1997 ASME Fluids Engineering Division Summer Meeting
FEDSM'97
June 22-26, 1997

FEDSM97-3249

EFFECT OF AIR INJECTION ON THE CLOUD CAVITATION OF A HYDROFOIL

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ABSTRACT

This paper describes experiments investigating the effects of air injection on the cloud cavitation of an oscillating hydrofoil. The effects of continuous air injection were investigated using two different hydrofoils. Measurements of the acoustic pressure were made on the downstream test section floor and on the surface of one of the hydrofoils, and the extent of noise reduction provided by air injection at various volume flow rates was determined. The acoustic surface pressure measurements were also correlated with visual observations made using high speed motion pictures of the cloud cavitation. Thus the effects of continuous air injection on specific cavitation structures could be identified. In addition, the effectiveness of pulsed air injection in achieving greater reductions in cavitation noise at volume flow rates equal to those used in continuous air injection experiments was investigated.

NOMENCLATURE

c	Chord of hydrofoil
k	Reduced frequency, $\omega c/2U$
p_∞	Upstream pressure
p_a	Radiated acoustic pressure
p_t	Threshold radiated acoustic pressure
p_v	Vapor pressure
Q	Volume flow rate of air injection
q	Dimensionless flow rate of air, Q/Ucs
s	Span of hydrofoil
T	Period of imposed oscillation
U	Upstream velocity
α_f	Angle of attack
$\overline{\alpha_f}$	Mean angle of attack
σ	Cavitation number, $(p_\infty - p_v)/\frac{1}{2}\rho U^2$
ω	Radian frequency of imposed oscillation

INTRODUCTION

The term "cloud cavitation" is used to refer to the process of coherent growth and collapse of clouds of cavitation bubbles. Its occurrence in flows around hydrofoils has been closely studied (Knapp 1955, Bark 1985, Bark and van Berlekom 1978, Le *et al.* 1993, Shen and Peterson 1978 and 1980, Kubota *et al.* 1989 and 1992, de Lange *et al.* 1994, Wade and Acosta 1966, Hart *et al.* 1990) because of the severe cavitation damage and enhanced radiated noise which can result from this form of cavitation. In recent experiments on hydrofoils, Reisman and Brennen (1997) have shown that very large pressure pulses occur within collapsing cavitation clouds and the radiation of these pulses produces the noise characteristic of cloud cavitation. Within the cloud, the pulses can have magnitudes larger than $10 bar$ and durations of the order of $10^{-4} s$. Reisman and Brennen showed that these pressure pulses are associated with bubbly shock waves which propagate through the cavitation. The existence of shock wave structures had earlier been anticipated by Mørch, Hanson, and Kedrinskii (Mørch 1980, 1981, 1982 and Hanson *et al.* 1981) and had been demonstrated in a simple spherical geometry by the calculations of Wang and Brennen (1994, 1995, 1997).

Furthermore, the experiments of Reisman and Brennen revealed several specific shock wave structures within the cavitation. One of these is the mechanism by which the large coherent collapse of a finite cloud of bubbles occurs. This is called a *global* event or pulse. In addition, the investigation found more localized bubbly shock waves propagating within the cloud in several forms, as crescent-shaped regions and as leading edge structures. These are collectively termed *local* structures or pulses; they produce foil surface pulses within an order of magnitude of the global events and could therefore also contribute to cavitation damage. However, because they are more localized and do not reach a central focus, the radiated noise they produce is much smaller.

The presence of a non-condensable gas inside a single cavitation bubble reduces the rate of collapse and increases the minimum bubble volume (Brennen 1995). Thus one strategy for the mitigation of the destructive effects of cavitation is the deliberate injection of air to cushion the collapse, thereby reducing the noise and damage potential. Several previous investigations have explored this strategy. Ukon (1986) used air injection from the leading edge of a stationary hydrofoil and found a consistent reduction in cavitation noise in the frequency range $0.6kHz$ to $100kHz$. The maximum noise reduction achieved was about $20dB$. Arndt *et al.* (1993) performed similar air injection tests with a stationary foil and measured noise reduction factors between 3 and 5 in a range of frequencies of $10kHz$ to $30kHz$. Above a certain air flow rate no further noise reduction could be achieved.

Minimizing the volume of air injected by such a system is desirable, as it would improve the efficiency of the system, reduce any adverse effects on performance, and reduce the number of bubbles present in the wake. One strategy for the minimization of the air flow rate is to inject pulses of air, rather than a continuous stream.

The objective of the present study was to examine and quantify the effectiveness of air injection in the reduction of cloud cavitation noise, to identify the physical process responsible for the noise reduction, and to investigate the effectiveness of pulsed air injection.

