Cavitation Noise

The violence of cavitation bubble collapse also produces noise. In many practical circumstances, the noise

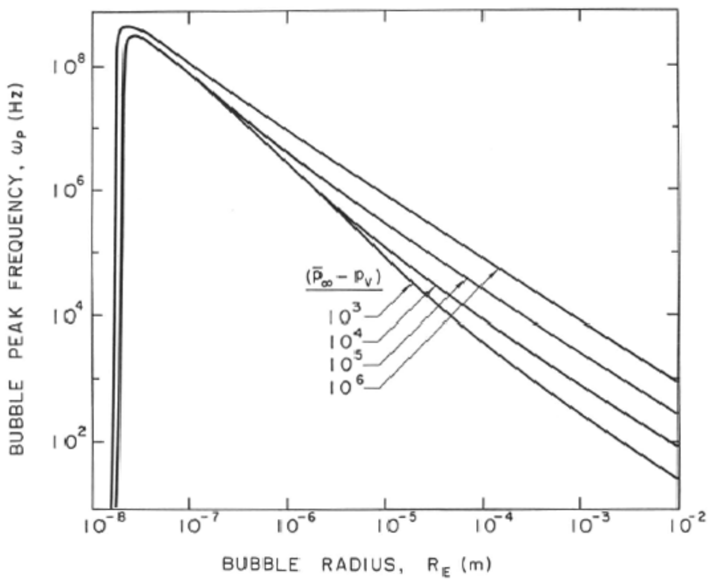

Figure 1: Bubble natural frequency, ω_P, in Hz as a function of the bubble radius and the difference between the equilibrium pressure and the vapor pressure (in $kg/m\ sec^2$) for water at $300°K$.

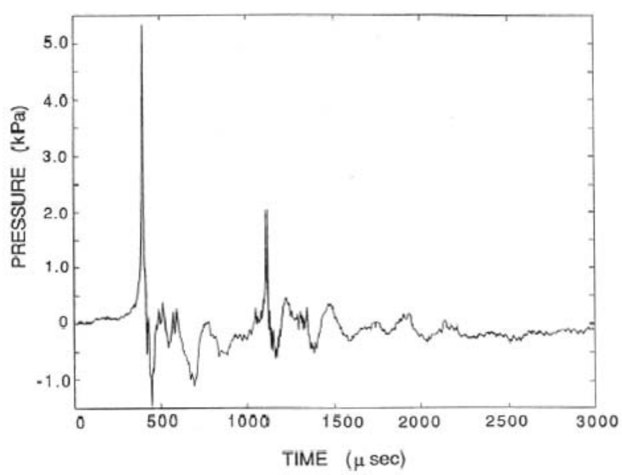

Figure 2: Typical acoustic signal from a single collapsing bubble (from Ceccio and Brennen 1991).

is important not only because of the vibration that it may cause, but also because it advertizes the presence of cavitation and, therefore, the likelihood of cavitation damage. Indeed, the magnitude of cavitation noise is often used as a crude measure of the rate of cavitation erosion. For example, Lush and Angell (1984) have shown that, in a given flow at a given cavitation number, the rate of weight loss due to cavitation damage is correlates with the noise as the velocity of the flow is changed.

Prior to any discussion of cavitation noise, it is useful to identify the natural frequency with which individual bubbles will oscillate a quiescent liquid. This natural frequency can be obtained from the

Rayleigh-Plesset equation (Mbew1) by substituting an expression for $R(t)$ that consists of a constant, R_E, plus a small sinusoidal perturbation of amplitude, $\tilde{R}$, at a general frequency, ω. Steady state oscillations like this would only be maintained by an applied pressure, $p(t)$, consisting of a constant, $\bar{p}$, plus a sinusoidal perturbation of amplitude, $\tilde{p}$, and frequency, ω. Obtaining the relation between the linear perturbations, $\tilde{R}$ and $\tilde{p}$, from the Rayleigh-Plesset equation, it is found that the ratio, $\tilde{R}/\tilde{p}$, has a maximum at a resonant frequency, ω_P, given by

$$\omega_P = \left[\frac{3(\bar{p} - p_V)}{\rho_L R_E^2} + \frac{4\mathcal{S}}{\rho_L R_E^3} - \frac{8\nu^2}{R_E^4} \right]^{\frac{1}{2}} \tag{Mbei1}$$

