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On the physical origin of conical bubble structure under an ultrasonic horn

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ABSTRACT

The cavitation field generated by an ultrasonic horn at low frequency and high power is known to self-organize into a conical bubble structure. The physical mechanism at the origin of this bubble structure is investigated using numerical simulations and acoustic pressure measurements. The thin bubbly layer lying at horn surface is shown to act as a nonlinear thickness resonator that amplifies acoustic pressure and distorts acoustic waveform. This mechanism explains the self-stabilization of the conical bubble structure as well as the generation of shock wave and the focusing at very short distance.

1. Introduction

Different types of cavitation bubbles structures are observed in the acoustic field. Acoustic Lichtenberg figures, which appear near pressure antinodes in standing acoustic wave fields, have been extensively studied [1,2]. Their structure is explained by interaction of bubbles with the acoustic field (primary Bjerknes force) and interaction between nearby pulsating bubbles (secondary Bjerknes forces), while the effect of bubbles on the macroscopic acoustic field is neglected. At high intensity, another type of bubble structure, made of streamers building into a conical shape, can be observed at the vicinity of a cylindrical horn surface [3] (Fig. 1). When this bubble structure appears, the radiated acoustic field suddenly changes into a progressive highly nonlinear wave with spectacular associated effects such as high speed streaming, non-zero mean quasi-static pressure and focusing at very short distance [4,5]. The cone-like bubble structure also exhibits the properties of a self-organized criticality [6]: no need of fine tuning of the control parameters, $1/f$ behavior of power spectra and scale-invariant distribution function of fluctuations.

The cone-like bubble structure is a problem of general interest as it governs the spatial distribution of the cavitation field in horn-type device at high intensity [7–11]. However, its mechanism of generation remains unexplained. In this paper, the role of the thin layer of bubbles lying at horn surface is studied. High speed images have shown that the build-up of the cone-like bubble structure is preceded by the emergence of a layer of high bubble density just below the vibrating surface [4] (Fig. 2). It is hypothesized that unusual properties of cone-like bubble structure can be explained by the very low acoustic wave velocity in this bubble layer as follows:

– Cavitation bubbles constituting the bubble layer arise from cavitation nuclei (air bubble) trapped at the horn surface which leave the surface under acoustic pressure and then undergo the classical cycle of cavitation bubbles. These small cavitation bubbles remain very close to horn surface due to attractive forces such as secondary Bjerknes force from bubbles nucleated at horn surface [11].
– Bubble layer thickness grows up when the velocity amplitude of the vibrating surface increases. If the layer thickness reaches an acoustic half wavelength (typically 1.5 mm at 20 kHz for a sound velocity in the bubbly medium of 60 m s^{-1}), the acoustic wave generated by the vibrating surface is in phase with all the waves having performed an integer number of round-trip in the layer. This is the well-known thickness resonance phenomenon. Thus, when the resonance thickness is reached, a sudden amplification of the pressure fields (inside and behind the layer) is taking place, leading to the subsequent formation of the cone of bubbles. If the layer thickness increases further, the resonance effect disappears and the acoustic pressure in the layer decreases. As a consequence, the bubble density falls down and the layer shrinks. The whole process tends to self-stabilize the layer around resonance thickness (Fig. 3). It can be noted that the stability is lost if the layer thickness shrinks below resonant thickness: a further decrease of thickness would be

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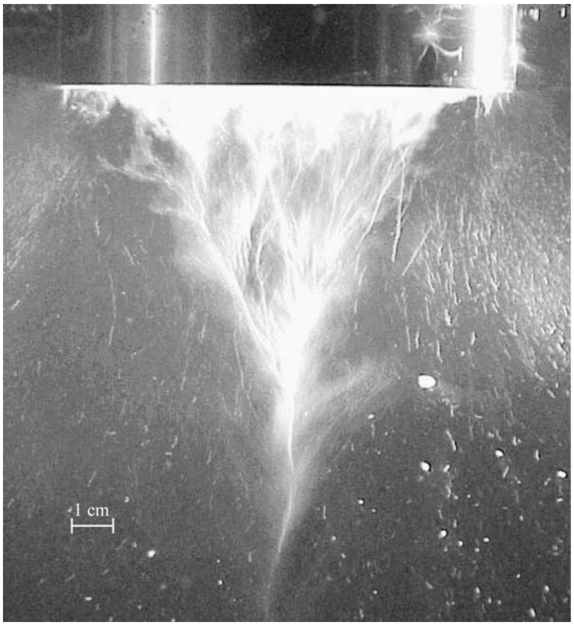

Fig. 1. Conical bubble structure.

