Pulsating Supercavities: Occurrence and Behavior

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Abstract

Low Froude number ventilated cavities developed behind a disk cavitator, in a horizontal flow, under the influence of a vertical gravity field are considered. Pulsation is shown to occur in two different regions on the $C_Q - \sigma$ phase map, the hysteresis region and at vent rates greater than those necessary to maintain twin vortex cavities. Two conditions are necessary to initiate pulsation. One condition is a ventilation rate too great for either re-entrant jet or twin vortex closure regimes. The other condition is a finite amplitude pressure wave needs to force the cavity into pulsation.

Keywords: Supercavitation, Pulsation

Introduction

There are three main cavity closure regimes: (1) re-entrant jet, (2) twin vortex, and (3) pulsation. While the first two regimes have been studied at length, less attention has been given to the third regime and it remains less understood. Another regime is the over-ventilated cavity, foamy cavity, or free jet. This type is not a contiguous gas-filled cavity, but a bubbly gas-liquid mixture. The distinguishing feature of over-ventilated cavities is mixing occurs immediately behind the cavitator. Pulsation is a resonance phenomenon, with the cavity gas acting as a spring, resulting in gas ejection through periodic events. Pulsating cavities may have characteristics of both re-entrant jet and twin vortex closure but they are distinguished by their overall regular, periodically pulsating size and shape [1,2]. Ventilated supercavity pulsation has been experimentally observed by a number of researchers and under somewhat differing conditions. Some researchers have noted that pulsation occurs in what is typically referred to as the *hysteresis region* [3,4] while other researchers have observed pulsation at roughly the maximum sustainable cavity ventilation flow rate prior to cavity breakdown [5,6]. Thus, on a ventilated cavity phase map, pulsation has been observed in two distinct regions. It does not appear that any single previously published study has reported pulsation in both regions.

Methods

Experiments were conducted in the 0.305 m diameter water tunnel at the Penn State University Applied Research Laboratory. The test setup is shown in Figure 1. Gas was supplied from 6 gas bottles that vented out through the vent ports to form a cavity behind a 34.29 mm diameter disk. The freestream speed was set to 1.7 m/s so the Froude number was 3.0. The tunnel pressure was 103 kPa and to facilitate pulsation, the tunnel test section was filled just until there was no free surface visible. A Measurement Specialties XPM5 pressure sensor measured the cavity interior pressure while a Benthowave BII-7071 hydrophone measured the radiated sound pressure. The sampling rate and sample time was 25 kHz and 10 seconds, respectively. An in-situ calibration was used to remove the effects of the tunnel walls and transfer the signal to the equivalent free-field condition. Gas ventilation rates were measured by a Sierra Instruments FlatTrak 780S thermal gas flow meter and manufacturer supplied conversion factors were used to compensate for different ventilation gases.

The computational portion of this work was performed with StarCCM+. Previous work has shown that an approach using StarCCM+ captures cavity pulsation [7]. It was found that time dependent finite volume discretization with a compressible gas and incompressible liquid without a turbulence model was sufficient to capture pulsation. The same scheme employed previously was used in this study to computationally capture pulsation at a Froude number of 24.6 because pulsation could not be easily captured computationally at such a low Froude number (3.0). A 34.29 mm diameter floating disk without tunnel walls was studied.

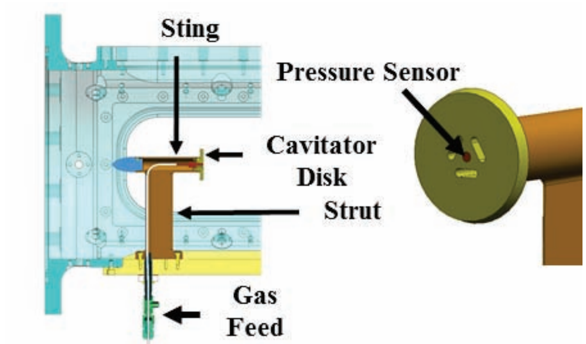

Figure 1: Experimental setup in the 0.305 m diameter water tunnel.

Results

There are two heuristic conditions necessary to induce pulsation: (1) the cavity must be transitioning between closure regimes and (2) a finite amplitude pressure wave must initiate pulsation. The first pulsation region is found at the transition between re-entrant jet and twin vortex closure regimes, commonly called the hysteresis region. Pulsation in this region will be called hysteresis pulsation. The second pulsation region is at the transition between twin vortex and over-ventilated cavities. Pulsation in this region will be called high-vent pulsation. Pulsating cavities can occur in both regions but the nomenclature is adopted to distinguish between the two. In Figure 2a, from CFD simulations, the cavitation number history for a one second duration of Fr=24.6 cavity pulsation is given. Pulsation of both the hysteresis and high-vent kind are presented. The hysteresis pulsation has a higher frequency at approximately 17 Hz while the high-vent case pulses at roughly 14 Hz. Per the Song model [8], the higher ventilation rate results in a larger cavity while not significantly increasing the pressure so the lower frequency is expected. In Figure 2b, water tunnel experimental results are presented. The high-vent pulsation (green trace in Figure 2a and horizontal line in Figure 2b) falls within the experimentally observed pulsation regions. The pulsation regions are denoted by P1 and P2 and closure regimes are separated by dashed blue lines. The hysteresis pulsation (black trace in Figure 2a and horizontal line in Figure 2b) falls within the range that is believed to be the hysteresis region, given by RJ/HYS. However, for the water tunnel data, the noise floor of the flow meter is higher than the ventilation rate for the hysteresis region. The red triangle close to the horizontal axis with p_c approximately equal to 104 kPa is a re-entrant jet cavity while the next lowest vent rate (3) is an RJ/TV transitioning cavity.

