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Cyclic Liquid Jet Production in Pulsating Bubbles

by

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Introduction

A considerable amount of acoustic cavitation research effort has been directed toward the examination of liquid jets produced by bubbles collapsing near a boundary. It is thought that these high-velocity jets are the principal mechanism for cavitation erosion, and thus information concerning this damage mechanism is of interest to those involved in erosion control.

It is a difficult problem to examine liquid jet development, however, due to the extremely short time intervals involved. Researchers have observed liquid jet development previously only in collapsing vapour cavities and jet lifetimes of a few microseconds are quite common. The excellent movie of cavity collapse that has been made by W. Lauterborn,for example, shows sequences of jet production that have been filmed at frame rates exceeding one hundred thousand frames/sec. Such high-speed camera and sophisticated timing requirements are not available to the average researcher and prevents his study of this important mechanism.

This paper presents a method, however, that can be used to study jet behaviour with equipment available to most cavitation researchers. Further, the method also allows observations to be made by the naked eye for extended periods of time and the phenomenon can be filmed easily with either still photography or low-speed cinephotography.

The principal reasons that the jet mechanism is difficult to observe are (a) the time interval is very short, (b) the size of the collapsing bubble containing the jet is quite small, and (c) the event is a single event as the jet normally destroys the bubble or cavity in which it is produced. Ideally, one would like to produce a jet that develops each cycle in a large bubble pulsating at a low frequency. Interestingly enough, these requirements can all be met if the bubble is made to pulsate near its resonance frequency, close to a boundary and in a container in which the ambient pressure is reduced to near that of the vapour pressure of the liquid. To see why these conditions favour jet development, we must first look at some fundamental equations of bubble pulsation.

Flynn[(1)] states that the resonance frequency of a pulsating bubble is given approximately by

$$\omega_o^2 = \frac{1}{\rho R_o^2} \{ 3\eta (P_o - P_v) + (3\eta - 1) \frac{2\sigma}{R_o} \} \tag{1}$$

where ρ is the liquid density,

R_o is the radius of the bubble,

P_o is the ambient pressure above the liquid,

P_v is the vapour pressure of the liquid,

σ is the surface tension of the liquid, and

η is a constant that depends upon the thermodynamic behaviour of the air within the bubble. For isothermal pulsations, $\eta = 1.0$; for adiabatic pulsations, $\eta = 1.4$. Since we shall deal here with relatively large bubbles, $\eta \approx 1.4$.

If we suppose that the ambient pressure above the liquid is reduced to near that of the vapour pressure, then $P_o - P_v \cong 0$, and the radius of the bubble driven near its resonance frequency is given by

$$R_o^3 \approx (3\eta - 1) \frac{2\sigma}{\rho\omega_o^2} \qquad (2)$$

Here, the bubble pulsation is governed principally by the surface tension of the liquid. Thus, if we construct a container that can sustain a reduced pressure of approximately one atmosphere, and oscillate the container on a vibration table at a low frequency, say 60 Hz, then the diameter of the resonant bubble in water will be approximately 3 mm. This bubble is easily seen with the naked eye.

The pulsation amplitude, $\alpha = \Delta R/_R$, near resonance will be quite large and depends primarily upon the damping of the bubble pulsations. I have observed pulsation amplitudes up to 0.5 for this system and values of α on the order of 0.2 can lead to jet development. Further, since the frequency is quite low, growth by rectified diffusion is so slow that bubbles can be made to sustain jet development each cycle for periods of several minutes.

Let us consider the acoustic pressure amplitudes required to develop these jets, and thus determine the requirements on the oscillatory system. For a vibration table containing a liquid, the acoustic pressure at a specific point is given as a function of position and time by

$$p(z,t) = P_o + \rho g z + \omega^2 \rho A z \sin(\omega t),$$

where z is the distance below the surface of the liquid, g is the acceleration of gravity, and A is the displacement amplitude of the table.

The requirement of $\alpha \gtrsim 0.2$ is normally met with an acoustic pressure amplitude of a few tenths of an atmosphere, which requires a table displacement of a few millimetres for a frequency of 60 Hz and a depth of 10 cm.

Finally, the air bubble can be made to pulsate near a boundary by placing a horizontal platform in the vibrating container. The air bubble is forced downward by a radiation pressure force expressed by[2]

$$F = -\frac{4}{3}\pi R_o^3 \rho g + 2\pi \rho \alpha \omega^2 A R_o^3 , \tag{4}$$

and will remain semi-attached to the platform as long as the force is maintained positive.

Experimental Apparatus

The apparatus that I have used to produce cyclic liquid jets in pulsating air bubbles is as follows:

1. A cylindrical vessel approximately 6 inches in diameter and 3 inches long with flat, transparent end windows, containing a horizontal platform across the diameter and capable of sustaining a reduced ambient pressure of approximately one atmosphere.

2. A vibration table capable of achieving a vibration amplitude of at least 1 mm at a frequency of 60 Hz when loaded with the examination vessel.

3. A stroboscope capable of operating at a frequency of 60 Hz.

For photography, I have used a 35 mm still camera, an ordinary movie camera operating at a frame rate of 60 frames/sec, and a high speed camera that will achieve 5000 frames/sec. If one uses a strobe and an ordinary low-speed movie camera, the strobe must of course be synchronized with the camera in order to obtain exposure of the film when the shutter is open.

Results

Since this paper represents a written version of an oral paper presented at the conference on acoustic cavitation, most of the results, contained primarily in a movie film shown at the conference, can not be presented here. However, some observations of events that can be seen on the film are listed below:

1. Liquid jets are formed by bubbles pulsating on the platform provided that the amplitude of the pulsation is sufficient.

2. The jets develop each cycle, in most cases, and yet the bubble is not destroyed by the jet. As the bubble reexpands, the jet is withdrawn, the bubble becomes spherical, and the sequence repeats itself each cycle.

3. By strobing the bubble exactly at the pulsation frequency, a jet can be made to remain "motionless" long enough for still photographs to be made.

4. The jet sometimes penetrates the bottom of the bubble and a "doughnut" shape is momentarily achieved.

5. On occasion, as the bubble collapses, an inverted air jet develops above the bubble which is then drawn through the top surface with increased velocity to form a normal liquid jet.

6. Maximum jet velocity is smaller than that reported by previous investigations of single jet collapse, rarely exceeding 100 cm/sec here.

7. The geometrical shape of the jet has been shown to be closely approximated by a series of Legendre Polynomials and is nearly identical to shapes reported by other investigators.

Summary

A simple method is presented for obtaining low-speed, cyclic, liquid jets in pulsating air bubbles. The jets are similar in most respects to high-speed jets but are more easily generated and observed.

Acknowledgement

The author wishes to gratefully acknowledge the financial support of the U.S. Office of Naval Research for parts of this research effort.

References

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