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EXPERIMENTAL INVESTIGATION OF AN INSTABILITY ON A CAVITATING PROPELLER

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ABSTRACT

This paper presents results from experiments investigating an instability observed on a cavitating propeller. Preliminary visual observations were made of the attached cavities on the blades of the propeller, and particular note was made of similarities between the behavior of the re-entrant jets and that found recently by Laberteaux and Ceccio (1998). It was also noted that the nature of the instability is closely related to the partial cavity instability observed on single, two-dimensional foils. (Knapp, 1955; Wade and Acosta, 1966; Brennen, 1994,95).

The flow conditions (cavitation number and advance ratio) under which the instability occurs were mapped and it is shown that the onset corresponds to a specific configuration of attached cavity lengths on the propeller. Pressure measurements were obtained from two different locations within the experimental facility, and the acoustic signature of the instability is identified. A simple model based on cavity volume estimates obtained from high speed video footage is developed, and the predictions of the model are compared with the experimentally obtained pressures.

NOMENCLATURE

- c Chord of the hydrofoil
- f Frequency (Hz)
- J Advance ratio, $U\pi/\Omega R$
- J_o Design advance ratio
- ℓ Cavity length
- p_v Vapor pressure
- p_∞ Upstream fluid pressure
- R Propeller blade tip radius
- U Upstream fluid velocity
- V_c Volume of the cavity
- α Angle of attack
- ρ Liquid density
- σ Cavitation number, $(p_\infty - p_v)/\frac{1}{2}\rho U^2$
- σ^* Propeller tip cavitation number, $(p_\infty - p_v)/\frac{1}{2}\rho\Omega^2 R^2$
- τ Fractional time during period
- Ω Propeller rotational frequency (rad/s)

INTRODUCTION

A great deal of research, both experimental (Shen and Peterson, 1978; Bark and van Berlekom, 1978; Franc and Michel, 1988; Kubota *et al.*, 1989; Hart *et al.*, 1990; McKenney and Brennen, 1994; Reisman *et al.*, 1998), and theoretical (van Wijngaarden, 1964; d'Agostino and Brennen, 1983; Reisman *et al.*, 1998) has demonstrated the important role played by unsteady cavitation in the generation of cavitation noise and damage. Most often, the flow explored by these researchers is that past a two dimensional hydrofoil. However, some recent work (Jessup, 1997; Laberteaux and Ceccio, 1998) has investigated three dimensional swept hydrofoils and identified some important three dimensional phenomena.

In this paper, an attempt is made to utilize many of the concepts garnered from this previous research to describe and explain a previously unobserved instability occuring on a cavitating propeller. The experimental setup used in this investigation

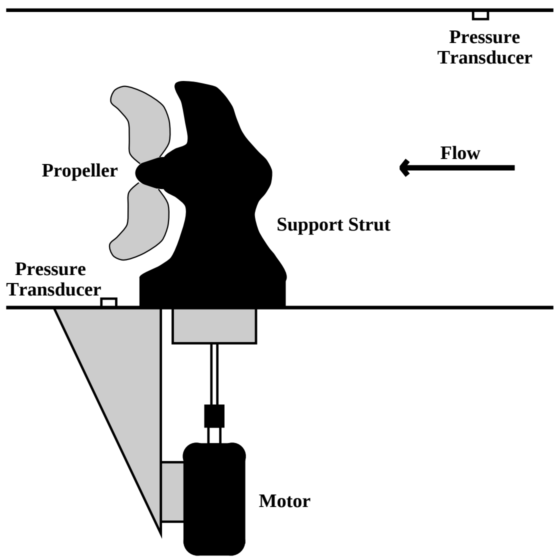

Figure 1. Schematic of the propeller installation and pressure transducer locations in the water tunnel.

