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Invited Lecture

Cloud Cavitation: The Good, The Bad and the Bubbly

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ABSTRACT

In many cavitating liquid flows, when the number and concentration of the bubbles exceeds some critical level, the flow becomes unsteady and large clouds of cavitating bubbles are periodically formed and then collapse when convected into regions of higher pressure. This phenomenon is known as cloud cavitation and when it occurs it is almost always associated with a substantial increase in the cavitation noise and damage.

These increases represent serious problems in devices as disparate as marine propellers, cavitating pumps and artificial heart valves. This lecture will present a brief review of the analyses of cloud cavitation in simplified geometries that allow us to anticipate the behavior of clouds of cavitation bubbles and the parameters that influence that behaviour. These simpler geometries allow some anticipation of the role of cloud cavitation in more complicated flows such as those in cavitating pumps.

NOMENCLATURE

- A Typical dimension of the cloud of bubbles.
- R Typical equilibrium radius of the bubbles.
- α Equilibrium void fraction in the cloud.
- β Interaction parameter, $\alpha A^2/R^2$

INTRODUCTION

It has become abundantly clear in recent years that knowledge of the dynamics and acoustics of bubble clouds (as opposed to single bubbles) is essential to our understanding of a very broad range of physical effects involving bubbles. For example, the collapse of clouds of cavitation bubbles often results in much greater noise and damage than would result from the sum of the effects of individual bubbles. In the context of cavitating propellers or turbomachines this is a cause for grave concern and the lack of understanding of the processes of periodic formation and collapse of cavitation clouds remains a key issue. Similar concerns surround the formation of clouds of cavitation bubbles in contexts as diverse as artifical heart valves or the earthquake-induced cavitation effects on dams. But there are also contexts in which these cloud effects can be an advantage such as in the destruction of kidney stones by lithotripsy.

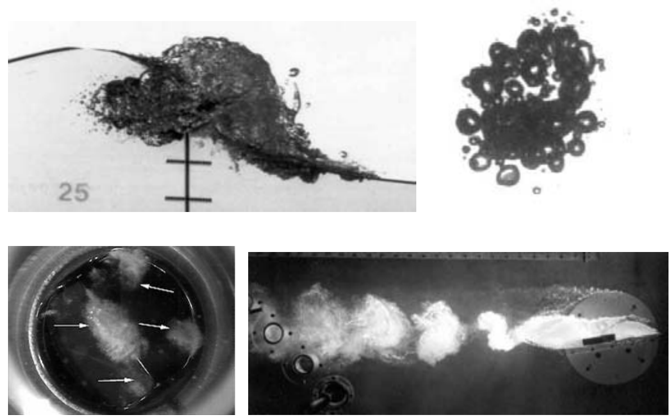

Figure 1. Examples of bubble clouds: Clockwise from upper left: a breaking wave (Petroff [1]), a cloud formed after collapse of a vapor bubble (Frost and Sturtevant [2]), clouds formed in the wake of an oscillating hydrofoil, clouds formed downstream of an artificial heart valve closure (Rambod et al. [3]).

In this paper we give a very brief account of analyses that provide our current understanding of the dynamics of cavitation clouds. This will be followed by several examples of experimental observations of cloud cavitation in water tunnel experiments and in pump tests.

REVIEW OF BUBBLE CLOUD EFFECTS

Natural Frequencies

Though the first analysis that indicated how bubbles might behave collectively was conducted by van Wijngaarden [4] on a plane layer of bubbles next to a wall, it is more convenient to focus attention on a finite spherical cloud surrounded by pure liquid and to briefly review the dynamics and acoustics of such a cloud. We begin with the simplified case shown in figure 2 in which all the bubbles in the cloud have the same equilibrium size, R_0, and are uniformly distributed within the cloud. Thus the population as represented by the initial equilibrium void fraction, α_0, is uniform within the cloud. Radial position within the cloud is denoted by r and the initial radius of the cloud by A_0.

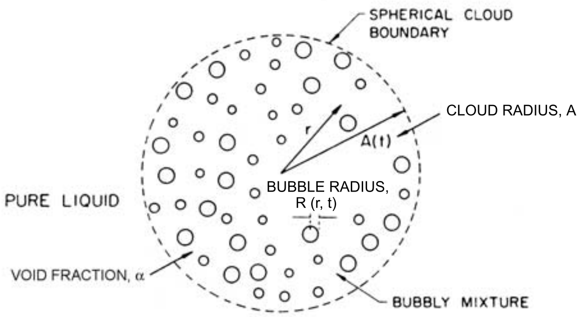

Figure 2. Schematic of a spherical cloud of cavitation bubbles [5,6].

d'Agostino and Brennen [5,6] showed that a linearized dynamics analysis of such a cloud reveals that it has its own, infinite set of natural frequencies denoted by ω_n and given by

$$\omega_n = \omega_N \left[1 + \frac{4}{3\pi^2(2n-1)^2} \; \frac{A_0^2}{R_0^2} \; \frac{\alpha_0}{1-\alpha_0} \right]^{-\frac{1}{2}}$$

for n = 1, 2, 3 ….. and where ω_N is the natural frequency of an individual bubble oscillating alone in an infinite liquid. The above is an infinite series of frequencies of which ω_1 is the lowest. The higher frequencies approach ω_N as n tends to infinity.

