Ultrasonic Cavitation in Thin Liquid Layer

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Introduction

Ultrasonic devices used to generate cavitation are mainly resonant piezoelectric transducers [1, 2]. These devices have a high quality factor Q, a narrow frequency band, a small active surface and are difficult to drive electronically. To avoid these limitations, a different technique of cavitation threshold achievement with limited displacement amplification is proposed here. Ultrasonic cavitation is generated in a thin layer of liquid (with thickness much smaller than the acoustic wavelength) confined between a vibrating surface and an "acoustically hard" reflector. The lateral boundary of the layer is a liquid-gas interface which acts as a another reflective boundary and prevents acoustic energy radiation. Such geometry is expected to produce a large amplification of the acoustic pressure generated in the liquid layer, compared to a usual tank configuration

Theoretical analysis of thin layer cavitation

The following axisymmetrical configuration is considered. A uniform longitudinal velocity v_0 is prescribed on one side of the liquid layer and zero longitudinal velocity on the other side. Time dependency is $e^{+j\omega t}$ where t is the time and ω the angular frequency. h and a are the thickness and the radius of the liquid layer. ρ_f, c_f, $k_f = \omega/c_f$ and $\lambda_f = 2\pi/k_f$ are the density, the sound speed, the acoustic wave number and the acoustic wavelength in the liquid. The amplification factor A is defined as the ratio of the maximal pressure amplitude within the liquid layer to the pressure amplitude of a plane progressive wave generated by the same prescribed velocity

$$A = \frac{|p_{\max}|}{\rho_f c_f v_0} \qquad (1)$$

Assuming linear variation of velocity through the thickness, A is expressed as [3]

$$A = \frac{1}{k_f h}\left|\frac{1}{J_0(k_f a)} - 1\right| \qquad (2)$$

where J_0 is the Bessel function of the first kind and zero ordre. A is written as the product of two terms:

- the first term, $A_1 = \frac{1}{k_f h}$, characterises the constructive interference of the incident and reflective waves propagating along the layer thickness. A_1 is the amplification factor in a purely one-dimensional case (without lateral effects) i.e. plane waves;
- the second term, $A_2 = \left|\frac{1}{J_0(k_f a)} - 1\right|$, describes the amplification associated with the radial focalisation of pressure on the symmetry axis due to the zero-pressure lateral boundary condition (free surface).

Figure 1 displays the variation of amplification factor A versus normalized layer radius a/λ_f for several normalized layer thicknesses h/λ_f. Analytical and numerical values agree very well excepted for small values of a/λ_f. A very large amplification factor is obtained at the radial resonances of the thickness layer, $a/\lambda_f \approx 0.38$ and $a/\lambda_f \approx 0.88$, (first two zeroes of $J_0(k_f a)$).

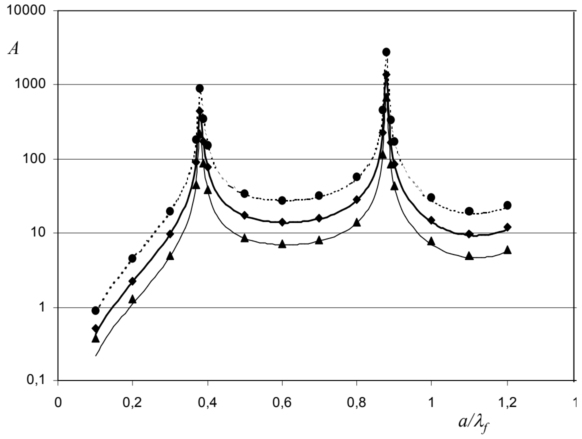

Figure 1: Variation of amplification factor A with normalized radius a/λ_f. Lines: analytical; symbols: FEM. Dotted line and ● : $h/\lambda_f = 0.02$; thick full line and ♦ : $h/\lambda_f = 0.04$; thin full line and ▲ : $h/\lambda_f = 0.08$

Experimental results on thin layer cavitation

Experimental set-up

In the experimental set-up (Fig. 2), a Langevin transducer with cylindrical sonotrode (radius $a = 3.5$ cm, length $L_1 = 12$ cm) made of stainless steel is used. The reflector is a cube made of optical glass whose relative position to the sonotrode is controlled by a precision screw. A water layer is introduced with a syringe between the sonotrode and the reflector. It is naturally maintained by capillarity forces. The transducer is driven by a wide band power amplifier connected to a function generator. Electrical current and voltage delivered to the transducer are monitored. Ultrasonic velocity of the sonotrode is measured using a laser vibrometre. Cavitation inception is detected acoustically from characteristic cavitation noise and visually using a CCD camera.

