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# Performance characterisation of a passive cavitation detector optimised for subharmonic periodic shock waves from acoustic cavitation in MHz and sub-MHz ultrasound

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ABSTRACT

We describe the design, construction and characterisation of a broadband passive cavitation detector, with the specific aim of detecting low frequency components of periodic shock waves, with high sensitivity. A finite element model is used to guide selection of matching and backing layers for the shock wave passive cavitation detector (swPCD), and the performance is evaluated against a commercially available device. Validation of the model, and characterisation of the swPCD is achieved through experimental detection of laser-plasma bubble collapse shock waves. The final swPCD design is 20 dB more sensitive to the subharmonic component, from acoustic cavitation driven at 220 kHz, than the comparable commercial device. This work may be significant for monitoring cavitation in medical applications, where sensitive detection is critical, and higher frequencies are more readily absorbed by tissue.

## 1. Introduction

Research involving acoustic cavitation is commonly reported relative to the noise spectrum of the signal collected by a single element passive cavitation detector (PCD), during cavitation occurrence [1–35]. Applications so reported can broadly (but not exhaustively) be categorised as industrial, including sonochemistry [1–7] and cleaning [8–10], and medical therapy[11–29], which may include the use of contrast agent microbubbles to promote cavitation activity [25–29]. Additionally, there is a sizeable volume of literature dedicated to fundamental studies of acoustic cavitation activity, with no particular application stated or investigated, that have incorporated a PCD to record the acoustic emissions [30–35].

In selecting a PCD device to monitor cavitation during an experiment, the researcher has a wide range of options available. Specialist suppliers, such as Sonic Concepts Inc., Precision Acoustics Ltd, and National Physical Laboratory (NPL) offer devices with a stated application as a PCD, supplied with an operating bandwidth, and perhaps the option of some sort of calibration data. Full technical construction details, however, including the active material of the element, are often proprietary [9,11–17,36]. Otherwise, commercially available generic hydrophones, particularly needle [22,29,32,33], and capsule devices [1,23,24] have also been used. Focused lead zirconate titanate (PZT) bowl transducers, that could also be used for transmission, are commonly used in passive receive mode to monitor cavitation activity [6,7,17,20,25]. Bespoke PCDs, developed in-house, are also commonly reported. These are typically constructed from PZT-elements in the form of disks [3,26,31,34,35], or Polyvinylidene fluoride (PVdF) [4,9,26,27].

As varied as the devices that have been utilised as a PCD, are the reporting protocols subsequently used to represent the cavitation measurements recorded, often in an attempt to classify or quantify the activity. PCDs typically exploit cavitation non-linearity, such that measurements are undertaken at frequencies other than the fundamental frequency of the acoustic driving, $f_0$. Common detection frequencies can be categorised into four groups; subharmonics ($f_0/m$, where $m$ is an integer value) [1,2,7,10,17,21,24,26,29–32,35], ultraharmonics ($nf_0/m$, where $n$ is also an integer value, $\neq m$) [1,2,10–13,17,26,27,30–32,36], overharmonics ($nf_0$) [1,2,7,10–13,17,19,21,24,26,28–32] and broadband noise, sampled from between spectral peaks [1,2,6,10,12,16–19,21,26,30–32,36]. Often, some combination of spectral features are reported, and an inference for stable or inertial cavitation made [2,7,12,21,24,26]. There is, however, an emerging realisation that cavitation activity often exhibits both stable and inertial characteristics, variously referred to as stable-inertial or repetitive transient [37–39]. In contrast to measuring combinations of individual features, the cavitation index quantifies the arithmetic mean power over a certain bandwidth of the spectrum, after the electrical noise has been subtracted [1,23].

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For cavitation emission measurements, generally, the benefits of standardisation for the detection and reporting of cavitation activity, and particularly for specific applications, is clear and increasingly recognised [5,27]. Ideally, this would facilitate direct comparison between work published from different groups working on similar applications, however, this is also hindered by a diverse range of experimental exposure configurations. Calibration/characterisation of the PCD used, in any case, is a precursor to any meaningful comparison between studies investigating similar applications. Of the literature sampled above, calibration data – at least at the frequency values monitored – is only sparingly reported [1,3,5,26,32,33]. Moreover, a lack of understanding of the signal emitted by acoustically driven bubbles, has prevented objective analysis of the performance of any given PCD device.

In this paper, we report on the development and characterisation of a PCD based on PVdF. A distinguishing feature of the work is that, from the outset, the device design is targeted at detection of periodic shock waves, and is therefore hereafter referred to as the shock wave PCD (swPCD). Using laser-plasma generated bubble collapse shock waves (BCSWs), and the spectral power distribution within the BCSW, [40], which informed the 'tuning' of the swPCD via backing and matching layers to maximise sensitivity. In Section 2, the rational for swPCD construction, based on a working knowledge of acoustics, is described. Section 3.1 is a description of the experimental arrangement used to test the swPCD, including against a commercially available PVdF-based PCD (Y-107, Sonic Concepts Inc., Bothell, USA). A finite element model supporting shock wave propagation, to verify each construction stage of the swPCD, is also described, Section 3.3. Section 4 presents both swPCD and Y-107 results for the detection of a single BCSW from a laser-plasma mediated bubble, and subharmonic periodic shock waves from a single cavitation cloud, driven by high-intensity focused ultrasound (HIFU).