As expected these natural frequencies correspond to modes with more and more nodes as n increases (see Brennen [7]). Note that the lowest natural frequency, ω_1 , is given by

$$\omega_1 = \omega_N \left[1 + \frac{4}{3\pi^2} \; \frac{A_0^2}{R_0^2} \; \frac{\alpha_0}{1-\alpha_0} \right]^{-\frac{1}{2}}$$

Note also that this can be much smaller than ω_N if the initial void fraction, α_0, is much larger than the square of the ratio of bubble size to cloud size, $\alpha_0 >> R_0^2/A_0^2$. If the reverse is the case ($\alpha_0 << R_0^2/A_0^2$) all the natural frequencies of the cloud are contained in a small range just below ω_N. This defines a special parameter, $\beta=\alpha_0 A_0^2/R_0^2$, that governs the cloud interaction effects and that is termed the ``Cloud Interaction Parameter''.

If $\beta<<1$ there is relatively little bubble interaction effect and all the bubbles oscillate at close to the frequency, ω_N , as if each were surrounded by nothing but liquid. On the other hand when $\beta>1$ the cloud has natural frequencies much less than ω_N and there are strong interaction effects between the bubbles in the cloud.

Note that in various applications the magnitude of β could take a wide range of values from much less than unity to much greater than unity. It will be small in small clouds with a few large bubbles and a low void fraction but could be large in large clouds of small bubbles with higher void fraction.

Linear dynamics of a simple cloud

Further exploration of the forced linearized response of a cloud to oscillations in the pressure in the liquid far from the bubble (d'Agostino and Brennen [5,6]) reveals the following characteristics. In the absence of damping in the Rayleigh-Plesset equation for the bubble dynamics, infinite peaks in the response occur at all the natural frequencies as shown in figure 3. However, when a reasonable estimate of the damping is included (d'Agostino and Brennen [6]), the attenuation of the higher frequencies is much greater so the dominant peak in the response occurs at the lowest natural frequency of the cloud, ω_1. The response at the bubble natural frequency, ω_N , becomes much less significant.

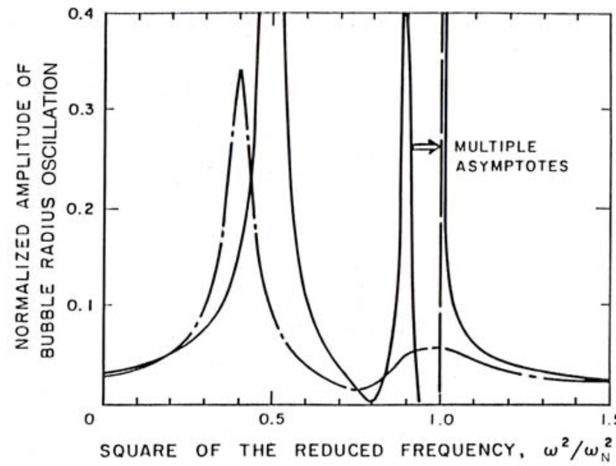

Figure 3. The amplitude of the bubble radius oscillation at the cloud surface as a function of frequency (for the case of β=0.8). Solid line is without damping; broken line includes damping. From d'Agostino and Brennen [6].

The effect of varying the cloud interaction parameter, β, is shown in figure 4, where the amplitude of bubble radius oscillation at the cloud surface is presented as a function of ω. Note that increasing β causes a reduction in both the amplitude and frequency of the dominant response at the lowest natural frequency of the cloud.