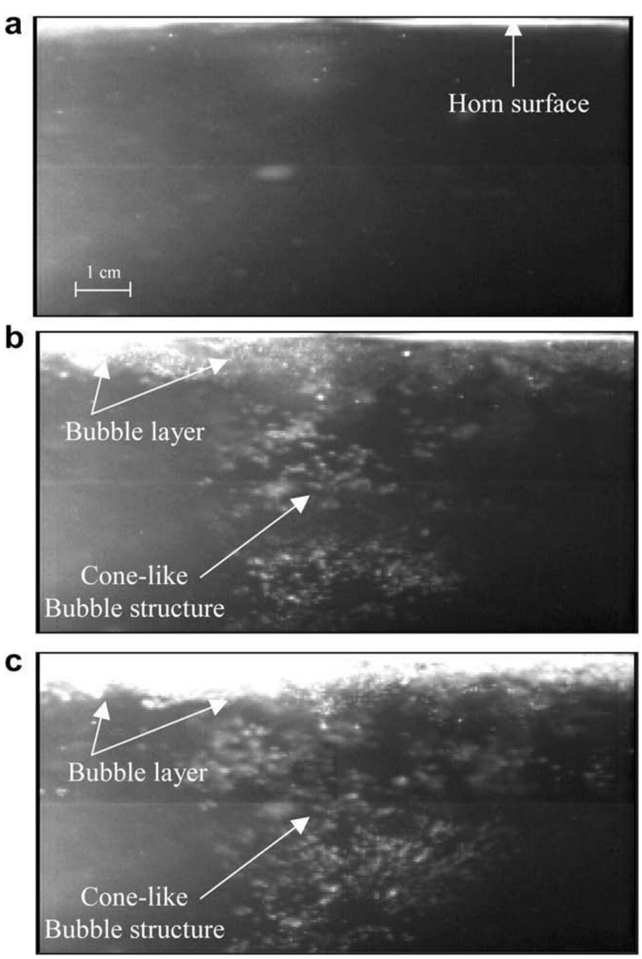

Fig. 2. Successive (from a to c) high speed pictures showing thin bubble layer observed at horn surface just before apparition of the conical bubble structure in burst regime (from Ref. [4]).

accompanied by a decrease of pressure. This loss of stability could also explain sudden disappearance of the conical bubble structure often observed experimentally.

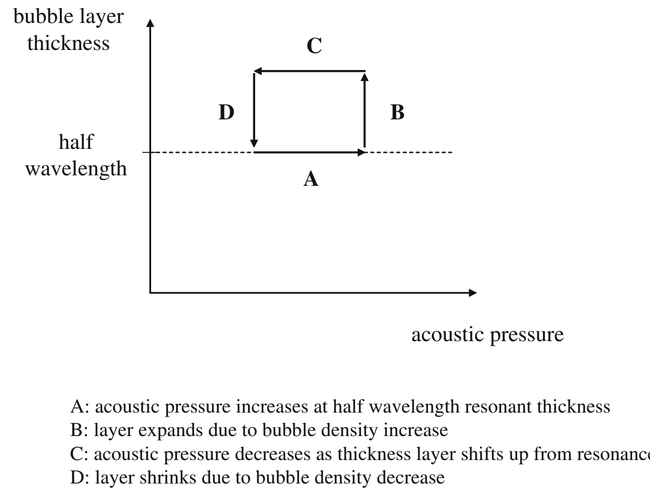

Fig. 3. Schematic process of stabilization of bubble layer thickness around half wavelength resonance.

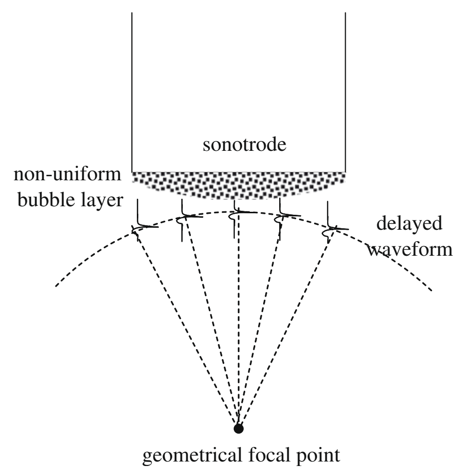

Fig. 4. Schematic process of short distance focusing due to bubble layer.

– Bubble layer is not uniform over horn surface, the layer being thicker with higher bubble density at the centre and thinner with lower bubble density at the periphery. This inhomogeneity induces a larger time delay of the pressure wave leaving the layer at the centre than at the periphery. Thus, the bubbly layer acts like a lens and focuses the acoustic field at very short distance (Fig. 4).

Numerical computations and experiments are presented in this paper to clarify the role of the bubbly layer on the cone-like bubble structure formation. In Section 2, a nonlinear numerical model is used to describe the interaction between an incident acoustic field and a bubbly layer. In particular, the effect of bubbly layer thickness on the transmitted acoustic waveforms is studied. Section 3 describes the experimental set-up and compares measured acoustic waveforms with theoretical predictions.

2. Numerical simulations

2.1. Geometry of the problem and physical model

One-dimensional semi-infinite liquid (water) domain is excited by a prescribed pressure at its boundary in order to generate an incident plane acoustic propagating wave. Part of this domain including a given density of gas (air) bubbles constitutes a bubbly layer. This layer of thickness h is placed at distance d from the