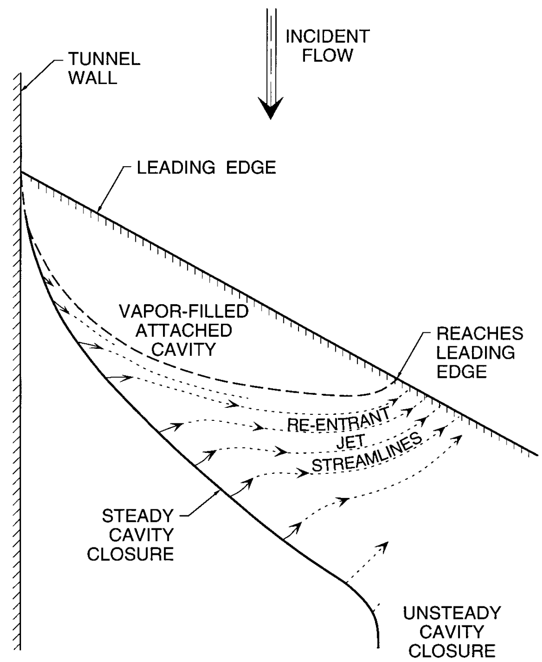

Figure 2. Sketch of the orientation and evolution of the re-entrant jet for the flow over a three dimensonal swept foil. Based on photographs in Laberteaux and Ceccio (1998).

consisted of a U.S. Navy model propeller, number 5236, with six blades, a diameter of about 19 *cm*, and a design advance ratio $J_o = 1.15$. The results presented in this paper were all obtained at rotating speeds between 1800 and 1850 *rpm*. As shown in Fig. 1, the propeller was attached to a supporting strut and drive mechanism developed by McKenney (1994), and installed in the Low Turbulence Water Tunnel at Caltech. Pressure transducers were mounted in both the floor and ceiling of the tunnel test section. The floor-mounted transducer was placed nearly directly underneath the propeller, while the ceiling-mounted transducer was placed approximately 40 *cm* upstream. (See Fig. 1.)

The propeller and supporting strut assembly can be rotated about their base, allowing the propeller to be mounted either upstream or downstream of the supporting strut. For reasons not understood, the instability was only observed when the propeller was located downstream and therefore in the wake of the supporting strut. When the instability did occur, it was characterized by a periodic oscillation in the extent of cavitation both on the propeller blades and in the tip vortices shed from the propeller blade tips. Furthermore, it occurred evenly and synchronously on all blades and at all rotational locations. The oscillation frequency was typically around 10 *Hz*, and did not show any significant variation with changes in propeller speed, cavitation number, or advance ratio.

CAVITATION STRUCTURE ON THREE-DIMENSIONAL FOILS

Preliminary visual observations of the cavitation occurring during the instability cycle showed similarities with recent work (Jessup, 1997; Laberteaux and Ceccio, 1998) investigating cavitation structures on three-dimensional, swept foils. A re-entrant jet was present for most of the instability cycle, and its behavior was observed to be strikingly similar to that reported by Laberteaux and Ceccio.

Figure 2 shows a diagram summarizing the cavitation and re-entrant jet structure noted by Laberteaux and Ceccio (1998). A fully developed cavity attached to the leading edge is encroached upon by a re-entrant jet emanating from the cavity closure region. As shown in the figure, the cavity closure line is not normal to the direction of incoming flow as would be the case with a two dimensional foil, but rather is swept as a result of the leading edge sweep. de Lange *et al.* (1994) note that the re-entrant jet is not directed upstream but instead at a “reflected angle” from the line of cavity closure. Downstream and outboard of the point where the re-entrant jet impinges upon the leading edge of the foil, very unsteady cavity closure is observed, in contrast to the clean and steady closure observed inboard of this point of impingement.

