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## SURFACE OSCILLATIONS AND JET DEVELOPMENT IN PULSATING BUBBLES

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Résumé.- Cet article décrit une méthode permettant de provoquer des jets liquides périodiques dans des bulles qui oscillent. Les bulles sont maintenues près d'une paroi plane dans un récipient qu'on fait vibrer. La pression ambiante au-dessus du liquide est réduite jusqu'à une valeur voisine de la pression vapeur. Dans ces conditions les bulles dont la fréquence de résonance est proche de la fréquence excitatrice (60 Hz) présentent des mouvements d'amplitude importante. Ceci est propice à la formation de jets liquides. Des photographies montrent les divers aspects de cette formation ainsi que quelques formes curieuses des bulles.

Abstract.- This paper describes a method for producing cyclic liquid jets in pulsating bubbles that have been acoustically trapped near a platform in a vibrating container. The ambient pressure above the liquid is reduced to near that of the vapor pressure of the liquid, and vapor-air bubbles driven near resonance size at 60 Hz develop large pulsations that can readily lead to jet development. Photographs are presented of various aspects of jet production as well as of some intriguing displays of bubble surface oscillations.

1.- INTRODUCTION : Considerable experimental and theoretical effort has been directed toward the study of liquid jet production in cavitation research /1-8/. These high velocity jets of water appear to be the dominant mechanism in cavitation damage and thus the problem is one of practical as well as academic interest.

Experimental investigations of cavity collapse with associated jet development for cavities near boundaries have encountered numerous difficulties. Specifically, the jet development has been difficult to observe because (a) the time interval is very short, (b) the location of a cavitation event is unpredictable in terms of position and time, (c) the size of the cavity during the final stages of collapse is quite small, and (d) the event is self-destructive.

In order to overcome these experimental difficulties, researchers have designed experimental techniques to induce cavity formation by such devices as spark-gaps /2/ or focused lasers/7/. Even if the cavity is precisely positioned in space and time, photographic requirements are still major. Lauterborn /8/, who has examined cavity collapse and jet production in sophisticated detail, has suggested that framing rates of over a million frames/sec are required in order to obtain accurate measurements of jet velocity.

We have developed a method that can be used to study many aspects of jet behaviour with modest equipment requirements. Furthermore, the method allows observations to be made of surface oscilla-

tions of the bubble in addition to the more familiar jet development during collapse. We shall briefly describe this method, discussed in more detail elsewhere /9/, for producing liquid jets in pulsating bubbles. Further, photographs will be presented of jet development as well as of interesting photographs of bubble surface oscillations.

2.- EXPERIMENTAL METHODS AND MATERIALS : We have constructed a container that can sustain a reduced pressure of at least one atmosphere and can be suitably mounted on a vibration table capable of oscillating the container at a low frequency to a displacement amplitude of a few millimeters. If the container is mostly filled with water and the ambient pressure above the liquid reduced to near that of the vapor pressure, bubbles containing considerable amounts of vapor will pulsate with large amplitudes and be drawn toward the bottom of the container by the primary Bjerknes force /10/. We have mounted a horizontal platform within the container and with some practice, it is possible to position a single bubble at a fixed location on the platform and cause it to pulsate at large amplitudes for several minutes. The resonance diameter of such a bubble driven at 60 Hz is nearly 3 mm and is large enough to be easily seen and photographed. Growth by rectified diffusion does occur, but the rate is reasonably slow at the necessary amplitudes. It has been discovered that the bubbles, once trapped near the platform, and under certain conditions of ambient pressure and

