect the measured power would be produced.
Further analysis of the acquired spectra showed that the level of the first ultraharmonic component (at a frequency of $3f_{0/2}$) behaved in a very similar manner to the subharmonic component. Use of a detection technique based on ultraharmonic detection was attractive, because the hydrophone used has a peak in its frequency response at around 1.5 MHz: in addition, 1.5 MHz is the primary subharmonic frequency for a 3 MHz source, and so a single tracking filter solution could potentially be used for the full frequency range of interest.

However, tests carried out showed that no cavitation of any significant level was generated by a 3 MHz transducer, even at 20 W in tap water. This finding enabled a simpler solution for cavitation detection to be used, and a specification was derived. The salient aspects of this were:

- Powered by internal battery; also operable whilst charging
- Input amplifier providing F.S.D. on display for input signal (at ~1.5 MHz) of 2 mV pk-pk
- Switchable gain of x1, x0.5; switchable signal averaging time period of 0.5 or 2 seconds
- Auto-tracking band pass filter centred at 1.5 x detected ‘fundamental’ frequency - centred nominally at 1.5 MHz; -3 dB bandwidth ±20 kHz, working range 1.4 MHz to 1.6 MHz
- LED indication of 1 MHz ‘reference’ signal being received, so that user knows that unit is then ‘searching’ for any ~1.5 MHz component present
- Threshold test: green LED if cavitation signal below threshold, red LED if above
- TTL state to positive when red LED comes on: accessible from rear panel
- All controls positioned behind a protective panel to prevent adjustment by unskilled users

A similar Dapco angled needle hydrophone to that used in the initial tests was procured for use with the CD. To provide protection from possible cavitation damage, the active element was protected through encapsulation with polyurethane rubber. A holder was developed that allows the hydrophone to be located reproducibly adjacent to the transducer under test.

4. Detector Realisation, Testing and Discussion

Full details of the principle of operation of the unit will be the subject of future publication: to achieve both a very narrow bandwidth and the necessary control of the centre frequency of the monitor, a Super Heterodyne Radio Receiver principle was adopted, using an internal oscillator of frequency

![Figure 3. Experimental results obtained on tap and filtered degassed water samples: the graph shows measured power and subharmonic level as a function of drive voltage squared.](image)
2 MHz. The final version of the CD unit and the encapsulated hydrophone are shown in Figure 4. In total, 4 CD/hydrophone systems were produced, one for each of the project partners.

To test the performance of each system, a similar experimental arrangement to that described in Section 3 was used, except using Enraf transducers of the type characterised during the EU project.

![Figure 4. Cavitation detector (with protective panel open) and encapsulated Dapco hydrophone.](image)

Measurements were made of ultraharmonic level as a function of drive voltage squared (converted to power through prior knowledge of the radiation conductance of the transducer), using the spectrum analyser and the CD simultaneously, and were carried out in tap, degassed and filtered water samples (filter specification: 95% of particulate of >5 µm removed). Representative results (from one CD) are shown in Figure 5. The graphs show the relationship between the derived spectrum analyser 1.5 MHz component level and CD displayed value for the three water samples: each measurement point is averaged over at least three independent measurement runs.

![Figure 5. Results on 3 water samples using Spectrum Analyser (left) and Cavitation Detector (right)](image)

Figure 5 shows that as the power is increased, cavitation activity at the 3f₀/2 ultraharmonic frequency is detected by both the Cavitation Detector (CD) and the Spectrum Analyser (SA), in all three water samples. The tap water case shows the first significant appearance of cavitation above the noise floor at around 4 W, and the highest detected level overall of 0.9 V (CD). The two detection instruments follow reasonably similar trends: the main difference between them is in the averaging time used. To
minimise noise effects, the SA was operated over 10 sweeps, which took around 4.5 seconds, whereas the CD was set to an averaging time of 0.5 seconds. In this way, the CD is better able to detect sporadic cavitation events, which the SA may average out.

The results obtained using filtered water showed that significant cavitation was detected, more so than might have been expected: this suggests that dissolved gas and suspended particulate are both of importance when considering a suitable medium for making measurements using a radiation force balance. The degassed water sample (which is also filtered) produced cavitation only at the highest power levels: this is thought to be attributable to pre-existing cavitation nuclei in the experimental vessel (prior to the medium being added), and also to small gas bubbles adhering to the hydrophone tip when introduced into the medium. It is considered unlikely, however, that the levels of cavitation measured in degassed water would be sufficient to have a detrimental effect on measured power.

From these measurements, the threshold level of the CD was set at 0.15V. At detected ultraharmonic levels beyond this, the CD will display an ‘Alarm’ condition, alerting the operator that the medium in which they are making measurements may be undergoing cavitation, such that the accuracy of the power values they derive may be impaired. The level chosen should be sufficiently high to avoid the alarm triggering when the effect on power is likely to be small.

5. Conclusions
- Cavitation has been seen to occur readily in nucleation site-rich media exposed to physiotherapy ultrasound fields at frequencies of 1 MHz or less;
- The effect of cavitation on measured power is dependent on the transducer field and environment: underestimates of 10 - 20% have been recorded;
- Cavitation activity can be detected via a simple acoustic emission technique (passive hydrophone);
- A sensitive Cavitation Detector (CD) has been developed to alert operators that their radiation force balance medium is inappropriate, and that power measurements may be adversely affected;
- The CD units are now undergoing testing with each of the project partners, before being coupled to the PPS and used in the Proficiency Testing of ultrasonic power measurement service providers.

6. References
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