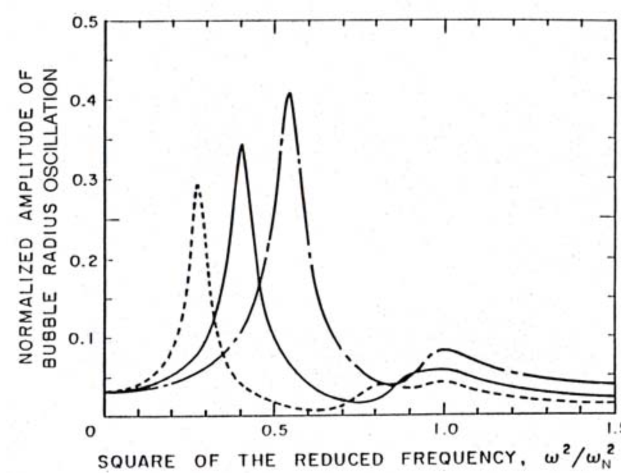

Figure 4. The amplitude of the bubble radius oscillation at the cloud surface as a function of frequency for damped oscillations at three values of β=0.8 (solid line), β=0.4 (dot-dash line), and β=1.65 (dashed line). From d'Agostino and Brennen [6].

It is important to emphasize that the results presented above are linear and that there are very significant nonlinear effects that we now proceed to describe. In addition we have focused exclusively on spherical bubble clouds since solutions of the basic equations for other, more complex geometries are not readily obtained. However, d'Agostino et al. [8] have examined some of the characteristics of this class of bubbly flows past slender bodies (for example, the flow over a wavy surface).

Cavitation of a spherical cloud

If a spherical cloud is subjected to an episode of sufficiently low pressure it will cavitate, in other words the bubbles will grow explosively to many times their original size. Subsequently, if the pressure far from the cloud increases again (as, for example, when the cloud is convected out of the region of low pressure) the bubbles will collapse violently. The reaction of a single bubble to such a low pressure episode has, of course, been studied extensively; typically the Rayleigh-Plesset equation is used to model the highly non-linear reaction of the single bubble. However, the response of a cloud of bubbles is more complex.

A valuable perspective on the subject was that introduced by Morch [9,10,11] and Hanson, Kedrinskii and Morch [12]. They suggested that the collapse of a cloud of bubbles involves the formation and inward propagation of a shock wave and that the geometric focusing of this shock at the center of cloud creates the enhancement of the noise and damage potential associated with cloud collapse. Wang and Brennen [13,14] and Reisman et al. [15] employed the use of continuity and momentum equations coupled to the Rayleigh-Plesset equation in order to model the two-phase flow within the cloud. Here we briefly review their numerical calculations that detailed the dynamics of a spherical cloud of cavitating bubbles. (Previous numerical investigations of the nonlinear dynamics of cavity clouds were carried out by Chahine [16], Omta [17], and Kumar and Brennen [18,19,20]).

It transpires that the response of a cloud to an episode of reduced pressure in the surrounding liquid is quite different depending on the magnitude of β. When β is much greater than unity the typical cloud response to an episode of reduced pressure is shown in figure 5 (upper). Note that the bubbles on the surface of the cloud grow more rapidly than those in the interior which are effectively shielded from the reduced pressure in the surrounding liquid. More importantly the bubbles on the surface collapse first and a collapse front propagates inward from the cloud surface developing into a substantial shock wave. Due to geometric focusing this shock wave strengthens as the shock proceeds inwards and creates a very large pressure pulse when it reached the center of the cloud.

On the other hand when β is small, the response of the cloud is quite different as shown in figure 5 (lower). Then the bubbles at the center of the cloud collapse first, resulting in an outgoing collapse front that weakens geometrically resulting in a quite different and much more benign dynamic