EXPERIMENTAL APPARATUS

The experiments were conducted in the Low Turbulence Water Tunnel (LTWT) at Caltech, a closed-circuit facility with test section dimensions of $30.5cm \times 30.5cm \times 2.5m$ (Gates 1977). Two finite span hydrofoils with a rectangular planform, a chord of $15.2cm$ and a span of $17.5cm$, were reflection-plane mounted in the floor of the test section as described in Hart *et al.* (1990). The thinner foil had a NACA 64A309 section. The other was specially chosen to allow the installation of recess-mounted pressure transducers and had a modified NACA 0021 section with increased thickness between the mid-chord and the trailing edge. A $750w$ DC motor was connected to a four-bar linkage which oscillated the foil in pitch about an axis near the center of pressure, 38% of the chord from the leading edge. The mean angle of attack, the oscillation amplitude, and the oscillation frequency (up to $50Hz$) were adjustable. For the current experiments, the amplitude of oscillation was $5°$. An optical shaft encoder mounted to the DC motor provided a digital signal which was used to correlate the foil motion with acoustic measurements and high speed movies taken during the experiments.

The unsteady pressures generated by the cavitation on the hydrofoil were measured by several transducers. A PCB model HS113A21 piezo-electric pressure transducer (denoted by #F) with a bandwidth of $100kHz$ was mounted flush with the floor of the test section, $5cm$ downstream of the trailing edge of the foil. Four PCB model $105B02$ pressure transducers (bandwidth $50kHz$, face diameter about $3mm$) were recess-mounted inside the NACA 0021 foil at locations 26% of the span from the foil base and 30%, 50%, 70% and 90% of the chord from the leading edge. These surface transducers are respectively denoted by #1 through #4. High speed movies with a framing rate of $500fps$ were taken to assist in the interpretation of the pressure transducer signals (Reisman 1997, Reisman and Brennen 1997).

Cavitation superimposes large pulses on the pressure signals registered by the transducers. A good measure of the magnitude of these cavitation pulses is the acoustic impulse, I (Ceccio and Brennen 1991, Kuhn de Chizelle *et al.* 1995), defined as the area of the pulse between upward and downward threshold crossings, that is,

$$I = \int_{t_1}^{t_2} p_a(t)dt \tag{1}$$

where t_1 and t_2 are the threshold crossing times. The choice of the threshold level was investigated carefully as described by Reisman (1997). A threshold of $20kPa$ was used for transducer #F, while $200kPa$ was used for the foil surface transducers. The average acoustic impulses presented below were obtained by averaging the acoustic impulses computed for 40 separate foil oscillation cycles.

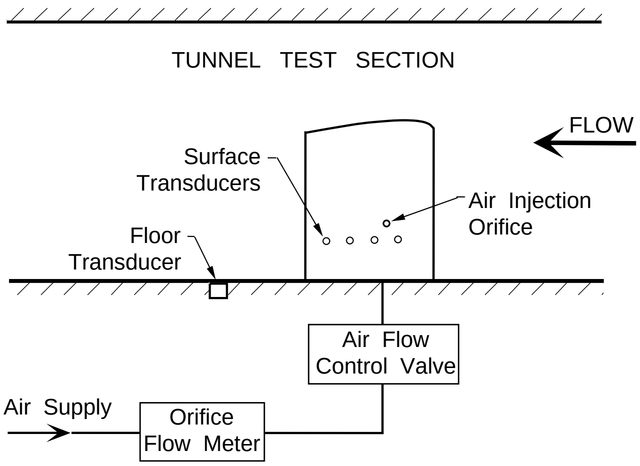

FIGURE 1: Sketch of the NACA 0021 foil and the air injection system.

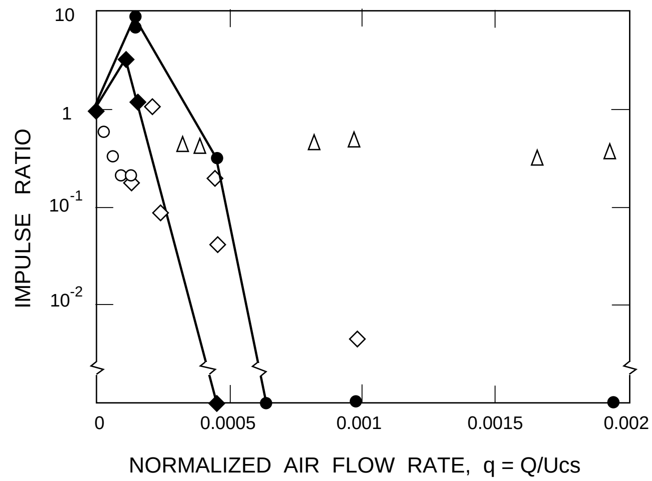

FIGURE 2: Effect of injected air on the radiated noise, normalized by the noise without air injection. Included are data for the NACA 64A309 experiments at $k = 0.8$, $\sigma = 1.2$, $\overline{\alpha_f} = 9°$, $U = 8m/s$, and an air content of $5-10ppm$ (◊); data for the NACA 0021 foil experiments at $k = 0.76$, $\sigma = 0.95$, $\overline{\alpha_f} = 5°$, $U = 8m/s$, and an air content of $6-10ppm$ (•); data from Ukon (1986) at $\sigma = 0.74$, $\alpha = 6.4°$, and $U = 8m/s$ (○); and data from Arndt *et al.* (1993) at $\sigma = 0.9$, $\alpha = 8°$ and $U = 15m/s$ and $17.5m/s$ (△). Some data for the NACA 0021 foil with pulsed air injection are also included (♦).