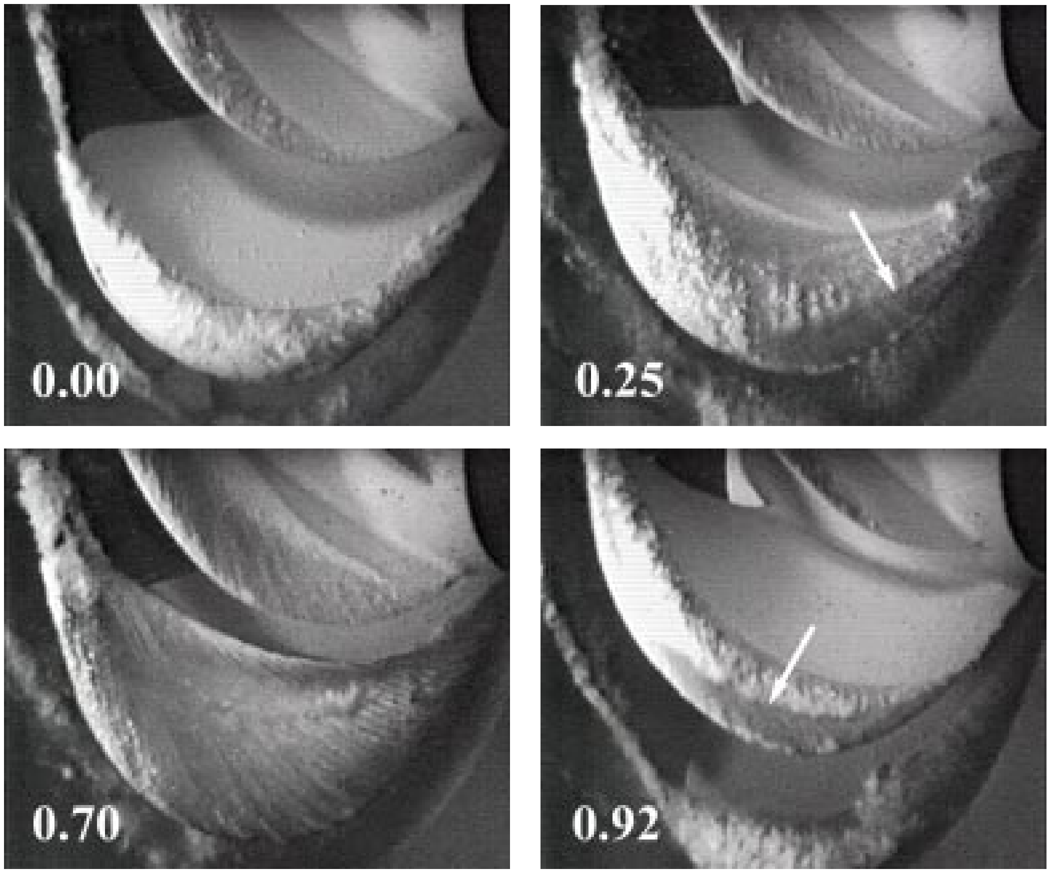

Figure 3. Sequence of frames taken from high speed video footage, showing selected events in the instability cycle. The number, τ, indicates the fraction of the instability cycle elapsed.

VISUAL OBSERVATIONS

Figure 3 shows selected frames from a high speed video of the instability on the cavitating propeller. The number in the lower left corner of each frame corresponds to the fraction, τ, of the instability cycle elapsed. Here, the origin of τ is chosen arbitrarily, and coincides with the minimal cavitation extent. This condition, shown in the first frame, is characterized by a relatively small region of frothy cavitation concentrated near the leading edge. The frothy nature of the cavitation is due to the fact that the re-entrant jet has filled the cavity over the entire span of the propeller blade.

Further into the cycle, at $\tau = 0.25$, the cavity has grown substantially. As it lengthens, the re-entrant jet is swept downstream; its position at $\tau = 0.25$ is indicated by the white arrow. The spanwise location at which the re-entrant jet reaches the leading edge of the propeller blade is easily seen, and, as was observed by Laberteaux and Ceccio (1998), the closure downstream and outboard (in this case above and to the left) of this location is very unsteady.

At approximately $\tau = 0.70$, the cavity reaches its maximum extent. At this stage, supercavitation is present near the tip of the propeller blades. As this cavitation is wrapped into the tip vortices it leads to a readily observed increase in the visibility of the vortices far downstream of the propeller. The attached cavities at this point in the cycle are essentially free of any signs of a re-entrant jet, presumably because the jet fluid has been entrained in the cavity closure region. By $\tau = 0.92$ the cavitation has begun to decrease in extent, receding towards the leading edge of the propeller blades as the re-entrant jet, once again indicated by the white arrow, rushes forward. Finally, the cavitation returns to the minimal configuration shown at $\tau = 0.00$.