The results of this calculation for bubbles in water at $300°K$ are presented in figure 1 for various mean pressure levels, $\bar{p}$. Note that the bubbles below about 0.02 μm are supercritically damped, and have no resonant frequency. Typical cavitation nuclei of size $10 \rightarrow 100$ μm have resonant frequencies in the range $10 \rightarrow 100$ kHz. Even though the nuclei are excited in a highly nonlinear way by the cavitation, one might expect that the spectrum of the noise that this process produces would have a broad maximum at the peak frequency corresponding to the size of the most numerous nuclei participating in the cavitation. Typically, this would correspond to the radius of the critical nucleus given by the expression (Mbew13). For example, if the critical nuclei size were of the order of $10 - 100$ μm, then, according to figure 1, one might expect to see cavitation noise frequencies of the order of $10 - 100$ kHz. This is, indeed, the typical range of frequencies produced by cavitation.

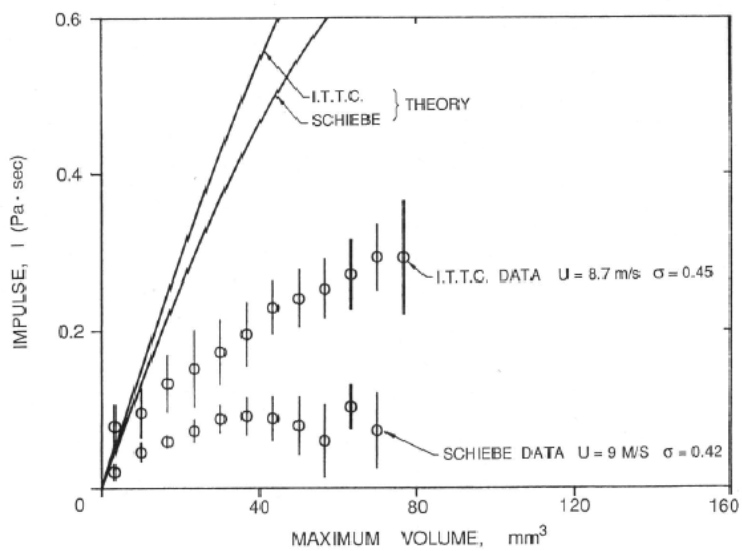

Figure 3: The acoustic impulse, I, produced by the collapse of a single cavitation bubble. Data is shown for two axisymmetric bodies (the ITTC and Schiebe headforms) as a function of the maximum volume prior to collapse. Also shown are the equivalent results from solutions of the Rayleigh-Plesset equation (from Ceccio and Brennen 1991).

Fitzpatrick and Strasberg (1956) were the first to make extensive use of the Rayleigh-Plesset equation to predict the noise from individual collapsing bubbles and the spectra that such a process would produce. More recently, Ceccio and Brennen (1991) have recorded the noise from individual cavitation bubbles in a flow. A typical acoustic signal is reproduced in figure 2. The large positive pulse at about 450 μs corresponds to the first collapse of the bubble. Since the radiated acoustic pressure, p_A, in this context is related to the second derivative of the volume of the bubble, $V(t)$, by

$$p_A = \frac{\rho_L}{4\pi\ell} \frac{d^2V}{dt^2} \tag{Mbei2}$$

(where ℓ is the distance of the measurement from the center of the bubble), the pulse corresponds to the very large and positive values of d^2V/dt^2 that occur when the bubble is close to its minimum size in the

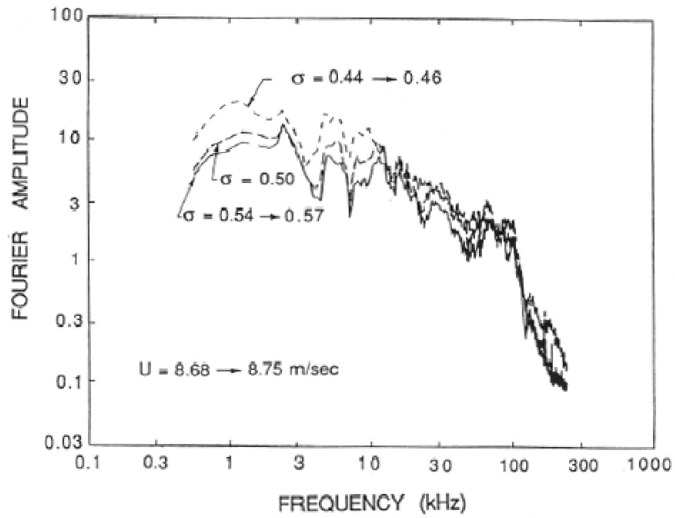

Figure 4: Typical spectra of noise from bubble cavitation for various cavitation numbers as indicated (Ceccio and Brennen 1991).