AIR INJECTION SYSTEM

Both the NACA 64A309 and NACA 0021 foils were equipped with ventilation holes to allow air to be ejected from the suction side of the foil. The NACA 64A309 foil had a $0.313in$ diameter central shaft drilled along the span at the axis of rotation. Four ventilation holes in the suction surface of the foil intersected this central shaft; these holes were $0.063in$ in diameter and were located at spanwise positions 15%, 36%, 58%, and 80% from the foil base. The number and size of these holes proved to be excessive since the asymptotic noise reduction limit flow rate was much lower than anticipated (see below).

The NACA 0021 foil had only a single, $0.125in$ diameter injection hole, located at a chordwise position 38% from the leading edge and a spanwise position 34% from the foil base. This was chosen to place the air injection near the spanwise location of cloud detachment and maximum sheet cavity thickness. The air supply to both foils flowed through a hole in the center of the support shaft as sketched in Fig. 1. The sizes of the air passages were selected to ensure that the choked flow rate would be substantially greater than the asymptotic noise reduction flow rate determined during preliminary tests. In order to perform experiments with both continuous and pulsed air injection, a solenoid valve (originally designed to be used as a fuel injector for a natural gas vehicle) was installed in the air supply line as close as possible to the foil. The objective here was to minimize the volume of air between the solenoid valve and the injection point in order to optimize the dynamic response of the air injection system. The valve itself had good frequency response up to $230Hz$. It was actuated by an electronic controller that utilized the output from the optical shaft encoder. The controller was designed to open and close the solenoid valve at pre-selected points during each foil oscillation cycle. Two adjustable thumbwheels allowed for selection of the delays between the time of maximum angle of attack of the foil and the times of the opening and closing of the solenoid valve.

The air flow rate was measured using a calibrated orifice flow meter (Reisman 1997) upstream of the solenoid valve. This was converted to a volume flow rate, Q, at the temperature and pressure in the test section of the water tunnel and then used to determine a non-dimensional air flow rate, $q = Q/Ucs$. Due to uncertainty in the measurement of the tunnel pressure, there was a $\pm 12\%$ uncertainty in the calculated values of q. Also, because of the compliance of the substantial air volume in the line between the orifice flow meter and the solenoid valve, the meter measured a steady air flow rate in both the continous and pulsed air injection experiments. Consequently, the values of q given for the pulsed air injection experiments correspond to the flow rates averaged over the entire period rather than the actual flow rate while the valve is open.

RESULTS FROM CONTINUOUS AIR INJECTION EXPERIMENTS

Air injection resulted in a dramatic reduction in the noise level during experiments conducted with the NACA 64A309 foil. At a sufficiently high air flow rate, the periodic "bangs" associated with cloud cavitation collapse could no longer be detected either by ear or by transducer. Figure 2 illustrates this noise reduction as a function of normalized air injection flow rate. The results of the current investigation are presented in the form of the ratio of average impulse at transducer #F at a given air flow rate to the average impulse without air injection. In the case of the results of Arndt *et al.* (1993) and of Ukon (1986), the ratio is the RMS acoustic pressure with air injection to that without air. In considering the comparison, it should be noted that the present experimental data showed a very strong correlation between the average impulse and the RMS acoustic pressure.

The experiments performed by Arndt *et al.* and Ukon utilized stationary hydrofoils. Although cavitation clouds can separate periodically from sheet cavitation on a stationary foil, the collapse usually lacks the intensity which results from an imposed periodicity. The result is a smaller ratio of cavitation noise to background noise than in the present oscillating foil experiments. Thus the current experiments provide greater potential for noise reduction. This may explain the smaller asymptotic noise reduction level in the data of Arndt *et al.*.

Indeed, our observations of the NACA 64A309 foil experiments indicate that the average impulse can be reduced by a factor greater than 200 at a dimensionless air flow rate, q, of approximately 0.001. At this flow rate, the pressure pulse magnitudes were reduced to less than the threshold pressure. Consequently, further increase in the air flow rate had no discernible effect on the noise.

The spectral content of the cavitation noise also changed with air injection. Figure 3 shows the average normalized Fourier spectra for three different air flow rates. As the air flow rate is increased, the Fourier magnitudes in the frequency range between $200Hz$ and $4kHz$ decrease relative to the high and low frequency content.