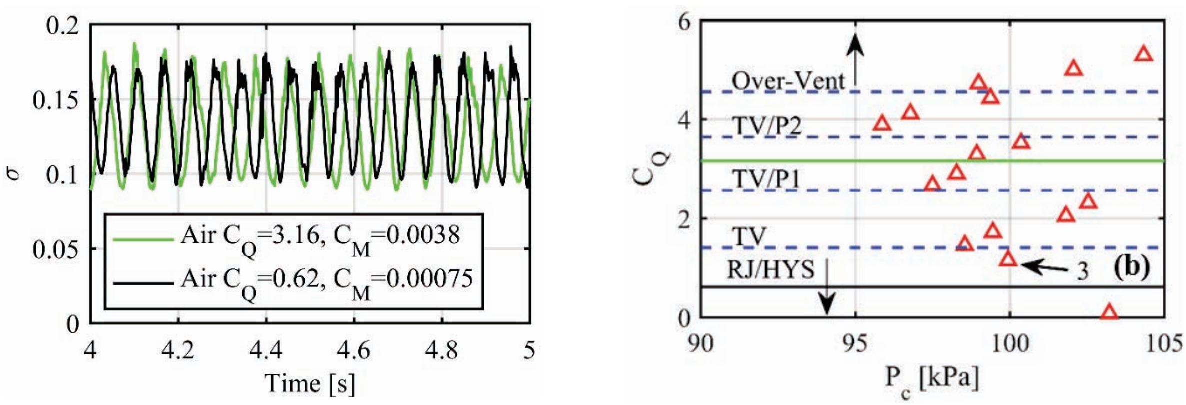

Figure 2: (a) Cavitation number for a period of 1 s. (b) Those ventilation rates correspond to both pulsation regions where the red triangles are experimentally measured cavity pressures.

While it was not possible (in the water tunnel) to visually ascertain pulsation in the hysteresis region, at the second lowest ventilation rate in Figure 2b, denoted by (3), there are strong indications of pulsation. The cavity interior and +25 dB shifted radiated pressure spectra for this cavity are given in Figure 3. Around 30 Hz is a tone that is related to pulsation and is pointed out by the blue arrow. High-vent pulsation had a tone at 33 Hz with an amplitude at 190 dB. While the frequency difference between the two pulsation experimental regions is similar to the CFD results, the pulsation amplitudes are nearly the same in the CFD results between the two pulsation regions. The cavity in Figure 3 has not fully transitioned to pulsation nor been initiated. Nonetheless, these results indicate there are two distinct pulsation regions and they occur when the ventilation rate is too great for either a re-entrant jet or twin vortex cavity. In this condition, pulsation is an efficient mechanism for gas removal from a cavity. While the ventilation condition is necessary, it is not sufficient for pulsation; there must be some kind of trigger to force the cavity into pulsation in regions susceptible to pulsation.

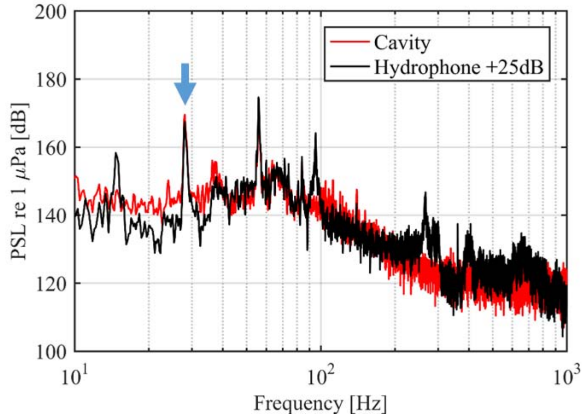

Figure 3: Cavity interior and +25 dB shifted radiated pressure spectra for an air ventilated cavity with C_M=0.0014/C_Q=1.15.

There are two methods, documented during water tunnel testing, to initiate pulsation. One method is through a pressure impulse and the other is by a high supply pressure. In Figure 4a, a pulsating cavity generated using the high pressure method, supply pressure set to 689.5 kPa, is shown. There is no cavity when a ball valve is opened and gas begins to vent into the tunnel. This method uses a high enough supply pressure to perturb the system into immediate pulsation without the need for an existing cavity. In Figure 4b, the impulse method was used to generate the cavity shown. This case is from work presented in reference [6] and was generated with a lower supply pressure (~69 kPa). To generate this pulsating cavity, a steady cavity is first formed, then the gas is shut off. When the cavity transitions to a re-entrant jet cavity, the ball valve is quickly opened, and the pressure wave generated from the unsteady action of quickly opening the ball valve initiates pulsation. The relatively low supply pressure demonstrates that high pressure is not needed to maintain pulsation. Thus, maintaining pulsation appears to be a linear process.