displacement amplitude that is best determined by trial and error, develop jets that are not self-destructive but are cyclic with the same frequency as that of the driving amplitude. This periodic nature of the jet development has allowed us to examine them at leisure and with modest photographic requirements. We have also found that the addition of 25 % by volume of glycerol to the water greatly increases the stability of the bubbles, retarding undesirable surface oscillations. Three methods for photography have been used. The first two make use of the jet's cyclic nature. If the pulsating bubble is illuminated stroboscopically, and with a frequency near that of its pulsation frequency, the jet development can be slowed accordingly. We then film the motion with an ordinary movie camera with a framing rate near that of the pulsation frequency. The camera shutter and strobe flash need of course be synchronized for proper exposures. The short duration of the strobe flash (0.8  $\mu$ sec.) gives sharp contrast even for rapid transients. With appropriate tuning of the strobe flash, the jet can be optically frozen at a particular stage of development and single photographs also made. For a third method, a Fastax high speed movie camera with framing rates of at most 5000 frames/sec. has been used. Due to the low driving frequency, this moderate framing rate allows several exposures to be made each cycle.

RESULTS : In this section are shown several photographs of jet development and bubble surface oscillations filmed under both stroboscopic illumination and in real time.

Fig.1 shows a typical bubble collapse and jet development history. This sequence has been photographed under stroboscopic illumination with a slight difference in frequency between the driving amplitude and the strobe flash. The consistent evolution of the sequence shows the cyclic nature of the event.

Occasionally, the bubble will cease its cyclic behavior and erupt into a dramatic display of surface oscillations. Figure 2 shows such a sequence, filmed again under stroboscopic illumination. In this figure, the strobe flash frequency was very near that of the driving frequency, and this sequence also shows the bubble at intervals of approximately one period. In this case, however, the motion was not cyclic and the bubble is shown

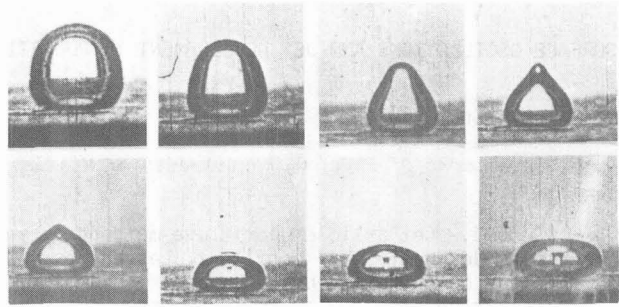


Fig. 1 - Liquid jet production during the collapse of a pulsating bubble filmed under stroboscopic illumination with a flash frequency slightly larger than the driving frequency. The frames are sequential but not necessarily consecutive. The maximum diameter of the bubble is approximately 1 mm.

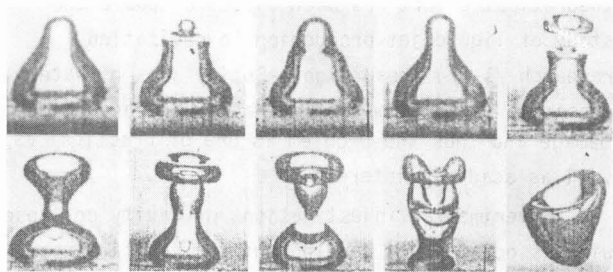


Fig. 2 - Surface oscillations of a pulsating bubble filmed under stroboscopic illumination with a flash frequency nearly equal to that of the driving frequency. The maximum diameter of the bubble is approximately 1 mm.

undergoing some intriguing surface oscillations. It is of interest to note that there appears to be jet development in frames 6, 7 and 8 even though the surface is in an unconventional shape.

It was desired to obtain photographs of the bubble throughout its cycle and consequently a high speed 16 mm Fastax movie camera was utilized. Figure 3 shows a sequence of jet development with a framing rate of approximately 5000 frames/sec. The frames are sequential but not necessarily consecutive. In contrast to the spark or laser-induced cavity collapse with accompanying jet development, this bubble that is driven mechanically, shows the production of an air jet before the subsequent liquid jet. It should be noted that our observations indicate that air-jet production is