Continuous air injection experiments were also performed using the NACA 0021 foil and a similarly dramatic reduction in the cloud cavitation noise was observed. Figure 2 includes the data for the NACA 0021 foil with continuous air injection. The data for the two foils differ in several respects. Unexpectedly, at the lowest air injection rate, the average acoustic impulse for the NACA 0021 foil increased relative to the case without air injection. The increase in the noise could also be detected audibly. This effect was verified by repeating the experiment at $q = 1.6 \times 10^{-4}$ four times, with all four plotted in Fig. 2. The scatter is representative of the scatter observed at the other flow rates. After this initial increase, the average impulse fell off rapidly as the air injection flow rate was increased further. The noise reduction limit was reached at lower flow rates than with the NACA 64A309 foil; no pressure pulse exceeded the threshold of $20kPa$ at flow rates greater than $q = 5\times 10^{-4}$. This lower asymptotic flow rate is probably due to the fact that the air is more effectively used in the NACA 0021 foil experiments by being injected through a single hole close to the cloud formation region.

During these experiments, the pressure measurements obtained from transducer #F could have been influenced by the presence of a large number of air bubbles in the acoustic transmission path between the cavitating foil and the transducer. This possibility motivated a study of the acoustic attenuation in the LTWT test section during conditions typical of the present experiments (Reisman 1997). This study indicated that the total air content did not significantly affect the acoustic transmission within the cavitating region. This is consistent with the fact that the average impulses measured at $q = 1.6 \times 10^{-4}$ and $q = 0$ were quite repeatable despite the fact that the air content increased from $6.6ppm$ to $9.1ppm$ during the course of the experiments. It is also consistent with the fact that the magnitudes of the 40 acoustic impulses obtained during a single continuous air injection experiment showed no consistent change with running time.

SURFACE PRESSURE MEASUREMENTS

The recess-mounted transducers installed in the NACA 0021 foil provided a clear indication of the effect of air injection on the acoustic impulses measured on the foil surface. Figure 4 depicts the average impulses measured at the four different locations on the foil surface as a function of normalized air flow rate, q. Only the average impulses measured near the trailing edge show the initial increase for low air flow rate that was characteristic of the NACA 0021 foil floor transducer data (Fig. 2). The average surface impulses also display an asymptotic noise reduction at high air flow rates similar to that of the more distant floor transducer. The reduction in the average surface impulses is as high as two orders of magnitude at flow rates above $q = 7 \times 10^{-4}$.

PHOTOGRAPHIC OBSERVATIONS

Examination of still photographs of the cavitating NACA 64A309 foil revealed several effects of air injec-

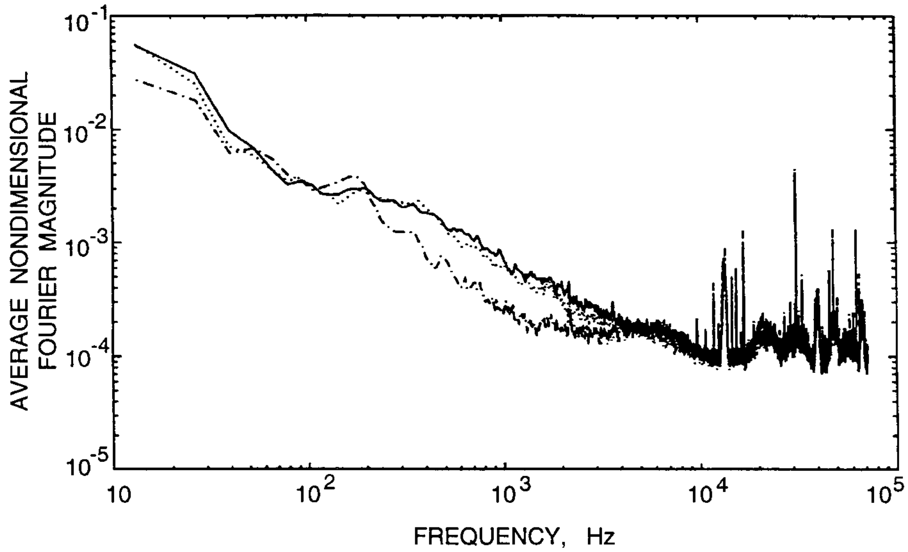

FIGURE 3: Effect of air injection on the spectral content of the noise for three normalized air flow rates. Data is from the NACA 64A309 foil with $k = 0.8$, $\sigma = 1.2$, $\overline{\alpha_f} = 9^\circ$, $U = 8m/s$, an air content of $7 - 10ppm$, $q = 1.3 \times 10^{-4}$ (—), $q = 2.4 \times 10^{-4}$ ($\cdots\cdot$), and $q = 9.8 \times 10^{-4}$ (— · — ·).