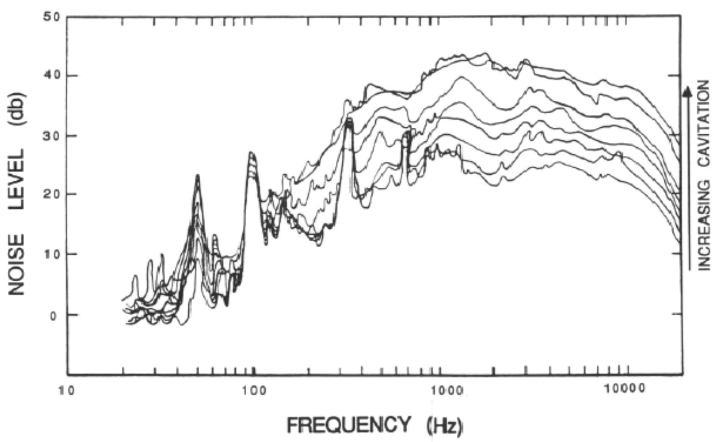

Figure 5: Typical spectra showing the increase in noise with increasing cavitation in an axial flow pump (Lee 1966).

middle of the collapse. The first pulse is followed in figure 2 by some facility-dependent oscillations, and by a second pulse at about 1100 μs. This corresponds to the second collapse; no further collapses were observed in these particular experiments.

A good measure of the magnitude of the collapse pulse in figure 2 is the acoustic impulse, I, defined as the area under the curve or

$$I = \int_{t_1}^{t_2} p_A dt \tag{Mbei3}$$

where t_1, t_2 are the times before and after the pulse when $p_A = 0$. The acoustic impulses for cavitation on two axisymmetric headforms (ITTC and Schiebe headforms) are compared in figure 3 with impulses predicted from integration of the Rayleigh-Plesset equation. Since these theoretical calculations assume that the bubble remains spherical, the discrepancy between the theory and the experiments is not too surprising. Indeed, the optimistic interpretation of figure 3 is that the theory can provide an order of magnitude estimate of the noise produced by a single bubble. This could then be combined with the nuclei number density distribution to obtain a measure of the amplitude of the noise (Brennen 1994).

The typical single bubble noise shown in figure 2 leads to the spectrum shown in figure 4. If the cavitation events are randomly distributed in time, this would also correspond to the overall cavitation

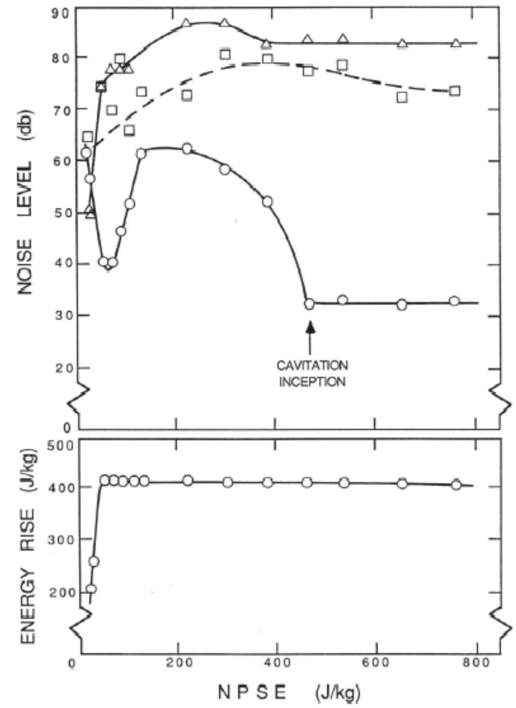

Figure 6: The relation between the cavitation performance, the noise and vibration produced at three frequency levels in a centrifugal pump, namely the shaft frequency (□), the blade passage frequency (△) and 40 kHz (○) (Pearsall 1966-67).

