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Hysteresis of inertial cavitation activity induced by fluctuating bubble size distribution

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ABSTRACT

Amongst the variety of complex phenomena encountered in nonlinear physics, a hysteretic effect can be expected on ultrasound cavitation due to the intrinsic nonlinearity of bubble dynamics. When applying successive ultrasound shots for increasing and decreasing acoustic intensities, a hysteretic behaviour is experimentally observed on inertial cavitation activity, with a loop area sensitive to the inertial cavitation threshold. To get a better insight of the phenomena underlying this hysteretic effect, the evolution of the bubble size distribution is studied numerically by implementing rectified diffusion, fragmentation process, rising and dissolution of bubbles from an initial bubble size distribution. When applying increasing and decreasing acoustic intensities, the numerical distribution exhibits asymmetry in bubble number and distribution. The resulting inertial cavitation activity is assessed through the numerical broadband noise of the emitted acoustic radiation of the bubble cloud dynamics. This approach allows obtaining qualitatively the observed hysteretic effect and its interest in terms of control is discussed.

1. Introduction

When looking for technological and acoustical improvements of the therapeutic benefits of ultrasound cavitation, one is led to the problem of understanding the critical process of bubble inception and its effect on the onset of cavitation, as well as overall cavitational effect uncertainties. Indeed ultrasound cavitation is a highly nonlinear phenomenon, sensitive to initial conditions such as the nuclei size and their spatial distribution for instance. At the scale of a single bubble, when driving acoustic intensity is moderate, bubble exhibits classical nonlinear behaviour, such as harmonic generation and resonance frequency shift [1]. For higher acoustic pressures, bubble may undergo non classical nonlinear behaviour, exhibiting period doubling, chaotic oscillations [2] and sonoluminescence [3]. At the scale of the bubble cloud, many nonlinear features also appear, the cloud being a collection of numerous nonlinear oscillators. Multibubble structures have been extensively studied in the aim of many technical and sonochemical applications of ultrasound [4], as well as multibubble sonoluminescence [3]. In particular, insight in the formation of multibubble structures has been provided through a complete spatiotemporal consideration of acoustically driven interacting bubbles [5,6]. Taking advantage of atypical nonlinear effects in underwater acoustics or nonlinear mesoscopic materials [7,8], powerful amplitude-modulated high-frequency waves have shown the possibility of decreasing the onset of cavitation and enhancing cavitation activity through the generation of a low-frequency parametric component [9]. Amongst the variety of complex phenomena encountered in nonlinear physics, such as period doubling, chaos, self-demodulation or memory effects, one can expect to observe hysteretic behaviour of ultrasound cavitation. Usually hysteretic effect result from acoustic energy dissipation induced, for instance, by the presence of microscopic defects such as cracks [10] in geomaterials, interbead contact heterogeneity in granular media [11] or intrinsic nonlinear constitutive stress–strain relationship in soft materials [12]. As peculiar nonlinear signatures are observed for strong acoustic amplitude, the regime in which acoustic bubbles undergo large oscillations leading to bubble collapse, named as the transient or inertial cavitation regime, is more likely to generate nonlinear phenomena. Moreover, in the aim of therapeutic applications, inertial cavitation is commonly considered as the main candidate to explain interaction between ultrasound and cells, leading to cell sonoporation for instance [13,14]. Thus, a full understanding of the inertial cavitation regime, both experimentally and theoretically, is of great importance for improving technological device and the spreading of therapeutic ultrasound. Experimentally, inertial cavitation is characterised by the emission

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of a broadband noise that has been quantified through an inertial cavitation indicator [15]. More recently the broadband emission has been numerically explained as the consequence of the fluctuation of bubble number and bubble size distribution during sonication time [16]. In [15], a hysteretic effect on the inertial cavitation indicator has been qualitatively observed but neither its origin or its relevance for cavitation-based technology have been discussed. This study focuses on a hysteretic effect on inertial cavitation. This effect, studied experimentally and numerically, results from temporal fluctuation in bubble size distribution. Openings on the real-time control of inertial cavitation during sonication are also discussed.

2. Experimental observations

2.1. Materials and methods

A plane piezoelectric transducer (frequency 501 kHz, diameter 20 mm) is immersed in a degassed water bath (20 L tank, O_2 rate in water between 2.3 and 3.7 mg/L). The transducer is located such as its acoustic axis is vertical and covered by 14 mm of water above its surface (Fig. 1). The transducer, electrically matched to 50 Ω, generates a continuous sinusoidal wave provided by a function generator (HP 33120 A), successively amplified by a variable gain amplifier (AD 603) and a power amplifier (50 dB, 200 W, Adece). The electrical power delivered by the generator is ranged between −12 and 9 dBm, which corresponds to acoustic intensities between 0.1 and 12.8 W/cm^2. The sonicated media is composed of 2 mL of degassed water at ambient temperature placed in a well of a culture plate in polystyrene (12 wells, diameter 20 mm, BD sciences). The sonicated well is located above the transducer and its height is adjusted so that the liquid surface corresponds to a node of the stationary wave field of the irradiated medium. A home-made hydrophone (cutting frequency 10 MHz) realised with a PVDF film (diameter 10 mm) moulded in resin (AY 103, Araldite) is located in the vicinity of the transducer to listen the cavitation noise in the exposed medium. The received signal is amplified (20 dB, NF Electronic Instrument® BX31), digitized (acquisition card PXI-5620, 14 bit resolution, 32 MHz sampling frequency, National Instrument®), transferred to a computer and analysed by Labview® software.