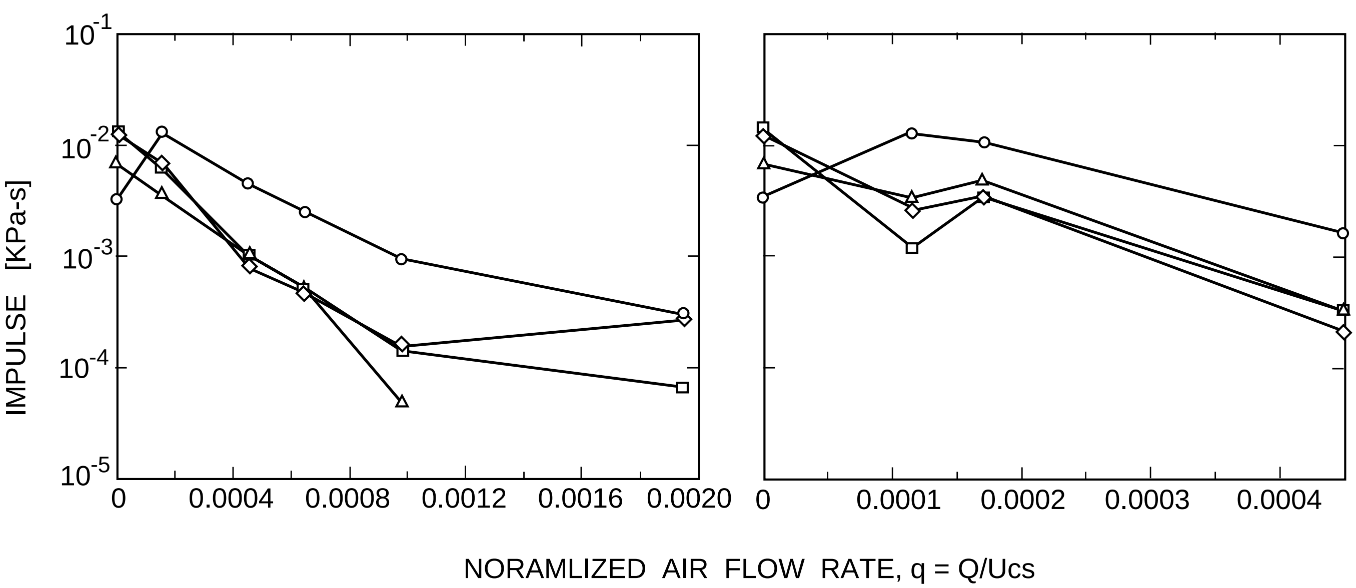

FIGURE 4: Average acoustic impulses measured at four different locations on the NACA 0021 foil surface as a function of normalized air flow rate, q. Data for transducer #1 (□), #2 (◊), #3 (△) and #4 (○) at $k = 0.76$, $\sigma = 0.95$, $U = 8m/s$ and an air content of $6 - 10ppm$. The data on the left is taken with continuous air injection, the data on the right with pulsed air injection. (Note that the range of air flow rates is larger in the left figure).