PARTIAL CAVITY INSTABILITY

The preceding description of the instability cycle demonstrates that it is very similar to the partial cavity instability on single, two-dimensional hydrofoils (Wade and Acosta, 1966; Franc and Michel, 1988; Le *et al.*, 1993). Wade and Acosta observed

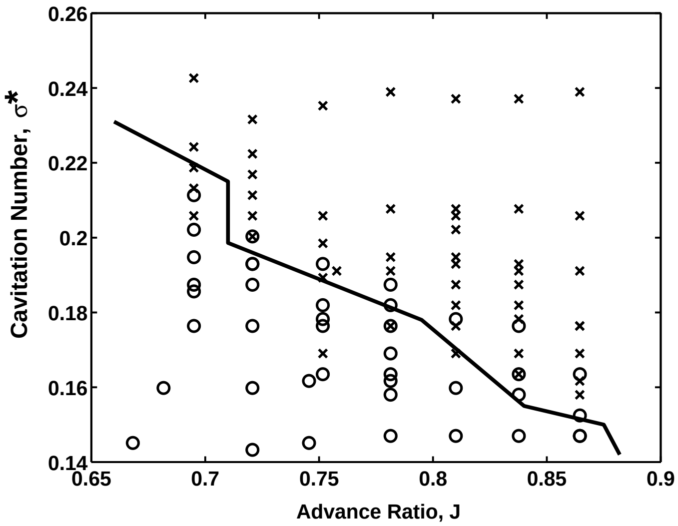

Figure 4. Unstable (○), marginally unstable (⊗), and stable (×) operating conditions in (J, σ^*) space for the 5236 propeller operating at 1850 rpm.

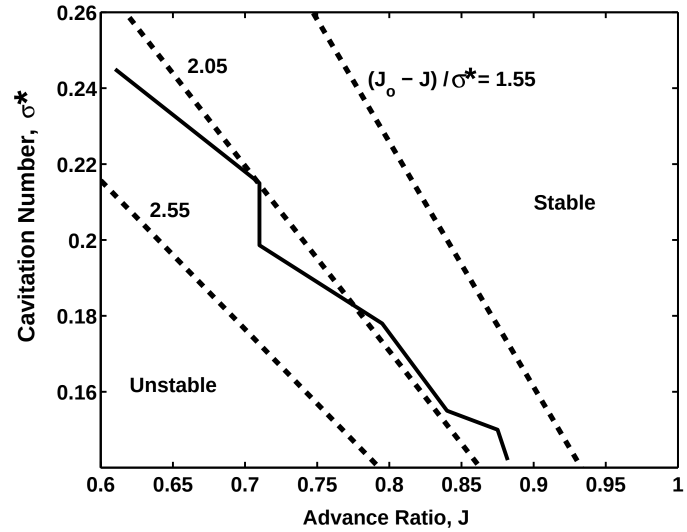

Figure 5. Comparison of the experimentally determined instability onset and that predicted by a cavity length stability criteria.

that an attached partial cavity on a two-dimensional hydrofoil becomes very unstable when the cavity length is close to the foil chord. Then the cavity length fluctuates violently, between about $\ell/c = 0.5$ and $\ell/c = 1.5$. The frequency of this oscillation was quite low, with reduced frequencies based on chord length and incoming flow rate ranging from $fc/U = 0.07$ to $fc/U = 0.14$.

The propeller instability cycle is very simliar in that the cavity length is oscillating between two very different but consistent values. Furthermore, the frequency of this oscillation is similarly quite low. In fact, the reduced frequency, based on incident velocity at the propeller tip and maximum chord length, is about 0.04, only slightly below the range reported by Wade and Acosta. Finally, the cavity lengths at which the oscillation occurs are comparable to the chord length of the propeller blade.

INSTABILITY ONSET

Figure 4 summarizes the results of experiments investigating the onset of the instability in (J, σ^*) space. The solid line dividing the stable and unstable regions corresponds to the onset of the instability. The unstable operating conditions are concentrated at advance ratios, J, below the design advance ratio of $J_o = 1.15$, and at lower cavitation numbers. Because cavitation numbers below $\sigma^* = 0.14$ could not be obtained in the experimental facility, it could not be determined whether or not the instability occurs at the design advance ratio.

Some insight regarding the onset of the instability can be gained by considering following argument. Studies of two-dimensional foils (for example Tulin, 1953, and Brennen 1995) have shown that the non-dimensional cavity length (ℓ/c) is essentially a function of the ratio (α/σ) of the angle of attack of the hydrofoil to the cavitation number. Based on purely geometric arguments, the angle of attack in the vicinity of a propeller blade tip is approximately proportional to the difference, $(J_o - J)$, between the design advance ratio and the operating advance ratio. Thus a particular configuration of cavity lengths on the propeller should correspond to a particular value of $(J_o - J)/\sigma^*$.