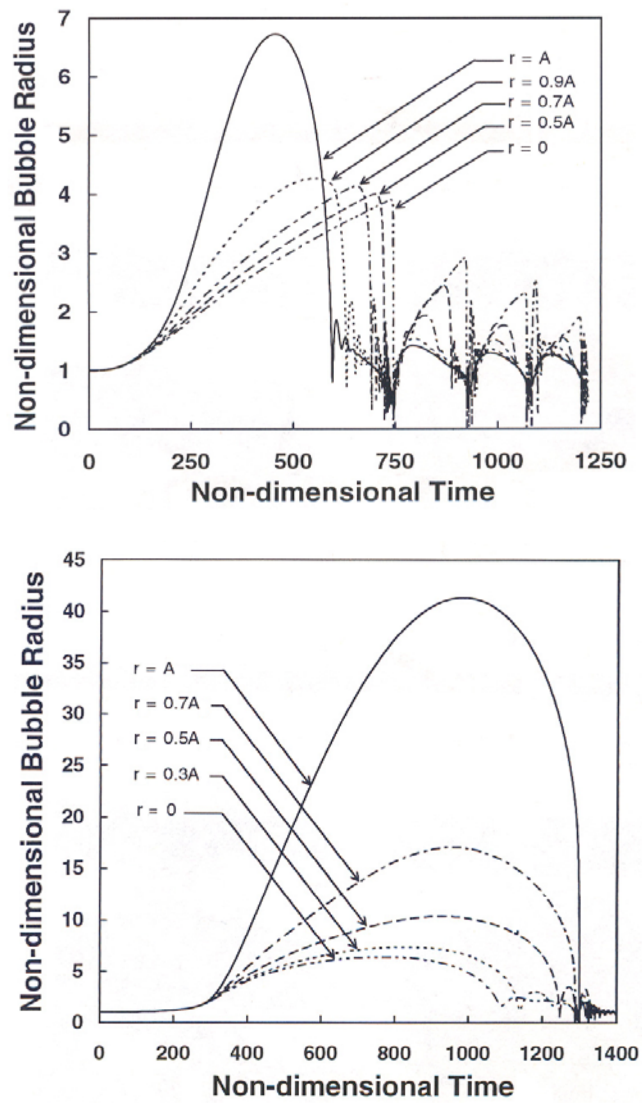

Figure 5. Typical time histories of the bubble size at six different Lagrangian positions in a spherical cloud in response to an episode of reduced pressure in the surrounding liquid (between t=0 and t=250). The upper figure is for the parameter β much greater than unity while the lower is for β order unity or less [13,14].

While real bubble clouds are often far from spherical the potential for similar shielding effects still clearly exist and below we will describe some experimental observations of shocks in collapsing bubble clouds.

EXPERIMENTAL OBSERVATIONS

Past Observations

The highly destructive consequences of cloud cavitation have been known for a long time and have been documented, for example, by Knapp [21], Bark and van Berlekom [22] and Soyama et al. [23]. The generation of these cavitation clouds may occur naturally as a result of the shedding of bubble-filled vortices, or it may be the response to a periodic disturbance imposed on the flow. Common examples of imposed fluctuations are the interaction between rotor and stator blades in a pump or turbine, the interaction between a ship's propeller and the non-uniform wake created by the hull and the periodic opening and closing of a heart valve. As a result numerous investigators (for example, Wade and Acosta [24], Bark and van Berlekom [22], Shen and Peterson [25,26], Bark [27], Franc and Michel [28], Hart et al. [29], Kubota et al. [30], Le et al. [31], de Lange et al. [32]) have studied the complicated flow patterns involved in the production and collapse of cloud cavitation, most of them examining a single hydrofoil. The radiated noise produced is characterized by pressure pulses of very short duration and large magnitude. These pressure pulses have been measured by Bark [27], Bark and van Berlekom [22], Le et al. [31], Shen and Peterson [25,26] and McKenney and Brennen [33].

Experimental observations using an oscillating hydrofoil

We describe here some experimental observations of Reisman et al. [15] who deployed an oscillating hydrofoil in a water tunnel to produce regular clouds of cavitation whose behavior could then be observed and measured. Several finite span hydrofoils with a rectangular planform were reflection-plane mounted in the floor of a water tunnel test section and, as described in Reisman et al. [15], were driven in an oscillatory pitching motion with frequencies up to 50Hz and incidence angle amplitudes of the order of 5-10 degrees. One of the hydrofoils was equipped with flush-mounted surface pressure transducers and additional dynamic transducers were located on the nearby tunnel walls. High speed motion pictures (taken at 500fps) allowed examination of the processes of formation, growth and collapse of a cloud of cavitation bubbles during each cycle of the hydrofoil oscillation.

The *global* cloud collapse occurring each cycle is illustrated by the four succesive movie frames included in figure 6. The collapse occurs between frames (b) and (c) and was accompanied by a large pressure pulse or *bang* that reverberated throughout the laboratory. The pulses are characterized by very large amplitude pressure pulses with magnitudes of the order of tens of atmospheres and typical durations of the order of tenths of milliseconds. The magnitude of the pulses measured some distance from the foil by a transducer in the tunnel floor was on the order of one atmosphere. Note that the collapse results in only a slight change in the cloud radius but a large change in the void fraction magnitude and distribution inside the cloud, an observation that is consistent with the previously described calculations of Wang and Brennen.

Reisman et al. [15] correlated the movies with the transducer pressure measurements and found that the pressure pulses recorded (both on the foil surface and in the far field) were clearly associated with specific structures (more precisely, the dynamics of specific structures) which are visible in the movies. This investigation revealed the following relationships between the pulses and specific flow structures. In particular, two different types of pressure pulse were identified. One set recorded almost simultaneously by all the transducers were, as previously described, associated with the *global* collapse of an identifiable, seperated cloud as illustrated in figure 6. These are therefore referred to as *global* pulses. But, unexpectedly, two other types of pulses and structures were also identified. Typically, these pulses were recorded by only one (perhaps two) foil surface transducers and were randomly distributed in time and space during the presence of a bubbly cavitation cloud. They were not repeated from cycle to cycle. They are referred to as *local* pulses. While these local events were smaller and therefore produced less radiated noise, the pressure pulse magnitudes recorded by the foil surface transducers were almost as large as those produced by global events.