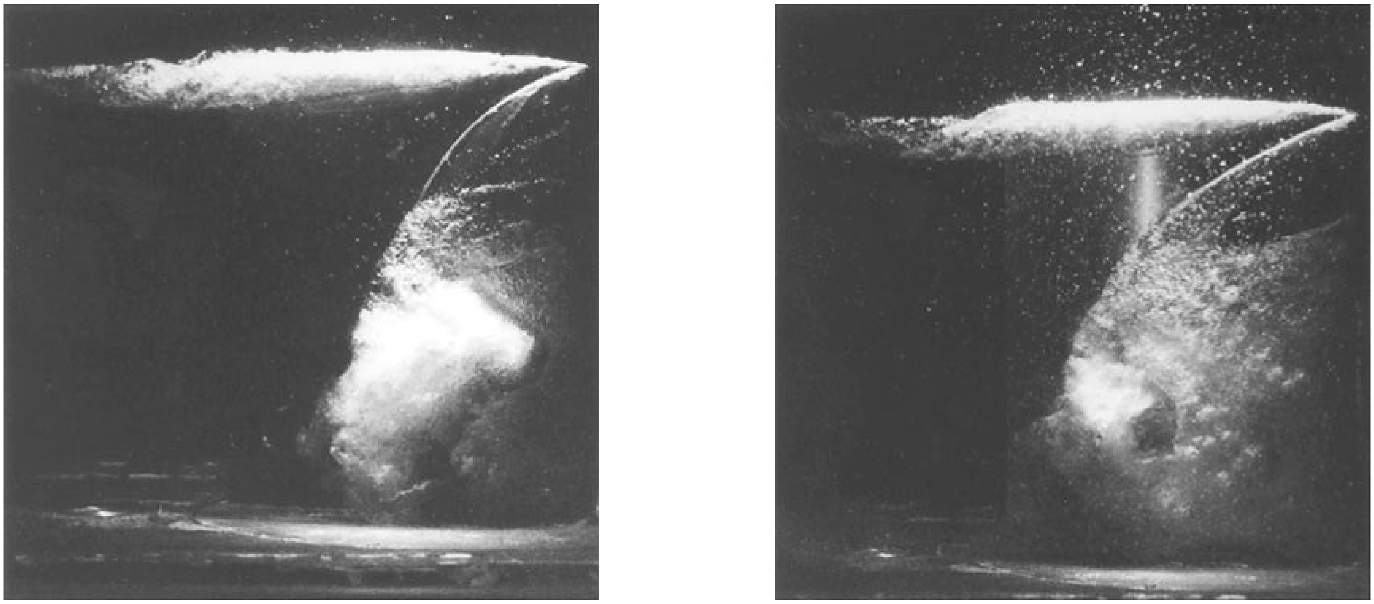

FIGURE 5: Visual effect of air injection on cloud cavitation. The photograph on the left is without air injection, the photograph on the right has a normalized air flow rate of $q = 4.5 \times 10^{-4}$. Both photographs are of the NACA 64A309 with $k = 0.8$, $\sigma = 1.2$, and $\alpha = 12.3^\circ$ (α decreasing).

tion on cavitation structure. One effect, previously noted by Ukon (1986), was an increase in the average size of the sheet cavity. Although the two photographs in Fig. 5 were taken at identical cavitation numbers (based on vapor pressure), reduced frequencies, and angles of attack, the cavity area is much larger in the air injection case. This effect is simply due to an increase in the mean pressure in the cavity and therefore a decrease in the effective cavitation number.

Other still photographs also show that the added air increases the size of the cloud generated when the sheet cavity collapses. This rules out the possibility that the noise reduction is due to suppression of the cloud cavitation. Instead, it seems probable that the bubbles in the cloud contain more air, which cushions their collapse and reduces the overall sound produced.

By examining the high speed motion pictures taken of both the NACA 64A309 and NACA 0021 hydrofoils during the continuous air injection experiments, further explanation for the reduction in cloud cavitation noise can be discerned. The injection of air at flow rates above the asymptotic noise reduction limit prevents the coherent global collapse of the cavitation cloud. The remains of the sheet cavitation, after detaching from the foil surface, persist as they are convected downstream. There is no rapid change in void fraction; rather, the cloud collapses gradually over a period of approximately $16ms$, an order of magnitude increase relative to the global collapse times observed with no air injection. Furthermore, there is no directional coherence to the collapse process. The void fraction decreases almost randomly within the large region in which there are bubbles. In contrast the flow without air injection formed a smaller cloud which collapsed much more coherently.

The films also show that the injection of air does not, however, preclude the occurrence of local events. Both crescent-shaped regions of low void fraction and leading edge structures are observed in the high speed movies of flows with air injection. Although these local structures are frequently seen in the movies, they seldom result in the production of impulsive pressures on the foil surface. In the few cases where impulsive pressures were generated by local events, the magnitudes of the pulses were significantly lower than those measured without air injection; indeed the magnitudes of the local pulses with air injection did not exceed $500kPa$. Conversely, when pressure pulses were detected by the foil surface transducers, they could always be connected with the visual observation of a local structure. This was also true in the experiments without air injection (Reisman and Brennen 1997).

Figure 6 includes selected frames from a high speed motion picture of air injection on the NACA 0021 hydrofoil with $k = 0.76$, $\sigma = 0.95$, $\overline{\alpha_f} = 5^\circ$, and $U = 8m/s$.

