Noise from Ventilated Supercavities and its Utility for Inferring Cavity Dynamics

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Abstract

Ventilated supercavities are shown to be monopole noise sources over a wide range of frequencies. As such, the radiated noise may have utility for providing insight into cavity characteristics, such as the entrainment rate of gas, cavity closure regime, and cavity stability. Lower frequency waves on the cavity interface define its shape and closure regime. When high amplitude, monotonic waves are present on the interface, corresponding high amplitude tones are present in the radiated noise. High frequency interface waves, associated with interface roughness, give rise to higher frequency broadband noise. Increased roughness increases the shear entrainment rate and ventilation requirements.

Keywords: Supercavitation, Supercavitation Acoustics

Introduction

It is widely accepted that the interface motion of a ventilated supercavity is related to its radiated noise. As such, this relationship presents an attractive means of inferring ventilated supercavity dynamics through its radiated noise. Previous work has studied ventilated supercavity noise either analytically or numerically and has shown that low frequency noise is expected to radiate as an acoustic monopole [1,2]. While these studies considered mainly the impingement of a gas jet on the cavity interface, Skidmore *et al*. [3] demonstrated that the noise from pulsating cavities is related to the dominant wave on the cavity interface and radiates as a monopole source at the wave frequency.

In addition to gross cavity motion, such as that occurring during pulsation, it is possible for several waves to be superimposed on the cavity interface with varying amplitudes that are controlled by the Kelvin-Helmholtz (KH) and Rayleigh-Taylor (RT) instabilities. The density and vortex sheets are colocated at the cavity interface, hence the existence of waves on the cavity interface. Perturbations that are amplified by these two instabilities are either generated by fluidic or mechanical sources [4]. The disturbances that are amplified by the KH and RT instabilities cause pressure fluctuations in the cavity gas. The cavity is unable to sustain pressure oscillations and the cavity deforms, resulting in volume oscillations. These volume oscillations not only act as monopole noise sources, thus cavities are efficient acoustic sources, but can also lead to cavity stability issues and alter the shear entrainment rate, depending on the disturbance scale.

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 1a. Gas from 6 gas bottles entered through the strut and sting, and then into the cavity through the vent ports. The cavitator disk diameter was 34.29 mm, the freestream speed was set to 1.7 m/s (Fr=3.0), and the tunnel pressure was 103 kPa. To facilitate pulsation generation, the test section was filled just until there was no free surface visible. A Measurement Specialties XPM5 pressure sensor measured the interior cavity pressure while 2 Benthowave BII-7071 hydrophones measured the radiated sound pressures. Only the downstream hydrophone measurements are presented. The resonance frequencies of the sensors were well above the frequency range of interest. The sampling rate and sample time was 25 kHz and 10 seconds, respectively. An in-situ calibration was performed to remove the effects of the tunnel walls and transfer the signal to the equivalent free-field condition. 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.

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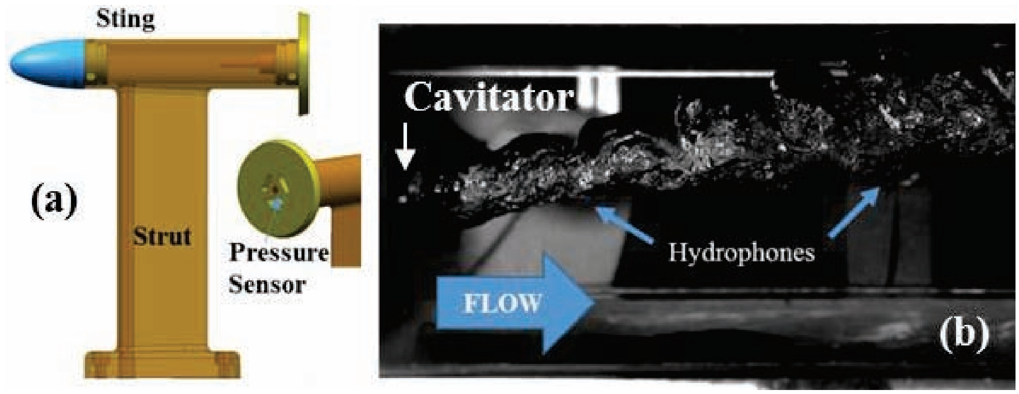

Figure 1: (a) Experimental setup in the 0.305 m diameter water tunnel tests. (b) High speed image of a 2nd order pulsating air cavity.

Results

Experimentally measured 2nd order pulsating air cavities have a frequency of 33 Hz and the surface area of the cavity can be estimated using the Song model [5]. A high speed image of a pulsating cavity is shown in Figure 1b. The interior pressure spectrum for the pulsating cavity is represented by the black line in Figure 2a. In addition to a pulsating cavity, there is a tone in an air twin vortex cavity that occurs at 60 Hz (represented by the red line in Figure 2a); a high speed image of this cavity is shown in Figure 2b. There is a tone around 30 Hz in the red pressure spectrum but the feedback tone is dominant. The twin vortex tone appears to be a due to a complex feedback loop that depends on the sound speed of the gas, cavity length, and delay time between an acoustic perturbation and the resulting disturbance rollup. For the cavities studied, there were no tones measured for re-entrant jet cavities and the broadband pressure spectral levels were lower than the broadband pressure spectral levels for twin vortex or pulsating cavities.