Several lines of fixed $(J_o - J)/\sigma^*$ are plotted in Fig. 5. Clearly the instability boundary (repeated here from Fig. 4) corresponds quite closely to the particular value of $(J_o - J)/\sigma^* = 2.05$. Thus the instability boundary corresponds to a particular configuration of cavity lengths on the propeller blade. This reaffirms the connection with the partial cavity instability observed on two-dimensional foils, where stability was also related to the length of the cavity.

RADIATED PRESSURE

Experimental Measurements

To further quantify the instability, pressure measurements were taken using the two pressure transducers indicated in Fig. 1. A typical signal obtained from the floor-mounted transducer is shown in Fig. 6. The signal is clearly periodic, with a frequency corresponding to the frequency of cavitation variation observed visually. The magnitude of the pressure oscillations produced by the instability was as high as $15 - 20$ kPa, at least one order of magnitude higher than the noise radiated under stable conditions. These pressure oscillations were strong enough to be read-

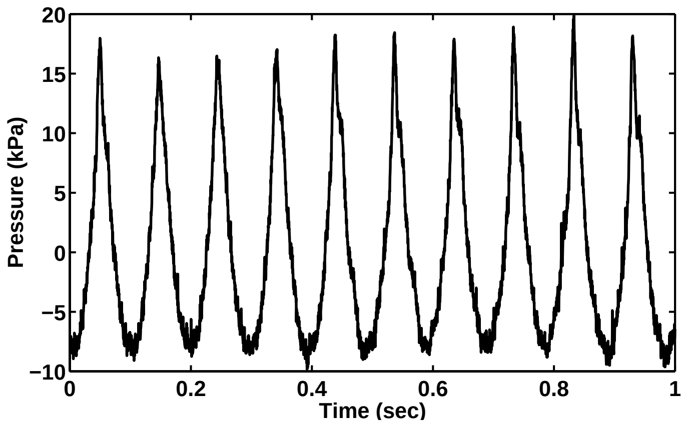

Figure 6. Typical signal obtained from the floor-mounted pressure transducer. The signal has been low pass filtered at $2\ kHz$.

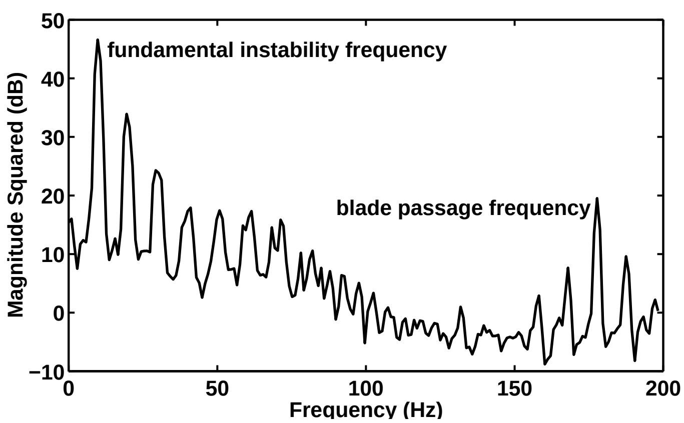

Figure 7. Average power spectral density of several typical signals obtained from the floor-mounted pressure transducer. The signals have been low pass filtered at $2\ kHz$.

ily heard in the laboratory and to shake the test section violently.

Figure 7 shows the average power spectral density of several typical floor-mounted transducer signals. Clearly visible is the fundamental frequency of the instability (about 10 Hz). This dominates the radiated noise by a margin of approximately 15 dB. Many harmonics can also be seen. Also visible is the blade passage frequency, in this case 180 Hz, corresponding to a six bladed propeller rotating at 1800 rpm. Finally, to either side of the blade passage frequency, the beat between the blade passage frequency and the fundamental instability frequency can also be discerned.