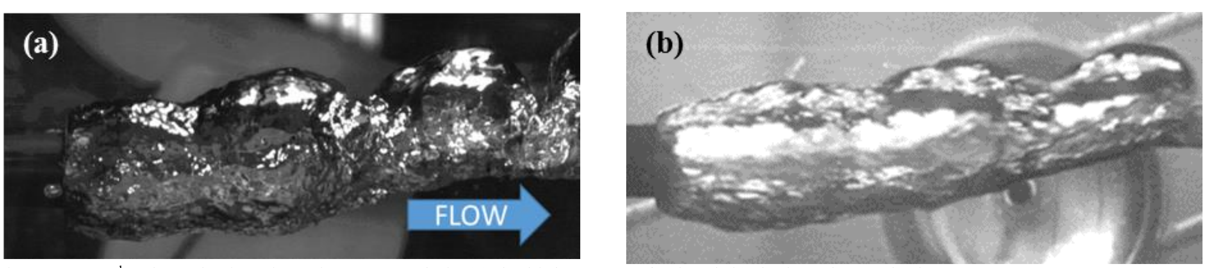

Figure 4: A 2nd order pulsating air cavity generated via (a) the high pressure feed and (b) the impulse method.

The high pressure feed method was verified using SF_6 as a ventilation gas. Since the density of SF_6, at fixed conditions, is greater than that of air, the pressure drop in the ventilation system is greater. Therefore, a higher supply pressure is needed to initiate pulsation. To trigger pulsation with SF_6, the needed supply was roughly 1379 kPa. In Figure 5a, the resulting cavity is shown. A twin vortex cavity, in Figure 5b, was generated with a supply pressure of 690 kPa. Undulations on the lower and upper interface indicate pulsation, seen in (a). The C_Q and pressure values are 0.67 and 95.6kPa (a) and 0.66 and 104.4kPa (b). The pressure reduction is also an indication of pulsation versus twin vortex. At the same ventilation rate, doubling the supply pressure caused the SF_6 supplied cavity to transition from twin vortex to pulsation; thus, altering the supply pressure for a non-choked flow leads to changes in cavity dynamics. This indicates a feedback loop between the ventilation system and cavity. Initiating cavity pulsation is a nonlinear process and requires a finite amplitude perturbation.

Skidmore *et al*. [9] have shown, both analytically and experimentally, that without altering the mean ventilation rate, pulsation can be disrupted with small amplitude modulation of the ventilation rate. By modulating the gas supply flow, waves on the cavity interface, evidence of which is given in the pressure spectra in Figure 3 and shown on the cavity interface in Figure 5a, are disrupted and pulsation is prevented. The amplitude dependence of this method of pulsation disruption has not been thoroughly investigated.

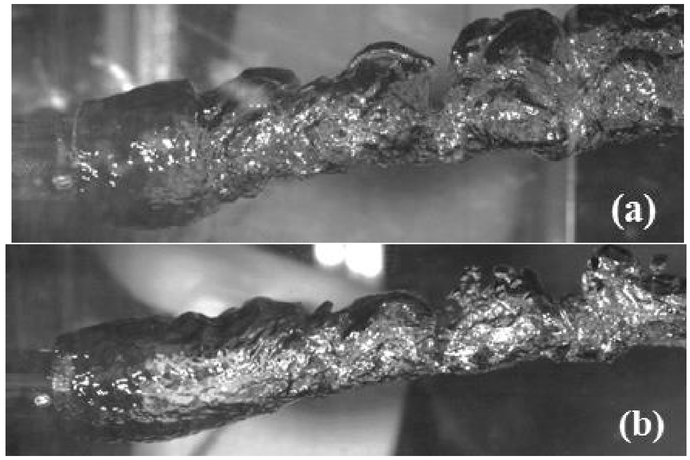

Figure 5: (a) A pulsating SF_6 cavity with supply pressure of 1378.95 kPa. (b) A twin vortex cavity with a supply pressure of 689.5 kPa

Conclusions

Two conditions are necessary for pulsation. One is that the cavity must be transitioning between closure regimes and the other is that an initializing, finite amplitude perturbation is required. Thus, unlike twin vortex or re-entrant jet cavities, pulsation is never history independent; twin vortex and re-entrant jet cavities can exist at vent rates where pulsation is not possible and other regimes are not attainable. When cavity closure regimes cannot efficiently remove gas, a cavity can pulsate, which is, for those cases, the most efficient method of gas removal, but causes strong fluctuations on the cavity interface. Mitigating pulsation occurs through disruption of the waves on the cavity interface that force pressure (and volume) fluctuations of the gas.

Acknowledgments

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