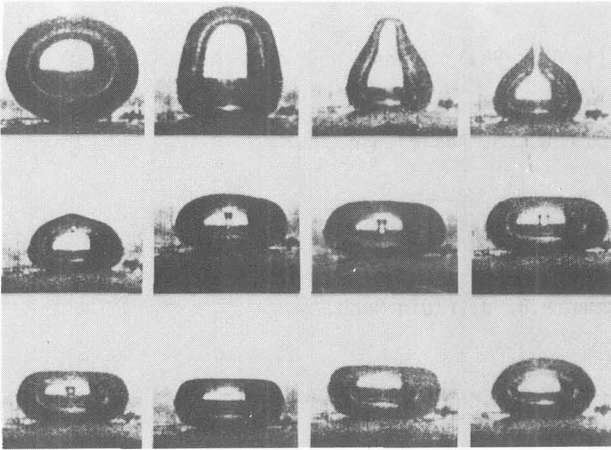


Fig. 3 Liquid jet production during the collapse of a pulsating bubble filmed at a framing rate of approximately 5000 frames/sec. The frames are sequential but not necessarily consecutive. The maximum diameter of the bubble is approximately 2 mm and the driving frequency is 60 Hz.

relatively rare - most collapses follow the conventional pattern. Frames 3, 4, and 5 are consecutive frames and show the impingement jet velocity to be quite small, with a displacement of approximately one millimeter between consecutive frames, giving a velocity on the order of 5 M/sec.

The inverted jet of air is of interest because it appears to be unique to the driven case and is probably an inertial effect. We have examined the collapse sequences that produce air jets and have recorded one that is of particular interest. Fig. 4 shows a high speed film sequence in which an air jet has broken off a small air bubble from its tip during collapse. During the expansion part of the cycle, the small bubble was engulfed by its parent causing a superb display of surface oscillations. We have also observed that the liquid jets will also occasionally break off a droplet of liquid from the tip; some observable structure is seen in the liquid jets in figure 3.

DISCUSSION AND CONCLUSIONS : We have presented a method whereby certain aspects of liquid jet development and other distortions of the shape of a pulsating bubble can be more easily observed. It is cautioned that this system does not represent true cavitation collapse and comparison with jet production from collapsing cavities, in contrast

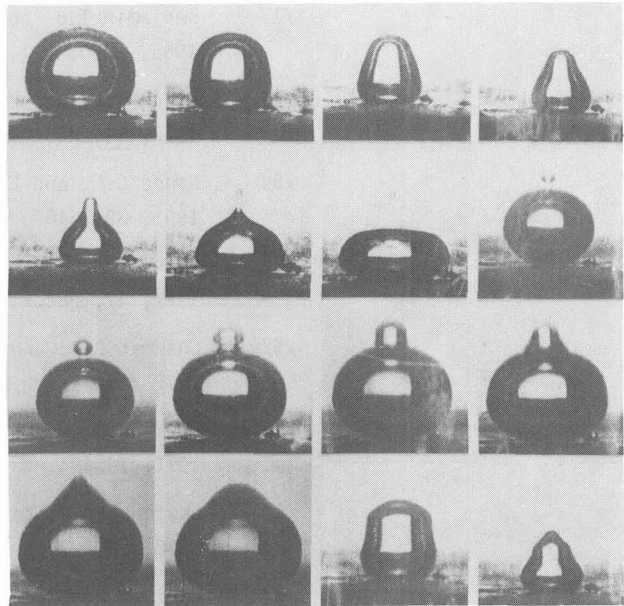


Fig. 4 Surface oscillations of a pulsating bubble filmed at a framing rate of approximately 5000 frames/sec. The frames are sequential but not necessarily consecutive. The maximum diameter of the bubble is approximately 3 mm and the driving frequency is 60 Hz.

to the pulsating bubbles described here, must be done very carefully. There appear to be many similarities between the two systems, however, and the relative ease at which this system can be assembled together with the multiplicity of information obtainable makes it a useful system for the study of the general aspects of jet production.

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