### 1.1. The cavitation signal

Clarification of the signal emitted by cavitation is evidently an important consideration for determining the suitability of a PCD for detection of that signal, including any distortions that the PCD characteristics may introduce [40].

We have recently reported high-speed shadowgraphic imaging (described in Section 3.1) of single cavitation clouds, driven by HIFU at fundamental frequencies, $f_0 = 254$ kHz [35] and 692 kHz [32]. Both reports used laser-nucleation (also described in Section 3.1), to predetermine the instant and location of cavitation inception [34]. The high speed observations indicated that for HIFU driving of pressure amplitudes in the MPa regime, the initial bubble that formed from the nucleation rapidly fragmented into a cloud of closely packed, and strongly interacting component bubbles, within the first few cycles of the resulting cloud. Under subsequent cycles of driving, the component bubbles adopt in-phase oscillations, such that the cloud oscillates at $f_0$, effectively as a single entity. Strong subharmonic cloud collapses at $f_0/m$, within the $f_0$ oscillations and with $m$ increasing for larger driving pressure amplitudes, were observed to be coincident with periodic shock wave emission. In the latter study [32], the combined imaging and acoustic detection of the emitted signal further indicated that periodic shock waves were predominantly responsible for all spectral features recorded at $nf_0/m$ (for all values of $n$ and $m$), other than ~15 dB of $f_0$, attributable to scattered driving.

## 2. Rationale for the swPCD

Taken collectively, these studies indicate that a swPCD designed for sensitivity to lower frequency components of periodic shock waves (and BCSWs, generally), may be expected to offer superior detection of the features commonly reported for cavitation-mediated effects, particularly the subharmonics and their ultraharmonics, but also significant contributions to the overharmonics of $f_0$.

However, the peak positive pressure amplitude of the shock waves generated by the subharmonic collapses of acoustically driven cavitation clouds are somewhat variable, with clouds of more than a few component bubbles emitting multi-fronted shock waves [32,35]. For the purposes of this report, objective testing of the swPCD is therefore undertaken relative to laser-plasma mediated BCSWs, which have a peak positive pressure amplitude of the shock wave proportional to the maximum radius the bubble attains following the expansion phase [41], through which peak positive pressure amplitude of the shock wave reproducibility may be confirmed.

To demonstrate the utility of identifying the component of the cavitation signal to be detected, as guidance for the design, we compare the performance of the swPCD to a commercially available device, Y-107 from Sonic Concepts Inc (Bothell, WA, USA). Y-107 is constructed to fit within a central 20 mm opening through a HIFU transducer, manufactured by the same company (H-149, Sonic Concepts Inc., Bothell, WA, USA), which we use to drive the acoustic cavitation activity reported below. Y-107 has a 17.5 mm active diameter and is geometrically focused to 68 mm [42], such that it is confocal to the focus of the H-149 HIFU transducer, when *in situ*. It has a stated bandwidth of 10 kHz–15 MHz, and its construction, provided by Sonic Concepts Inc on request, is described as a *"0.2 mm thick piezo-polymer stack, with high acoustic impedance backing material >4 MRayl and an EMI [electromagnetic interference] shielded plastic outer casing (20 mm OD × 40 mm length) to optimize the operating bandwidth and signal-to-noise ratios"*.

The swPCD was therefore designed to be interchangeable with Y-107, within the H-149 HIFU transducer, such that the outer diameter of the 3D printed casing is mm. The casing holds the active material, an unfocused disk of diameter equal to 15mm.

As we are seeking to assess shock wave sensitivity directly (including against a commercially available PVdF-based PCD), PVdF was therefore chosen as the active material for the swPCD. The thickness of PVdF film was selected on the basis of the power spectrum of the BCSW, as described in Johansen et al. [40]. The BCSW power peaks at <1 MHz, it is therefore desirable to select a PVdF-film sensitive to lower frequencies, which can be further tuned with backing and matching layers as outlined Section 3.3.1 and Section 3.3.2, to obtain the largest magnitude subharmonic features. As such, the swPCD is constructed from 110 μm PVdF, as the thickest commonly available film (9–110 μm being commonly available), with the lowest thickness mode resonance frequency of ~10 MHz.

## 3. Materials and methods

### 3.1. Experimental setup

The experimental arrangement within which all swPCD testing was undertaken, has been described in detail elsewhere [40,32]. Briefly, a long working distance microscope objective lens (50 × 0.42 NA Mitutoyo Kawasaki Japan) and a HIFU transducer, are arranged within a custom built chamber measuring $420 \times 438 \times 220\text{mm}^3$, such that the optical and acoustic foci are aligned, Fig. 1. The chamber has two recessed walls to allow the placement of an imaging optic (Monozoom 7 lens system, Bausch and Lomb, Rochester USA) in closer proximity to the combined foci, and filled with degassed deionized water. Bubble activity, in one of two regimes described below, is imaged with a Shimadzu HPV-X2 (Shimadzu Corp, Kyoto, Japan) high-speed camera, at $1 \times 10^6$ frames per second, and with 10 ns synchronous laser pulses (CAVILUX Smart, Cavitar, Tampere, Finland), providing the illumination and shadowgraphic capability for shock wave visualisation.

The HIFU transducer operates at a fundamental frequency of $f_0 = 220$ kHz and is geometrically focused to 68 mm, with an outer diameter of 110 mm and a 20 mm central hole through the body. The Y-107 PCD is geometrically focused to 68 mm, and designed for insertion