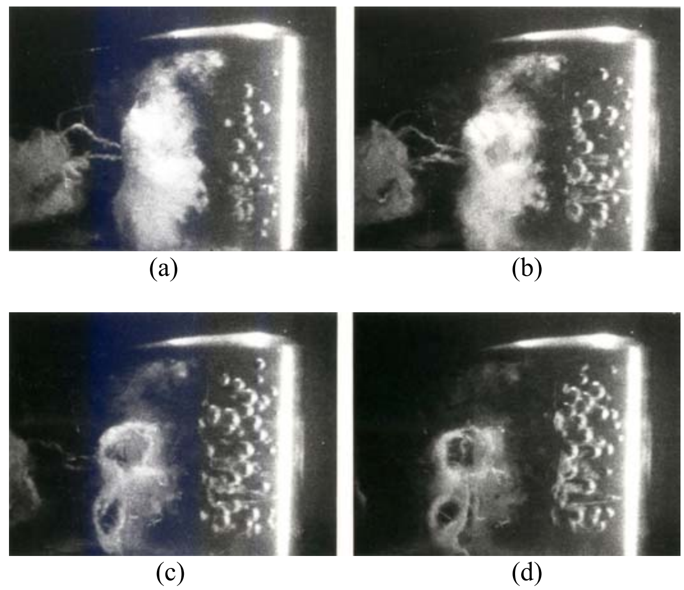

Figure 6. Four consecutive high speed movie frames (2ms apart) of the global collapse of a cloud of cavitation bubbles on the suction surface of a hydrofoil. The flow is from right to left. The global cloud collapse occurs between frames (b) and (c). From Reisman et al. [15].

Correlation of the high-speed movies with the transducer output revealed that local pulses occurred when one of two particular types of flow structure passed over the face of a transducer. The two types of structures will be referred to as *crescent-shaped regions* and *leading edge structures*; both occur during the less coherent collapse of clouds. Crescent-shaped regions are illustrated in photographs (a) through (c) of figure 7 and careful correlation revealed that the passage of one of these over an individual transducer produced a large local pulse in the output of that transducer. A crescent-shaped region has a low void fraction and, consequently, must involve a substantial compression pulse at its leading edge. These crescent-shaped regions appear randomly and ephemerally in the bubbly mixture. A close look at photograph (c) shows how complicated these flow structures can be since this crescent-shaped region appears to have some internal structure. Photographs (b) and (c) show that more than one crescent-shaped structure can be present at any moment in time.

In addition, the movie and pressure data consistently displayed a local pulse when the upstream boundary, or leading edge, of the detached bubbly mixture passed over a transducer. This second type of local flow structure is illustrated in photograph (d) of figure 7 and also produces a local pulse. These *leading edge structures* are created when the mixture detaches from the foil; they propagate downstream faster than the mixture velocity.

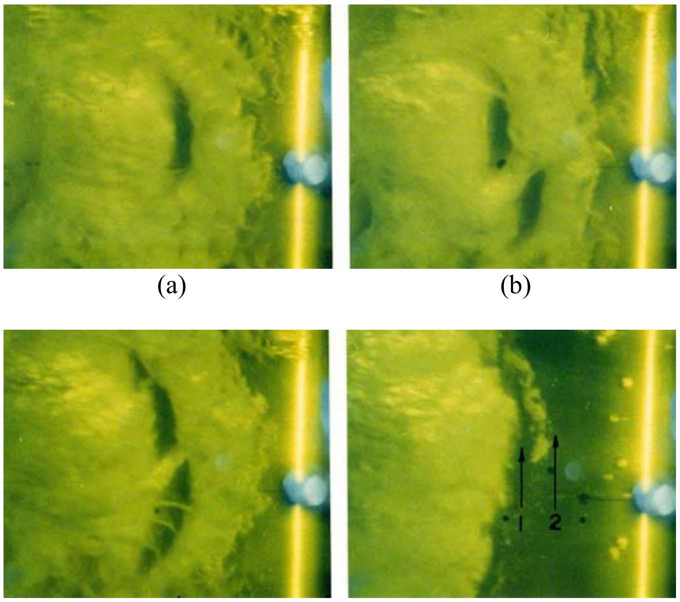

Figure 7. Local pulse structures in the cavitation on the suction surface of a cavitating foil. The flow is from right to left. Crescent-shaped structures are seen in (a), (b), and (c) and a leading edge event with two collapses is shown in photograph (d). From Reisman et al. [15].