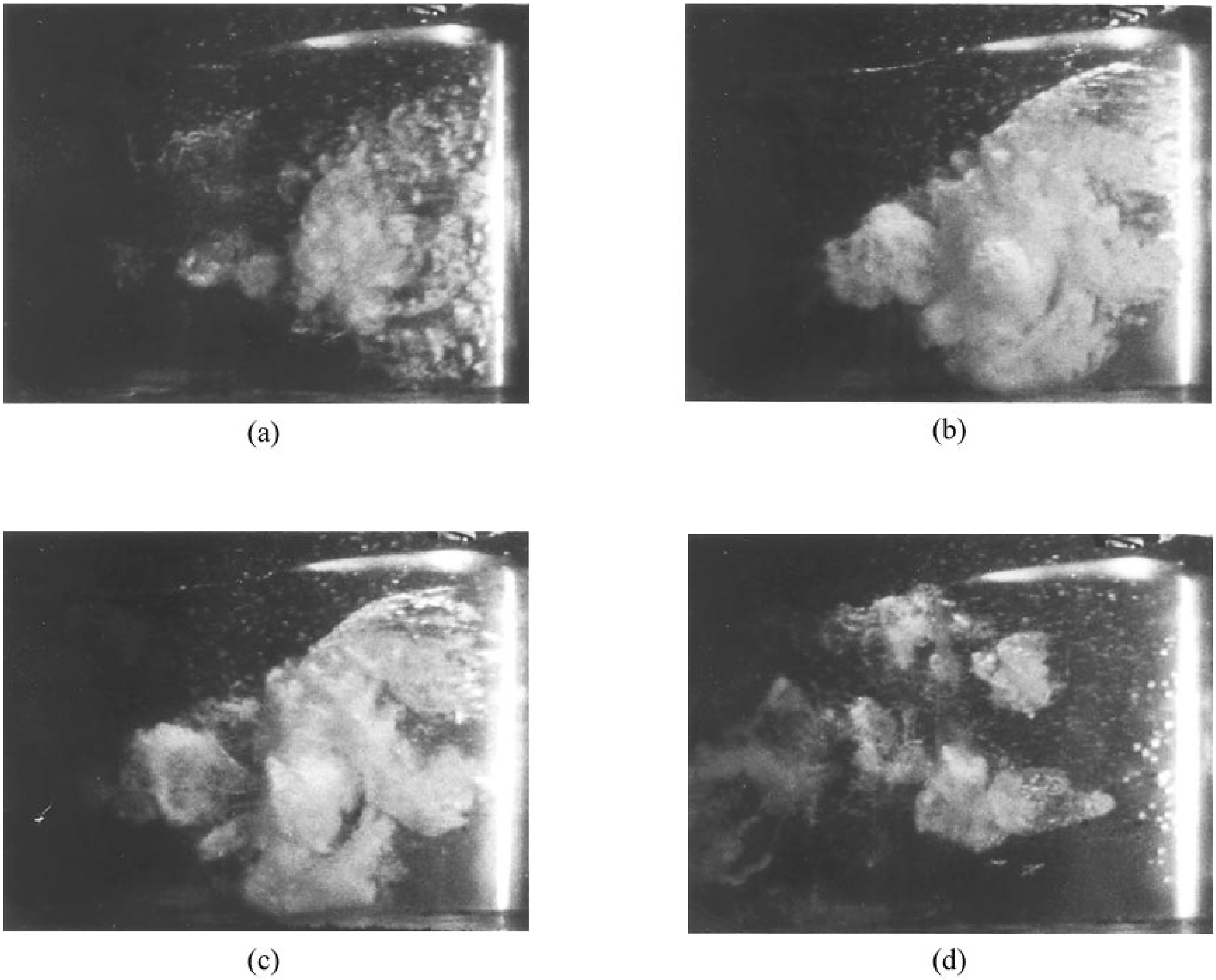

FIGURE 6: Cavitation structures observed during a single oscillation cycle with air injection. Selected frames from a high speed motion picture. Frames are successive but not necessarily consecutive. NACA 0021 foil oscillating at $k = 0.76$, $\sigma = 0.95$, $\overline{\alpha_f} = 5°$, and $U = 8m/s$.

The air flow rate here is significantly greater than the asymptotic noise reduction limit depicted in Fig. 2 and the simultaneous acoustic data displayed no impulses, either local or global, on any of the five transducers. In frame (a) of Fig. 6, the re-entrant jet has begun to penetrate the attached cavity which has already been broken up to some extent by the air injection, as is evident when this photograph is compared with similar photographs without air injection (Reisman and Brennen 1997). In frame (a), the jet has just reached the air injection point and, subsequently, only makes slow progress toward the leading edge of the foil.

The re-entrant jet is impeded by the air injection at this high flow rate and does not reach the leading edge of the foil. The air injection disturbs the vapor-liquid interface downstream of the injection point, and this disturbance appears to promote the formation of the re-entrant jet. Thus one possible explanation for the cessation of the jet motion prior to reaching the leading edge is that, since the jet formation is hastened by the air injection, the jet does not develop as much momentum as in the case without air injection. Another possible explanation is that the jet is deflected in a direction normal to the foil surface by the injection of air. This deflection could cause the jet to impact the vapor-liquid interface prior to reaching the leading edge. Either of these two scenarios would result in an effect similar to that observed by Kawanami *et al.* (1996) who placed obstacles on the suction side of a static hydrofoil to impede the motion of the re-entrant jet. The presence of these obstacles resulted in a broadband reduction in the cavitation noise spectra of between $5-20dB$ relative to the noise spectra generated without the obstacle.

Several leading edge and crescent-shaped regions are clearly evident in frames (b) and (c) of Fig. 6. Despite the presence of these structures, no local pulses are detected in the transducer data. Without air injection, pulses would almost always have been associated with these structures. Thus it appears that the injection of air does not suppress the formation of local shock wave structures but does substantially reduce the pressure pulses associated with them.

The presence of these shock structures without large amplitude pressure pulses is consistent with the observations of several previous investigators, such as Noordzij and van Wijngaarden (1974), who have performed shock wave experiments with mixtures consisting of a liquid and a non-condensable gas. The experiments of Kameda and Matsumoto (1995) show that a bubbly mixture of nitrogen in silicone oil only produced pressure pulses of about $100kPa$ in amplitude despite a rapid change in ambient pressure of over $100kPa$. Therefore, while it is clear that the air injection does not preclude the formation of the local shock structures, the lack of large pressure pulses is not inconsistent with the presence of these shocks when the bubbles contain large amounts of non-condensable gas.