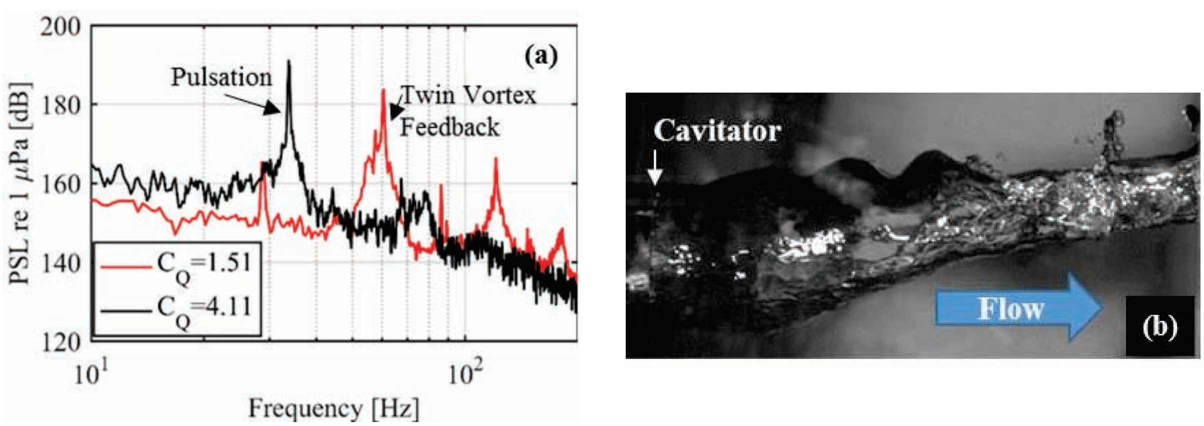

Figure 2: (a) Cavity interior pressure spectra for a pulsating (black) and twin vortex (red) cavity. (b) An air twin vortex cavity.

While the pulsation and feedback tones are tonal monopole noise sources, ventilated supercavities also act as broadband monopole noise sources. Given in Figure 3a, the cavity interior and the +25 dB shifted hydrophone pressure spectra show a range of frequencies where the pressure spectral levels are the same. The +25 dB shift compensates for the reduction in pressure spectrum level due to spherical spreading from the cavity interface to the hydrophone. To verify cavities are broadband monopole noise sources, the coherence between the cavity sensor and hydrophone for the Figure 3a cavity was found. The coherence, given in Figure 3b, is high between the two sensors and ensures a high degree of certainty that the measured pressure fluctuations are generated by the cavity. Using the coherence as a condition for a good signal, along with the signal-to-noise ratio, the phase of the cross spectrum between the sensors was found, given in Figure 3b. The frequencies are strongly correlated and the phase difference is around 0 degrees for a range of frequencies, indicating there is acoustic wave propagation between the sensors.

The effects of interface waves on cavity dynamics depends on their wavelength. Low frequency noise is related to deformations of the cavity interface while high frequency noise is related to roughness. The demarcation between these scales is currently unknown. Deformations mean the cavity interface is unstable. Pulsating cavities, such as those shown in Figure 1b, have wave motion on both the upper and lower interface, a hallmark of pulsating cavities. Conversely, a twin vortex cavity has a coherent wave only on the upper cavity interface. Both tones in the cavity interior pressure spectra for the pulsating and twin vortex cavities are over 180 dB, meaning both tones have strong volume velocities, O(10^{-3}-10^{-4}) m^3/s; therefore, these tones can cause cavity stability issues. It appears that deformations will cause a contraction in the cavity length at a given mass ventilation rate.