Cavitation thresholds

Two types of cavitation are observed in the liquid layer (Fig. 3). Above the first cavitation threshold (denoted threshold A), a stable bubble structure is formed on the symmetry axis. Above the second cavitation threshold (denoted threshold B), transient unstable bubble structures appear at several locations of the surface. These structures are similar to those observed at the surface of the sonotrode in the Cone-like Bubble Structure (CBS) [4]. Figure 4 displays the sonotrode surface velocity at the cavitation threshold for a layer thickness of 1 mm. Velocities keep relatively constant value in the whole frequency range, around 2-5 mm/s for threshold A and range from 1 to 10 cm/s for threshold B. For the same apparatus in a tank configuration, velocities are around 1-2 cm/s for threshold A and threshold B is never reached. The radial resonances of the layer are not observed experimentally because of their very low electromechanical coupling.

Mechanical activity

Mechanical activity of cavitation in the thin liquid layer is evaluated by erosion tests on metallic foils [5]. Aluminum foil and lead plate, 15 μm and 1 mm thick respectively, are inserted in the liquid layer and submitted to cavitation. At low intensity, a localized erosion is obtained (Fig. 5) as expected from bubble distribution displayed in Fig. 3a. The generation of a cavitational mechanical activity which is spatially localized is of great interest for highly selective mechanical etching, surface treatment or surface cleaning. At higher intensity, mechanical activity is distributed over the surface. When comparing aluminum foils exposed to cavitation in the liquid layer and in a tank for the same reactive intensities and exposure times, the mechanical activity is clearly more effective in the liquid layer.

References

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Acknowledgements

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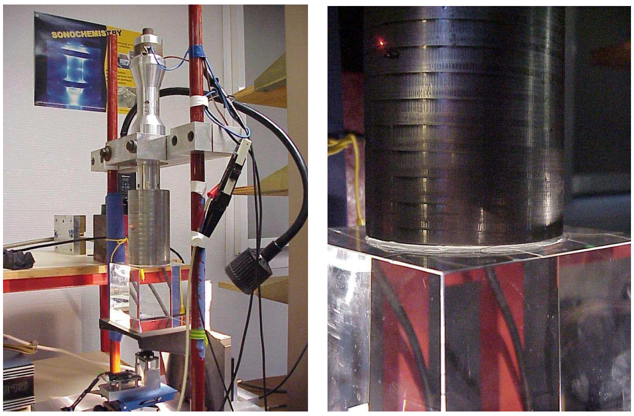

Figure 2: Experimental set-up

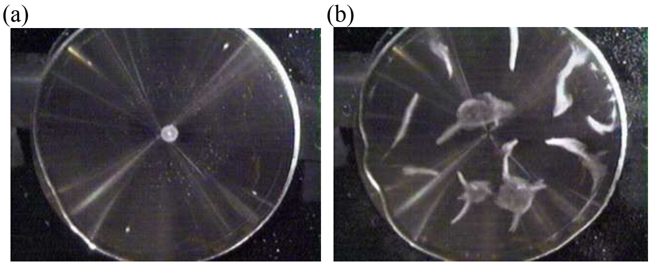

Figure 3: Bubble structures in the liquid layer (a) above threshold A (b) above threshold B

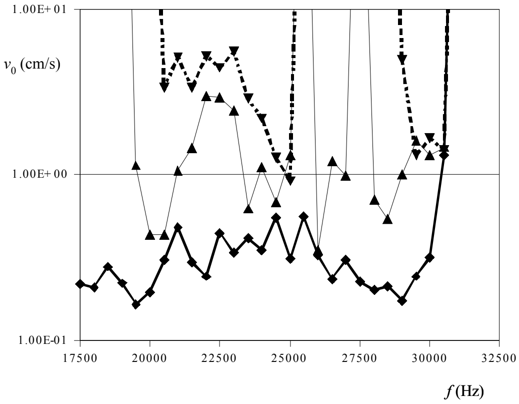

Figure 4: Variation of sonotrode velocity at cavitation threshold versus frequency. Thick full line: threshold A in 1 mm layer configuration; thick dashed line: threshold B in 1 mm layer configuration; thin full line: threshold A in tank configuration.

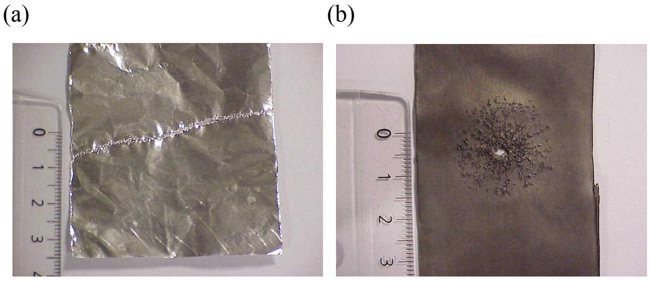

Figure 5: Test samples showing localized erosion after exposure to cavitation (above threshold A) in the liquid layer. (a) aluminium foil moved across the layer (a few seconds exposure); (b) lead plate inserted the layer (8 minutes exposure).