A non-referenced inertial cavitation level is calculated from the hydrophone signal: it is defined as the average level of the instantaneous spectrum in dB within the range of 0.1–7.1 MHz. Before sonication, the reference noise is measured then calculated in the same way when the excitation signal is off. The cavitation index quantifying the inertial cavitation level is determined by the subtraction of the non-referenced inertial cavitation level and the reference noise. It is calculated every 5 ms during sonication. This method is detailed in [17,18].

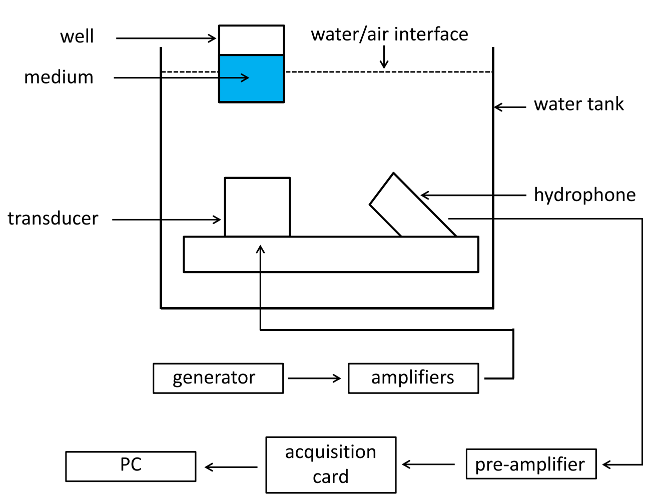

Fig. 1. Experimental setup.

2.2. Results

In order to investigate the hysteresis effects on acoustic cavitation as a function of acoustic intensity, measurements of the cavitation index are performed for increasing and then decreasing acoustic intensity in the same experiment. The protocol of measurements consists of successive ultrasonic excitations separated by times off. Each shot lasts 5 s at a fixed acoustic intensity with a time off between shots fixed to 0.5 s. The acoustic intensity lies in the range 0.1–12.8 W/cm^2 (with up and down logarithmic progression).

Two examples of cavitation index time evolution obtained for increasing and decreasing acoustic intensities are presented on Fig. 2(a) and (b). On these figures, when acoustic intensity increases, the cavitation index sharply increases (solid lines) around the inertial cavitation threshold, 1.3 W/cm^2 in Fig. 2 and 4 W/cm^2 in Fig. 2(b). When acoustic intensity decreases, there is inertial cavitation for acoustic intensities lower than the inertial acoustic threshold obtained for increasing intensities. It is worth noting that inertial cavitation threshold is variable because of the stochastic behaviour of acoustic cavitation. Two spectra calculated from cavitation index shown on the Fig. 2(a) for an acoustic intensity equal to 1.27 W/cm^2 (for increasing and decreasing acoustic intensity respectively) are presented on Fig. 2(c). The broadband noise level for decreasing acoustic intensity is much higher than for increasing acoustic intensity and so is the cavitation index. The broadband noise elevation is accompanied with the apparition of harmonics and subharmonics, ensuring that both stable and inertial cavitation are coexisting for this particular case. The lack of these harmonics and subharmonics on the spectrum corresponding to the increasing path could indicate that ultrasound cavitation is not yet fully initiated, even for the signatures of stable cavitation.

3. Numerical modelling

3.1. Model description

To get insight in the physical phenomena underlying the observed hysteretic loop, the time evolution of the bubble distribution in the medium is simulated. The impact of sufficiently strong acoustic field on the bubble population could modify the radii distribution (by rectified diffusion or fragmentation) but also the spatial location (through primary and secondary Bjerknes forces). For the sake of simplicity, we first focus on the bubble size distribution evolution by considering clouds of non-interactive bubbles. Once the bubble size distributions are obtained for the whole ultrasound protocol, bubble interaction dynamics are taken into account in the computation of the radiated acoustic emission of the bubble cloud in order to estimate the acoustic cavitation noise, following the model of Yasui [16].

For a given bubble size distribution in the medium before ultrasound excitation, fluctuation in this distribution would appear when bubbles experience weak nonlinear oscillations (through rectified diffusion process) or strong nonlinear oscillations and collapses (through fragmentation process), depending on their equilibrium radius R_0 and the applied acoustic intensity I_a. To know which mechanism will act on a bubble for a given couple (I_a, R_0), a map of the cavitation activity is performed by solving the