Parenthetically, we note that injection of air into the cavitation on the suction surface can substantially reduce the magnitude of the pressure pulses produced (Ukon [34], Arndt et al. [35], Reisman et al. [36]). However Reisman et al. [36] have shown that the bubbly shock wave structures still occur; but with the additional air content in the bubbles, the magnitude of the pressure pulses is substantially reduced. Finally we note that pulses like those measured on the surface of the hydrofoil with typical magnitudes as large as 10 bar and durations of the order of 10^{-4}s are certainly sufficient to explain the enhanced noise and cavitation damage associated with cloud cavitation.

SOME OBSERVATIONS IN A CENTRIFUGAL PUMP

The author was asked to investigate a particular case of a centrifugal wastewater pump that was exhibiting substantial vibration levels at the higher run speeds and, in the course of this investigation, gathered significant vibration data that suggests substantial cloud cavitation involvement (at higher speeds) due to interaction between the impeller vanes and the volute cutwater.

The pump was a vertical-axis, variable-speed, single volute pump with a 13.81in diameter, three-vaned impeller designed to run at speeds up to about 700rpm. The design included a suction line with a 90 degree elbow immediately upstream of the pump suction. The pump was intended for operation at a flow coefficient (based on impeller discharge flow area and tip speed) of 0.079 and a head coefficient of 0.425. Under these maximum speed conditions the available NPSH meant a suction specific speed of about 5860. As could have been anticipated, this suction specific speed meant that the pump cavitated but that the limited cavitation did not produce significant cavitation head loss. Measurements confirmed this lack of significant cavitation head loss. However, the vibration levels were much greater than expected and exhibited the following characteristics.

The pump(s) were instrumented with high fidelity accelerometers on the bearing housing just above the pump and both static and dynamic pressure transducers on the pump suction and discharge. Data was obtained for a range of speeds from 420rpm to about 680rpm, all at roughly the same NPSH. (Data was also taken with the injection of air at the suction flange, in one (vain) effort to reduce the vibration level substantially.) Though no cavitation head loss occurred, the vibration changed substantially in amplitude and character as the speed was increased so that the overall vibration level exceeded the ISO 10816 satisfactory vibration limit of 0.177ips-rms for all speeds above about 550rpm. We focus here on those vibration characteristics and the associated pressure oscillations. It should also be noted that the noise level varied somewhat over time since cavitation is dependent on the debris in the wastewater and this drifted up and down with time during the tests. During all tests the author monitored the pump noise at various points on the pump volute, suction and discharge lines using a mechanics stethoscope. The following observations were made:

- At low speeds (below 540 rpm) the cavitation noise was minor and relatively constant and continuous, a high frequency hissing sound superimposed on the mechanical noise. Its magnitude, both in absolute terms and relative to the mechanical noise, increased significantly with speed within this low speed range. This noise was always substantially attenuated with a small air injection rate of 0.1scfm and some further reduction occurred at higher air flow rates.
- At higher speeds (greater than 540 rpm), a different and much more violent noise began to dominate. This noise began as a *crackling* and transitioned into a severe *banging* as the speed increased. It had a dominant blade passage frequency component at three times the rotational frequency. Low levels of air injection (0.1 to 0.5scfm) caused some minor muting of this low frequency banging. Further reduction occurred with increasing air injection (up to the maximum tested namely 10scfm) but the benefits become less and less and the level of the banging noise seemed to asymptote to a level independent of the air injection rate.
- Two different (but single) injection locations were tested but the differences were minor.

It should be noted that there is documentation in the literature which indicates that cavitation noise level (usually defined at the high frequency hissing noise) can be utilized as an approximate, qualitative measure of the rate of cavitation damage within a particular pump. As far as the author is aware these studies pertain to pumps that do not manifest the extreme banging noise generated in these tests.

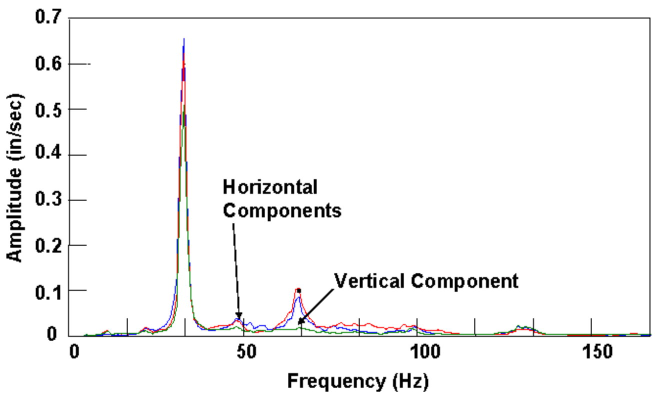

Figure 8. Accelerometer spectra for three different directions at 655rpm.