Frame (d) of Fig. 6 illustrates the fragmentation of the detached bubbly mixture when air is injected. Unlike the coherent bubble cloud formation and collapse which occur in the absence of air injection (Reisman and Brennen 1997), the remains of the sheet cavity become a highly non-uniform bubbly mixture when air is injected. These fragmented bubble clouds persist as they are convected downstream into the regions of higher pressure. There is no rapid or coherent global collapse. In contrast, the sheet cavity remains persist even into the next cycle of oscillation.

RESULTS FROM PULSED AIR INJECTION EXPERIMENTS

Experiments were also performed to study the effectiveness of pulsed air injection. By trial and error, it was determined that optimal injection initiation and termination times existed for any particular operating condition. The maximum reduction in the cloud cavitation noise was achieved by initiating the injection just prior to the time at which the downstream end of the sheet cavity passes the air injection hole. Furthermore, an injection duration of roughly 30% of the foil oscillation period resulted in the maximum noise reduction; decreasing the duration below $0.3T$ resulted in an increase in the noise level. Therefore, for all of the pulsed air injection experiments, the valve controller was set to initiate and terminate the air injection in this manner.

The average impulses measured with transducer #F during pulsed air injection are included in Fig. 2 and demonstrate that in comparison to the continuous air injection case, a smaller average impulse occurred when the volume of air injected was concentrated in the chosen, optimal time interval. Because of this greater efficiency, pulsed air injection also reached the asymptotic limit at a lower flow rate than continuous injection.

Figure 4 shows the average surface impulse data for the pulsed air injection experiments. It is interesting to note that the initial increase in the average impulse at low air flow rates also occurred in the pulsed injection data, especially for transducer #4; this increase is similar to that observed in the data measured by transducer #F (see Fig. 2). As with the radiated noise measured by transducer #F, this data shows that greater reduction in the average surface impulses can be achieved by concentrating the air injection in the chosen, optimal time interval.

SUMMARY

Reisman and Brennen (1997) recently showed that propagating bubbly shock waves play an important part in the dynamics and acoustics of cavitating flows such as occur on a hydrofoil. The present study focuses on the effects that the injection of air can have on these phenomena and, in particular, the effect it has on reducing the magnitudes of the large impulsive surface pressures and radiated acoustic pulses which are associated with these shock waves. Air was injected into the suction side of two cavitating hydrofoils of different cross-sections, and measurements of both surface and radiated pressures were made over a range of flow conditions. High speed movies of the cavitation were also made in order to correlate the measured surface pressures with specific structures observed within the cavitation.

Air injection was found to produce a reduction in the cloud cavitation noise (above a certain threshold) by two orders of magnitude. This level of reduction in the average acoustic impulse was found in both the foil surface pressures and the radiated pressures. Quantitative comparisons with the results of other investigators are complicated by the different levels of background noise (which place a limit of the possible reduction). However, it does appear as though the reductions achieved in the current experiments are greater than those achieved by Arndt *et al.* (1993) and Ukon (1986). This is probably due to the fact that the present experiments with oscillating foils produced a more coherent cloud cavitation collapse than in the stationary foil experiments of those earlier investigators. This resulted in larger ratios of signal to background noise and therefore greater potential for cavitation noise suppression.

One curious result was the small increase in noise which small air injection rates produced with one of the hydrofoils, namely the thicker one. This increase was very repeatable, was audible in the laboratory, and occurred over a wide range of flow conditions. It also occured with both continuous and pulsed air injection.

An explanation for the reduction in noise level due to air injection is provided by an analysis of the high speed motion pictures taken during the air injection experiments. The large amount of non-condensable gas prevents any rapid or coherent collapse process. The remains of the sheet cavity are fragmented into several bubbly structures that lack the coherence of the clouds observed without air injection. These fragments persist as they are convected downstream into regions of higher pressure. Despite the lack of global events, the *local* structures described by Reisman and Brennen (1997) are still observed during air injection. However, the impulsive pressures associated with these local pulses are substantially smaller than without air injection and often fall below detectable levels.

The injection of air also appears to impede the progress of the re-entrant jet. Kawanami *et al.* (1996) observed that when obstacles were placed on the suction surface of a cavitating hydrofoil, these impeded the progress of the re-entrant jet and thereby reduced the coherence and magnitude of the cloud cavitation pulses. Perhaps the air injection jet has a similar effect in the present experiments.

Experiments were also conducted with pulsed air injection. With a judicious choice of the injection period, greater noise suppression could be achieved by injecting the same volume of air during only part of the oscillation cycle. However, in all cases, air injection rates above a certain level produced no further reduction in the sound after it had been reduced to the background level.

ACKNOWLEDGEMENTS

This research program was supported by the Office of Naval Research under grant number N00014-91-J-1295. The authors also greatly appreciate the advice and encouragement of Professor Allan Acosta and the help of Roberto Zenit, Don Kwak and Amir Alagheband.

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