Mechanism of Cavitation Damage

The intense disturbances that are caused by cavitation bubble collapse can have two separate origins. The first is related to the fact that a collapsing bubble may be unstable in terms of its shape. When the collapse occurs near a solid surface, Naude and Ellis (1961) and Benjamin and Ellis (1966) observed that the developing spherical asymmetry takes the form of a rapidly accelerating jet of fluid, entering the bubble from the side furthest from the wall (see figure 1). Plesset and Chapman (1971) carried out numerical calculations of this "reentrant jet", and found good agreement with the experimental observations of Lauterborn and Bolle (1975). Since then, other analytical methods have explored the parametric variations in the flow. These methods are reviewed by Blake and Gibson (1987). The "microjet" achieves very high speeds, so that its impact on the other side of the bubble generates a shock wave, and a highly localized shock loading of the surface of the nearby wall.

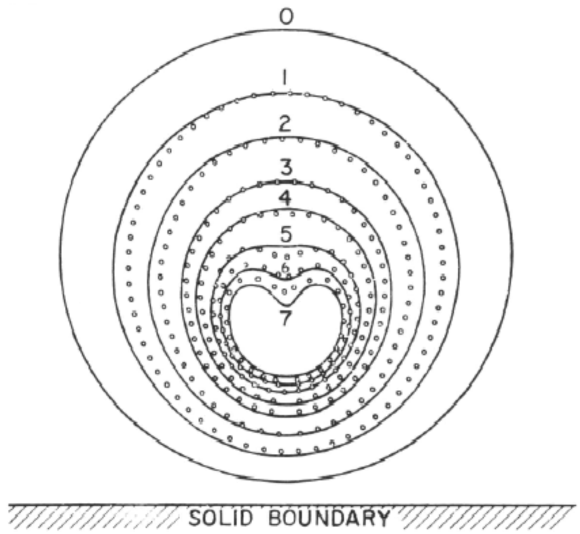

Figure 1: The collapse of a cavitation bubble close to a solid boundary. The theoretical shapes of Plesset and Chapman (1971) (solid lines) are compared with the experimental observations of Lauterborn and Bolle (1975) (points) (adapted from Plesset and Prosperetti 1977).

Parenthetically, we might remark that this is also the principle on which the depth charge works. The initial explosion creates little damage, but does produce a very large bubble which, when it collapses, generates a reentrant jet directed toward any nearby solid surface. When this surface is a submarine, the collapse of the bubble can cause great damage to that vessel. It may also be of interest to note that a bubble, collapsing close to a very flexible or free surface, develops a jet on the side closest to this boundary, and, therefore, traveling in the opposite direction. Some researchers have explored the possibility of minimizing cavitation damage by using surface coatings with a flexibility designed to minimize the microjet formation.

The second intense disturbance occurs when the remnant cloud of bubbles, that remains after the microjet disruption, collapses to its minimum gas/vapor volume, and generates a second shock wave that impinges on the nearby solid surface. The generation of a shock wave during the rebound phase of bubble motion was first demonstrated by the calculations of Hickling and Plesset (1964). More recently, Shima *et al.* (1981) have made interesting observations of the spherical shock wave using Schlieren photography, and Fujikawa and Akamatsu (1980) have used photoelastic solids to examine the stress waves developed in the solid. Though they only observed stress waves resulting from the remnant cloud collapse and not from the microjet, Kimoto (1987) has subsequently shown that both the microjet and the remnant cloud create stress waves in the solid. His measurements indicate that the surface loading resulting from the remnant cloud is about two or three times that due to the microjet.

Until very recently, virtually all of these detailed observations of collapsing cavitation bubbles had been made in a quiescent fluid. However, several recent observations have raised doubts regarding the relevance of these results for most flowing systems. Ceccio and Brennen (1991) have made detailed observations of the collapse of cavitating bubbles in flows around bodies, and have observed that typical cavitation bubbles are distorted and often broken up by the shear in the boundary layer or by the turbulence before the collapse takes place. Furthermore, Chahine (personal communication) has performed calculations similar to those of Plesset and Chapman, but with the addition of rotation due to shear, and has found that the microjet is substantially modified and reduced by the flow.