In the higher speed range typical vibration spectra from the accelerometers (for each of the three directions) is shown in figure 8. The dominant contribution to the vibration is at the fundamental vane passing frequency (or three times the rotational frequency, 3/rev for short) with an additional notable peak at twice the vane passing frequency (6/rev for short). The magnitude of the 3/rev peak increased fairly monotonically with speed as shown in figure 9.

The spectra from the pressure transducers contained similar components though the peaks at 6/rev were often larger than those at the fundamental 3/rev frequency as exemplified by the discharge pressure spectra shown in figure 10. This strongly suggests a highly non-linear vane/cutwater interaction consisting of a short pulse with each interaction that yields stronger higher harmonics in the pressure pulsations and thus a larger 6/rev peak. However, higher frequencies will be more highly attenuated as the oscillations are transmitted through the structure to the accelerometers and consequently the 6/rev frequency is not so dominant in the accelerometer spectra. This is consistent with the rapid collapse of a cavitation cloud following each vane/cutwater interaction.

Finally we summarize the effects of injecting air into the flow at one point around the suction flange. In the lower speed range (less than 550rpm) a small amount of air injection (less than 1scfm) produced a modest decrease of the order of 15% in the overall vibration level mostly by decreasing the high frequency *hissing* noise. Larger air injection rates generated little additional benefit. In the higher speed range (above 600rpm) the effect of air injection was still measurable but the effect on the *banging* was very modest. An average 14% decrease in the overall vibration was produced by air injection rates up to 10scfm. However, the resulting vibration with any amount of air injection was still greater than the ISO 10816 vibration limit.

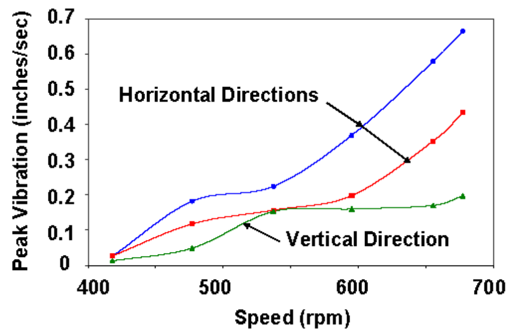

Figure 9. The magnitude of the accelerometer signal component vane passing frequency peak as a function of speed.

The main effect of air injection was to change the spectra of the oscillations rather than the magnitude. Figure 10 illustrates the dramatic change in the discharge pressure spectra that occurs between air injection rates of zero and 10scfm.

When the air injection rate is increased beyond about 1scfm, for example to the 10scfm level of lower plot in figure 10, the 6/rev pressure oscillation is essentially eliminated and even the 3/rev component is reduced.

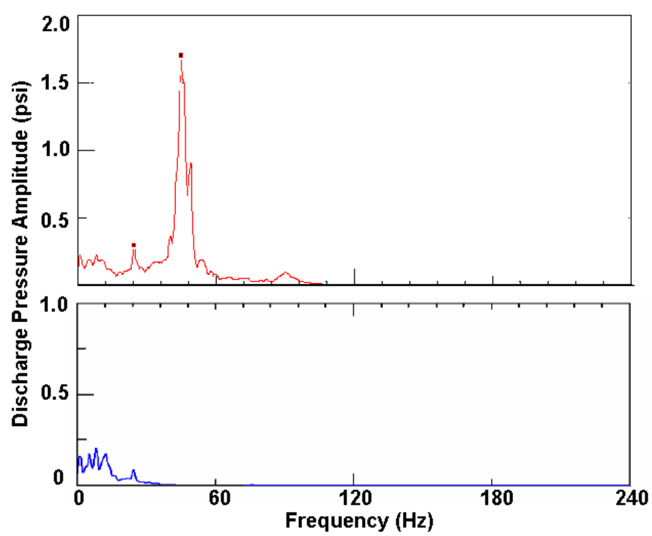

Figure 10. Typical discharge pressure spectra at 677rpm and at two air injection flows, zero (upper graph) and 10scfm (lower graph).

