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Shockwaves from Cavity Collapse

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XXI. Shockwaves from cavity collapse

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The determination of the stresses produced by cavity collapse has been of interest since Rayleigh's discussion of the problem. One theoretical calculation relating to this problem is the magnitude of the pressure pulse which is radiated when a spherical bubble collapses and rebounds in a liquid. A calculation of this kind has been made although it was necessary to idealize the physical situation. The peak pressures predicted by this treatment were of the order of some thousands of atmospheres and could, therefore, furnish a mechanism for the damage of solid surfaces. Since these peak pressures decrease rapidly with distance from the centre of the bubble, the solid boundary must be in the immediate neighbourhood of the bubble in order that damage may be produced by this mechanism. In this situation spherical collapse or rebound cannot be expected to take place. An additional disturbance from spherical symmetry arises because the spherical shape is unstable. There is now both theoretical and experimental evidence that jet formation may develop from this unstability, and could under suitable conditions give rise to cavitation damage. This evidence is briefly discussed.

Some general features of the damage produced in solids by cavitation are readily inferred from laboratory observations. For very soft materials the damage appears to begin with surface indentations so that one may infer that the stresses which accompany the collapse of the cavitation bubbles have produced a plastic flow of the surface. It also appears that this plastic flow may result from a single bubble collapse provided the collapse takes place near the solid boundary under suitable conditions. These suitable conditions appear to be rather critical. In the laboratory experiments performed at the California Institute, the cavitation bubbles are generated with a magnetostrictive oscillator which gives a periodic pressure amplitude of approximately 10 atm oscillating with a frequency of 15×10^3 per second, and the number of bubbles which grow and collapse in each cycle is roughly of the order of 10^3. Even with the very soft materials it takes of the order of 10 cycles of exposure before one observes a few indentations. Of greater interest perhaps is the behaviour of solids which have high surface hardness and high yield strength. With such materials no change in the solid surface is evident upon visual examination after exposure for many thousands of cycles. A solid which has been exposed in this way has, however, undergone significant work hardening. This alteration in the condition of the solid can be shown by means of X-ray analysis of a previously annealed specimen. The Laue X-ray pattern before the specimen has been exposed to cavitation consists of sharp spots. The Laue pattern becomes diffuse after exposure even though there is no optical evidence of damage (Plesset & Ellis 1955; Plesset 1956). This kind of observation shows that the damage follows plastic deformation of the solid structure and is therefore essentially a fatigue process. This view of the damage process is particularly helpful in understanding the observation that the damage rate increases markedly in a corrosive environment. A similar increase can be observed in suitable laboratory experiments (Plesset 1963).

Experiments have been carried out (Ellis 1956; Sutton 1955) which give the general features of the stresses which accompany cavitation bubble collapse. It is found that the duration of the stress pulse from a single bubble collapse is of the order of 1 μs. This finding is in accord with the familiar qualitative feature that the sound spectrum of cavitation noise contains appreciable energy in the very high frequency range. The intensity of the stress pulse on the surface of a solid exposed to cavitation is so far rather uncertain and could be expected to vary over wide limits depending upon the details of the bubble collapse, but it appears that the stress pulse may easily exceed 10^3 atm. While the magnitude of the stress pulse is indeed impressive, it must be emphasized that the effects produced in a solid are limited by the extremely short time of application. This short time of application of the cavitation stress means that one cannot use the ordinary fatigue properties of a material to predict its behaviour for cavitation damage.

One mechanism which has been suggested as the source of cavitation damage is the shock, or pressure pulse, which would be radiated when the collapse motion of a cavitation bubble is arrested. An estimate of the magnitude of these shocks was first made by Rayleigh (1917), and the calculations which have followed have for the most part put particular emphasis on the effects of the compressibility of the liquid in the neighbourhood of the cavity. The physical conditions toward the end of the collapse of a cavitation bubble are so complicated that some approximations appear to be necessary. A cavitation bubble may be expected to contain some permanent gas in addition to the vapour of the liquid. In the initial stages of collapse motion while the bubble wall velocity is small, the condensation rate of the vapour is sufficiently rapid to keep the vapour pressure constant. When the bulk temperature of the liquid is appreciably below the boiling temperature, the heat of condensation does not lead to a significant rise in the temperature of the bubble or of the adjacent liquid in this stage of the motion (Plesset 1964). Toward the end of the collapse the vapour behaves like a permanent gas, and the compression of the vapour together with any small amount of ordinary permanent gas will lead to a sharp temperature rise of short duration. This compression heating on bubble collapse appears to be the mechanism for the appearance of sonoluminescence for appropriate gases in the bubble (Hickling 1963). This high temperature does not extend far beyond the boundary of the compressed bubble, and there does not appear to be any particular evidence of temperature effects in cavitation damage.