noise spectrum. It displays a characteristic frequency content in the range of $1 \rightarrow 50$ kHz (the rapid decline at about 80 kHz represents the limit of the hydrophone used to make these measurements). Typical measurements of the noise produced by cavitation in an axial flow pump are illustrated in figure 5, and exhibit the same features demonstrated in figure 4. The signal in figure 5 also clearly contains some shaft or blade passage frequencies that occur in the absence of cavitation, but may be amplified or attenuated by cavitation. Figure 6 contains data obtained for cavitation noise in a centrifugal pump. Note that the noise at a frequency of 40 kHz shows a sharp increase with the onset of cavitation; on the other hand, the noise at the shaft and blade passage frequencies show only minor changes with cavitation number. The decrease in the 40 kHz cavitation noise as breakdown is approached is also a common feature in cavitation noise measurements.

The level of the sound produced by a cavitating flow is the result of two factors, namely the impulse, I, produced by each event (equation (Mbei3)) and the event rate or number of events per second, $\dot{N}_E$. Therefore, the sound pressure level, p_S, will be

$$p_S = I\dot{N}_E \qquad \text{(Mbei4)}$$

Here, we will briefly discuss the scaling of the two components, I, and $\dot{N}_E$, and thus the scaling of the cavitation noise, p_S. We emphasize that the following equations omit some factors of proportionality necessary for quantitative calculations.

Both the experimental observations and the calculations based on the Rayleigh-Plesset equation, show that the nondimensional impulse from a single cavitation event, defined by

$$I^* = 4\pi I\ell/\rho U D^2 \qquad \text{(Mbei5)}$$

(where U and D are the reference velocity and length in the flow), is strongly correlated with the maximum volume of the cavitation bubble (maximum equivalent volumetric radius $= R_M$), and appears virtually independent of the other flow parameters. In dimensionless terms,

$$I^* \approx R_M^2/D^2 \qquad \text{(Mbei6)}$$

It follows that

$$I \approx \rho U R_M^2 / \ell \tag{Mbei7}$$

The evaluation of the impulse from a single event is then completed by some estimate of the maximum bubble size, R_M. For example, we earlier estimated R_M for traveling bubble cavitation (equation (Mbew12)), and found it to be independent of U for a given cavitation number. In that case I is linear in U.

Modeling the event rate, $\dot{N}_E$, can be considerably more complicated than might, at first sight, be visualized. If all the nuclei flowing through a certain known streamtube (say with a cross-sectional area, A_N, in the upstream reference flow), were to cavitate similarly then, clearly, the result would be

$$\dot{N}_E = N \; A_N \; U \tag{Mbei8}$$

where N is the nuclei concentration (number/unit volume). Then the sound pressure level resulting from substituting the expressions (Mbei8), (Mbei7), and (Mbew12) into equation (Mbei4), is

$$p_S \approx \rho U^2 \left(-\sigma - C_{pmin}\right)^2 A_N N D^2 / \ell \tag{Mbei9}$$

where we have omitted some of the constants of order unity. For the simple circumstances outlined, equation (Mbei9) yields a sound pressure level that scales with U^2 and with D^4 (because $A_N \propto D^2$). This scaling with velocity does correspond to that often observed (for example, Blake, Wolpert, and Geib 1977, Arakeri and Shangumanathan 1985) in simple traveling bubble flows. There are, however, a number of complicating factors. First, as we have discussed earlier in section (Mbew), only those nuclei larger than a certain critical size, R_C, will actually grow to become cavitation bubbles, and, since R_C is a function of both σ and the velocity U, this means that N will be a function of R_C and U. Since R_C decreases as U increases, the power law dependence of p_S on velocity will then be U^m where m is greater than 2.

Different scaling laws will apply when the cavitation is generated by turbulent fluctuations, such as in a turbulent jet (see, for example, Ooi 1985, Franklin and McMillan 1984). Then the typical tension and the typical duration of the tension experienced by a nucleus, as it moves along an approximately Lagrangian path in the turbulent flow, are very much more difficult to estimate. Consequently, estimates of the sound pressure due to cavitation in turbulent flows, and the scaling of that sound with velocity, are more poorly understood.