Further illustration of these effects is provided in figure 11 which plots the change in the magnitudes of the 3/rev and 6/rev peaks as the air injection rate is increased. Note that at air injection rates less than 1scfm, there is essentially no change in the amplitudes. Between 1scfm and 3scfm, there is a substantial decrease in both components. As illustrated in figure 10, the 3/rev and 6/rev peaks are largely replaced by a group of lower frequencies clustered around the rotation frequency and with amplitudes higher than in the absence of air injection. These correspond to the low-frequency ``banging'' described earlier. This is consistent with bubble clouds that have a higher bubble density, a higher void fraction and/or lower frequency bubbles containing more

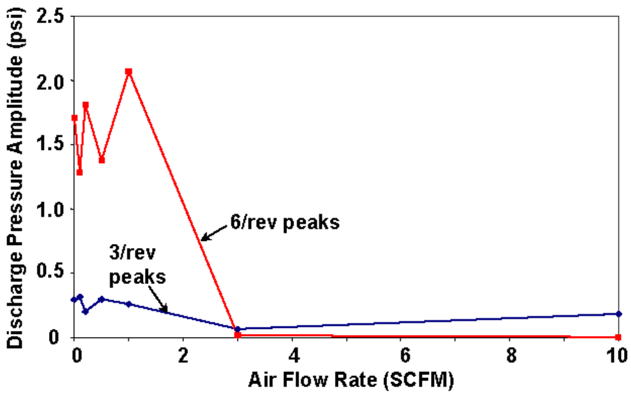

Figure 11. Discharge pressure components as a function of air injection at 677rpm.

While the evidence is not completely conclusive, all of the above features of the excessive vibration in this pump are consistent with the periodic formation and collapse of a cavitation cloud at each impeller vane/cutwater encounter. It seems likely that this interaction is amplified by the small number of vanes and a flow incidence mismatch at the volute cutwater. An attempt to ameliorate the vibration by injection of air was largely unsuccessful but produced a significant downshift in the dominant frequencies that would be consistent with clouds with a larger void fraction and bubbles and clouds with lower resonant frequencies.

CONCLUDING COMMENTS

In this paper we have summarized some of the recent advances in our understanding of bubbly cloud cavitation. It has become clear that effects due to the interaction between bubbles may be crucially important especially when they give rise to the phenomenon called cloud cavitation. Calculations of the growth and collapse of a spherical cloud of cavitating bubbles show that when the cloud interaction parameter β is large enough, collapse occurs first on the surface of the cloud. As was anticipated by the work of Morch, Kedrinskii and Hanson (Morch [9,10,11] and Hanson et al. [12]), the inward propagating collapse front becomes a bubbly shock wave which grows in magnitude due to geometric focussing. Very large pressures and radiated impulses occur when this shock wave reaches the center of the cloud.

Of course, actual clouds are far from spherical. And, even in a homogeneous medium, gasdynamic shock focussing can be quite complex and involve significant non-linear effects (see, for example, Sturtevant and Kulkarny [37]). Nevertheless, it seems evident that once collapse is initiated on the surface of a cloud, the propagating shock will focus and produce large local pressure pulses and radiated acoustic pulses. It is not, however, clear exactly what form the foci might take in the highly non-uniform, three-dimensional bubbly environment of a cavitation cloud, for example, in a pump.

Experiments with hydrofoils experiencing cloud cavitation have shown that very large pressure pulses occur within the cloud and are radiated away during the collapse process. Within the cloud, these pulses can have magnitudes as large as 10 bar and durations of the order of 10^{-4}s. This suggests a new perspective on cavitation damage and noise in flows that involve large collections of cavitation bubbles with a sufficiently large void fraction (or, more specifically, a large enough β) so that the bubbles interact and collapse coherently. This view maintains that the cavitation noise and damage is generated by the formation and propagation of bubbly shock waves within the collapsing cloud. The experiments reveal several specific shock wave structures.

The phenomena described are expected to be important features in a wide range of cavitating flows. However, the analytical results clearly suggest that the phenomena may depend strongly on the cloud interaction parameter, β. If this is the case, some very important scaling effects may occur. It is relatively easy to envision a situation in which the β value for some small scale model experiments is too small for cloud effects to be important but in which the prototype would be operating at a much larger β due to the larger cloud size (assuming the void fractions and bubble sizes are comparable). Under these circumstances, the model would not manifest the large cloud cavitation effects which could occur in the prototype.

It is also the case that experimental observations of cloud cavitation in pumps are very limited though Soyama et al. [23] conducted a valuable experiment that demonstrated the existence and importance of the phenomenon in a centrifugal pump. In this paper we have added some different and detailed observations of what we believe is a similar phenomenon in a wastewater pump and have identified some key vibration characteristics that might help the diagnosis in other applications.

In conclusion, these recent investigations provide new insights into the dynamics and acoustics both of individual cavitation bubbles and of clouds of bubbles. These insights allow tentative identification of the phenomenon in other practical contexts. The insights also suggest new ways of modifying and possibly ameliorating cavitation noise and damage.

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