This physical picture gives some basis for a model which has been used to describe the final stages of the collapse and rebound of a cavitation bubble (Hickling & Plesset 1964). In this model the bubble is supposed to contain a small amount of permanent gas only. This simplification is considered reasonable since the small amounts of vapour and gas which occur in a typical cavitation bubble have little effect on the motion of the interface until the final stage of collapse. In this final stage, both vapour and gas will be compressed and will contribute to rebound in a similar manner. The detailed behaviour of the compressed gas and vapour in the bubble will of course affect the hydrodynamics of the liquid. If the bubble interior is more nearly isothermal than adiabatic, collapse would be more violent. In the calculations of Hickling & Plesset (1964) the pressure of the gas in the bubble was taken to be proportional to ρ^γ where ρ is the density, and the index γ could be varied to simulate different types of gas behaviour. The effects of liquid compressibility were considered completely, but viscous effects in the liquid were neglected. This neglect should not be of significance for the results. The assumption was also made that the bubble

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remained spherical throughout the motion. It is known that this assumption that a spherical interface will be maintained is not justified, and further comment on this point will be made below. The ambient pressure, p_∞, was given the values 1 and 10 atm, and the initial gas pressure in the bubble, p_0, was varied from 10^{-1} to 10^{-4} atm. The index γ was taken to be 1 or 1·4. Numerical solutions were then obtained for the compressible flow in the liquid. There is some theoretical interest in the collapse of a completely empty bubble in which case the bubble collapse velocity increases without limit as the bubble radius, R, approaches zero. It was found in the numerical solutions of Hickling & Plesset (1964) that the bubble wall velocity tends to infinity like $(R_0/R)^{0\cdot785}$ both for $p_\infty = 1$ atm and for $p_\infty = 10$ atm. This result is in good agreement with a similar estimate by Hunter (1960). The insensitivity of the hydrodynamics relative to the external pressure, p_∞, was also found in the region near the minimum radius for a bubble containing gas. The behaviour of the final stages of collapse and the initial stages of rebound were sensitive to the initial gas pressure, p_0, in the bubble and the effective value of γ. Detailed results were obtained for $p_0 = 10^{-3}$ and 10^{-4} atm with $p_\infty = 1$ atm and $\gamma = 1\cdot4$. The compression wave which is radiated into the liquid was followed outward until it steepened into a shockfront. At this stage the numerical solution becomes unstable. While there are methods available for overcoming this instability and proceeding further, these calculations were not carried further since it was not necessary for the immediate purpose of the investigation. The variation in the pressure with distance from the bubble wall at different times during the collapse and the rebound was obtained in a straightforward way. As would be expected, the acoustic approximation is reasonably accurate even during the rebound when a shock front is developing. The wave remains of the same thickness and form, and attenuates with distance as $1/r$ as it propagates outward from the centre of symmetry. The pressure front steepens quite gradually. This behaviour is to be expected since pressure pulses and shocks are weak with very small entropy changes even for rather large variations in pressure. The attenuation of the peak pressure with distance means that a solid must be close to the collapsing bubble if the pressure pulse is to have a large value at the solid surface. For $p_0 = 10^{-3}$ atm, $\gamma = 1\cdot4$, the peak pressure in the outgoing wave is about 1000 atm for $R/R_0 \simeq 0\cdot3$, where R_0 is the initial radius of the bubble. This same wave has a peak pressure of 200 atm at $r/R_0 \sim 2$. If $p_0 = 10^{-4}$ atm, the peak pressure is of the order of 1000 atm at $r/R_0 \sim 2$.

On the basis of the calculations just described, it appears possible that the pressure shocks radiated from cavitation bubble collapse and rebound could produce damage on solid surfaces. While this mechanism is possible, it cannot be expected to occur with high probability. The collapse must occur in the immediate neighbourhood of the solid, and the collapsing bubble can contain only minute quantities of gas. In addition, the liquid must be at a sufficiently low temperature so that the vapour density will be small. Except in special circumstances, the magnitude of the pressure shocks appears marginal for the production of the observed damage in view of their short duration.

The assumption of spherical symmetry which is usually made in bubble dynamics is dictated by the complexities of more realistic calculations. Spherical symmetry, however, cannot be justified for two important reasons. First, since the collapse of a bubble must, as calculations indicate, be close to a solid boundary to give the kind of effects observed, the flow configuration does not have the assumed symmetry. Secondly, the collapse of a spherical cavity even under idealized conditions is known to be unstable with respect to deformations from the spherical shape (Plesset & Mitchell 1956). These considerations have suggested that jets could form during cavity collapse and that the damage would result from their impingement on the solid surface. Some observations by Naudé & Ellis (1961) gave support for this mechanism. Shutler & Mesler (1966) also have observed the formation of such jets in collapsing cavities, and they also observed damage on adjacent solid surfaces. They found, however, that the damage did not appear to occur at the point of jet impingement, but at some distance from that point. While these observations do not support this mechanism, it still seems to be a possibility that cavitation damage could result from jet impingement. Deformation of solids by liquid impact is a familiar effect (Bowden & Brunton 1961). For jet impact to be a mechanism for cavitation damage it is necessary for the bubble asymmetry to lead to jets with sufficiently high velocity. Further experimental evidence is needed, and experiments with large cavitation bubbles such as are planned by Benjamin & Ellis will be most helpful in clarifying the situation.

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