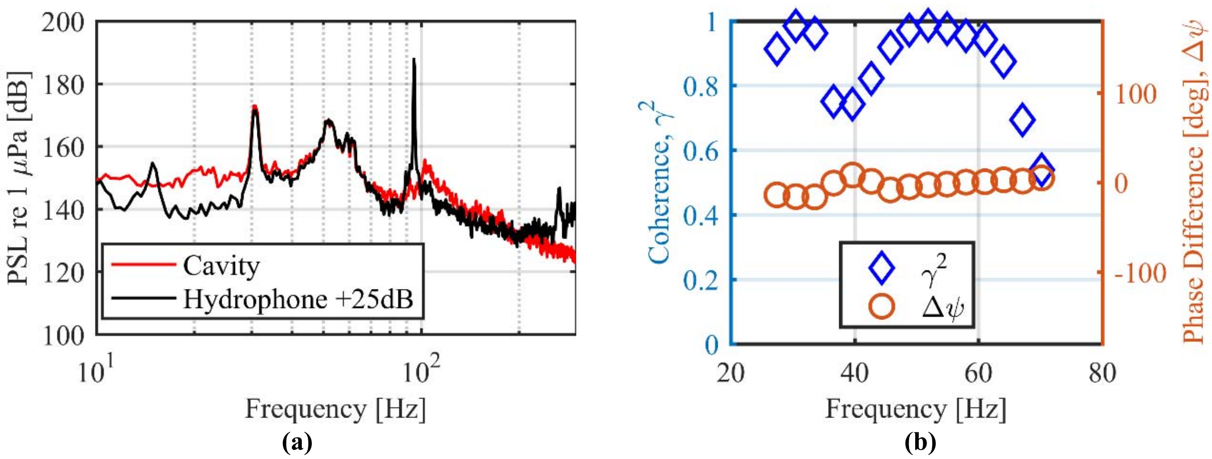

Figure 3: (a) Cavity interior and shifted radiated pressure spectra with C_Q=1.72. (b) Coherence and phase difference between cavity interior pressure sensor and downstream hydrophone for C_Q=1.72.

Gas jets provide broadband forcing to the cavity and, as a result, are responsible for radiated noise over a range of frequencies. Thus, higher frequency perturbations are present. The higher frequency or shorter wavelength cavity disturbances are expected to increase the ventilation rate by increasing the shear entrainment rate caused by the rougher cavity interface. Assuming an average wavelength of $O(10^{-3})$ m for surface roughness, the frequency of the waves that are radiated by those surface roughness disturbances are $O(10^3)$ Hz for the given freestream speed. Unfortunately, external noise sources, such as vibration induced noise and flow noise, dominated the cavity interior pressures at frequencies near 1 kHz but high speed images of ventilated cavities can be used to ascertain roughness.

Impingement of the ventilation gas jet and the acoustic disturbances generated by the turbulence of the gas jet which perturb the interface at the separation point are two sources of disturbances on the cavity interface. To reduce the ventilation speed, a denser gas was used to generate an equivalent cavity at an equivalent mass flow rate. Lower velocity gases are expected to result in lower broadband pressure spectral levels for this cavity. In other cavities tested, however, it was observed that helium ventilated cavities possessed smoother cavity interfaces than air ventilated cavities; therefore, there is a complex dependence on the ventilation gas speed and density of the vent gas on cavity interface disturbances. Given in Figure 4 are the cavity interior pressure spectra for air and SF_6 ventilated cavities at the same mass flow rate. The ventilation speed decreases by a factor of 5 with SF_6. For this operating condition and cavitator, the reduction in vent speed leads to a lower cavity interior pressure spectrum level, which means a lower volume velocity. Disturbances on the cavity interface drive pressure oscillations in the gas that cause volume oscillations of the cavity. At these lower frequencies (<100 Hz), cavities behave as broadband monopole noise sources so the cavity is quieter because of the reduced volume velocity and the cavity experiences less intense radial size fluctuations. The lower amplitude deformations should lead to less contraction of the cavity length. In addition to the lower kinematic viscosity, the roughness of the cavity interface is less due to the lower vent rate so the shear entrainment should decrease on a volumetric basis.

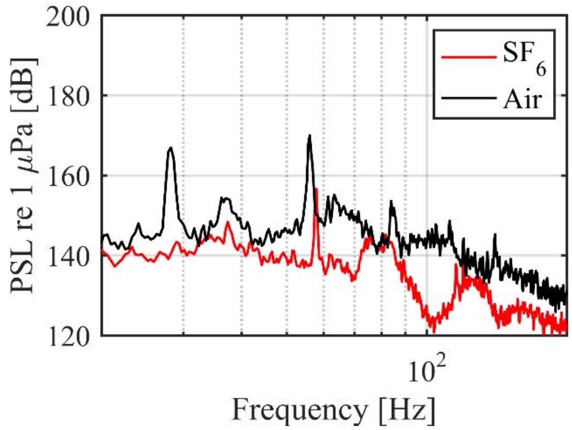

Figure 4: The cavity interior pressure spectra for air and SF_6 ventilation gases at similar mass flow rates.

Conclusions

This work has shown that ventilated supercavities are broadband as well as tonal monopole noise sources. High amplitude, monotonic waves on the cavity interface give rise to corresponding tones in the cavity interior pressure and radiated noise spectra, whereas lower amplitude waves give rise to broadband cavity interior pressures and radiated noise. The high amplitude tones are present in pulsating and twin vortex cavities. Cavity dynamics are affected by both the amplitude and the length of the interface waves. Long length interface waves appear to lead to a significant contraction of the mean cavity length to maintain the cavity surface area. Small length interface waves give rise to cavity roughness that results in high frequency broadband cavity interior pressures and radiated noise. Cavity roughness affects the shear entrainment rate and ventilation rate requirements. Rougher cavity interfaces entrain gas at a faster rate than smooth cavity interfaces for a given Reynolds number for the gaseous boundary layer and require increased ventilation rates. For the experimental setup reported herein, changing the ventilation gas while maintaining the same mass flow rate, has shown the broadband noise levels are reduced and the cavity motion and roughness are reduced using a denser gas.

Acknowledgments

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