Pressure measurements from the ceiling-mounted transducer are shown in Fig. 8, and are compared with a signal from the floor-mounted transducer. The two signals exhibit the

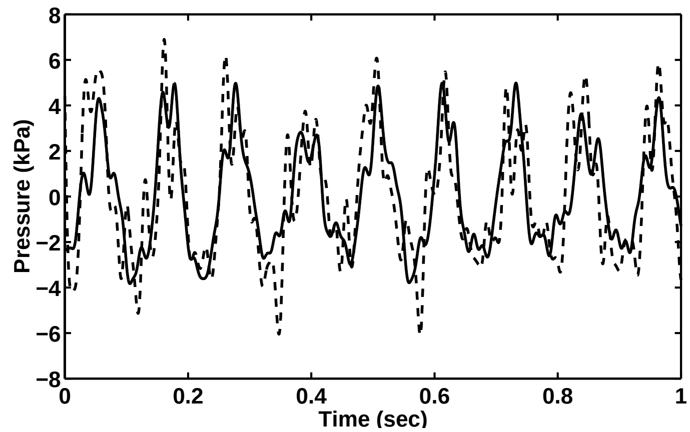

Figure 8. Comparison of signals obtained from the floor (—) and ceiling (- - -) mounted transducers. The signals have been low pass filtered at $2\ kHz$.

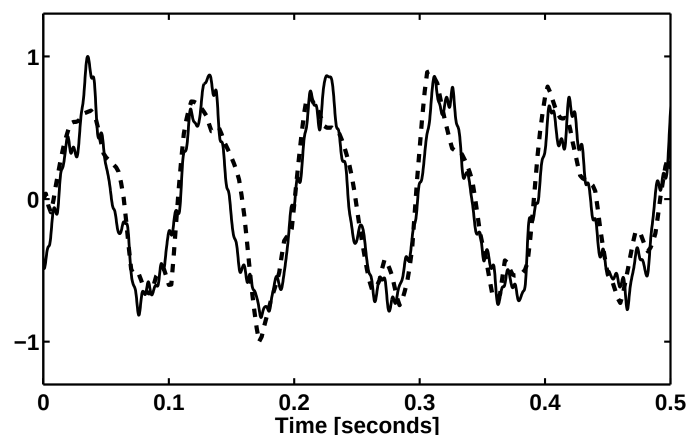

Figure 9. Comparison of floor-mounted transducer signal (—) and the radiated pressure predicted by the second derivative of the cavity volume (- - -).

same period and phase. Despite the fact that the ceiling-mounted transducer was 40 cm upstream of the propeller while the floor-mounted transducer was at almost the same axial location as the propeller, the amplitudes of the two signals are very similar. This indicates that the pressure pulses radiated from the instability did not attenuate significantly over this distance.

Modeling the Pressure

A simple model was developed to assess these radiated pressures. Simultaneous high speed video footage and pressure measurements from the floor-mounted transducer were obtained and correlated using a timing pulse. The cavity lengths on the propeller blades were then measured in the frames of the video footage. By assuming the cavity shape to be similar throughout the instability cycle, the cavity length measurements were converted to volume estimates. The resulting cavity volume was proportional to the square of the cavity length and the diameter of the propeller (Blake, 1986). Using a finite difference method, the second derivative (d^2V_c/dt^2) of this series of volume estimates was then computed. It is reasonable to believe, and it is supported by previous work (for example Huse, 1972, and Weitendorf, 1989), that the radiated pressure should in some way be related to this volumetric acceleration imposed upon the flow.

Figure 9 shows the comparison between the pressure measurements from the floor-mounted transducer and the second derivative calculation based on the cavity volume estimates. The correspondence between the two is good not only in terms of period and phase, but also shape, with the cavity volume calculation tracking some of the smaller features found in the troughs of the floor-mounted transducer signal. However, the vertical scales in Fig. 9 are arbitrary, and the magnitudes of these two signals have yet to be correlated.

CONCLUSIONS

In conclusion, a severe periodic instability has been observed in experiments investigating the cavitating behavior of a model U.S. Navy propeller. The pressure oscillations generated by this instability were orders of magnitude larger than those occurring under stable operating conditions.

Visual observations of the cavitation during the instability cycle revealed similarities to previous work on three-dimensional hydrofoils. In particular, the presence of a re-entrant jet was noted, and its effect on cavity closure was similar to that seen by previous researchers. In addition, the nature of the cavity length oscillations observed during the instability were reminiscent of the partial cavity instability seen on two-dimensional hydrofoils. Indeed, the experimentally obtained onset of the instability corresponded closely to an onset predicted by a stability criteria based on cavity length.

Pressure measurements revealed that the instability noise is dominated by the visually observed low frequency of cavity oscillation. The pressure measurements were shown to correspond closely to the volumetric acceleration imposed upon the flow by the varying cavity volume on the propeller blades.

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