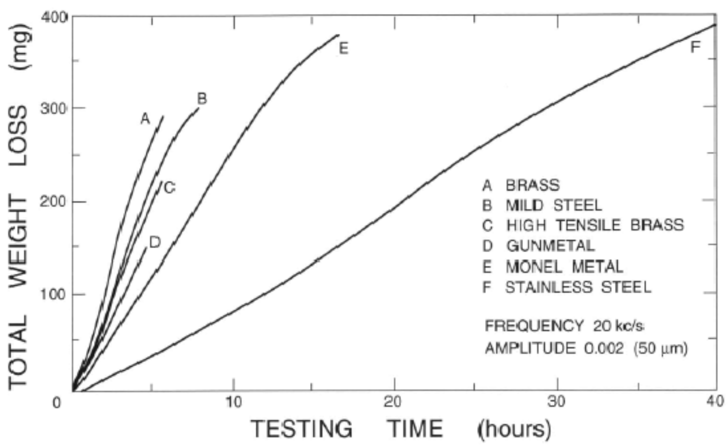

Figure 2: Examples of cavitation damage weight loss as a function of time. Data from vibratory tests with different materials (Hobbs, Laird and Brunton 1967).

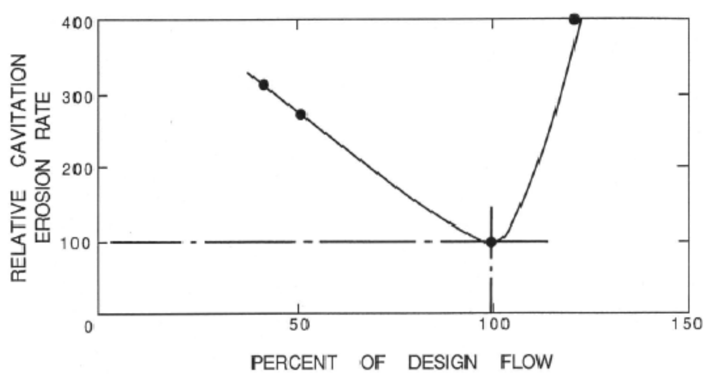

Figure 3: Cavitation erosion rates in a centrifugal pump as a function of the flow rate relative to the design flow rate (Pearsall 1978 from Grist 1974).

The other important facet of the cavitation damage phenomenon is the reaction of the material of the solid boundary to the repetitive shock (or "water hammer") loading. Various measures of the resistance of particular materials to cavitation damage have been proposed (see, for example, Thiruvengadam 1967). These are largely heuristic and empirical, and will not be reviewed here. The reader is referred to Knapp, Daily, and Hammitt (1970) for a detailed account of the relative resistance of different materials to cavitation damage. Most of these comparisons are based, not on tests in flowing systems, but on results obtained when material samples are vibrated at high frequency (about 20 kHz) in a bath of quiescent liquid. The samples are weighed at regular intervals to determine the loss of material, and the results are presented in the form typified by figure 2. Note that the relative erosion rates, according to this data, can be approximately correlated with the structural strength of the material. Furthermore, the erosion rate is not necessarily constant with time. This may be due to the differences in the response of a collapsing bubble to a smooth surface as opposed to a surface already roughened by damage. Finally, note that the weight loss in many materials only begins after a certain incubation time.

The data on erosion rates in pumps is very limited because of the length of time necessary to make such measurements. The data that does exist (Mansell 1974) demonstrates that the rate of erosion is a strong function of the operating point as given by the cavitation number and the flow coefficient. The influence of the latter is illustrated in figure 3. This curve essentially mirrors those of figures 4 and 5, section (Mbeg). At off-design conditions, the increased angle of incidence leads to increased cavitation and, therefore, increased weight loss.