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A Method of Mitigating Pulsation in Ventilated Supercavities

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Abstract. A method for mitigating ventilated supercavity pulsation is presented. The method, which has its roots in parametric oscillators, shifts the supercavity resonance frequency by modulating its gas ventilation rate. When appropriately modulated, the supercavity is driven off resonance by the waves on the gas/water interface (that remain unchanged) and pulsation is, therefore, suppressed. Initial experimental results indicate that the gas ventilation rate modulation frequency must be sufficiently different from the supercavity resonance frequency to mitigate pulsation. If the modulation frequency is not sufficiently different from the supercavity resonance frequency, pulsation is simply shifted in frequency with a corresponding small reduction in the supercavity interior pressure spectrum level and radiated noise.

1. Introduction
It is possible to reduce the skin friction drag of a body, up to an order of magnitude, using supercavitation to reduce the wetted surface area. In order to develop a supercavity for many applications, gas must be ventilated in the low pressure region behind the cavitator. Thus, for high speed supercavitating vehicles, ideally only the control surfaces and the cavitator should remain in contact with the water after a supercavity is developed via ventilation. While this idea works well in theory, in practice the process of generating a supercavity is often plagued by a resonance phenomenon known as pulsation. When a supercavity pulsates, the walls of the supercavity begin to periodically expand and contract; the periodic increase and decrease of cavity size can lead to the cavity walls clipping the body, which can be an issue for the stability of the body as well as a strong source of radiated noise [1]. Oftentimes, it is possible to transition from the pulsating closure regime to either twin vortex or re-entrant closure by simply adjusting the ventilation gas flow rate, pressure/depth, or velocity. However, for cases when these parameters are fixed and pulsation occurs, an alternative means for control is desired. Thus, in this paper, a method to mitigate the pulsation phenomenon in ventilated supercavities is outlined and preliminary experimental results are presented. Please note that here, as in the remainder of this document, the terms cavity and supercavity are used interchangeably.

2. Background
Supercavities can be generated with natural cavitation and with gas ventilation. Ventilation provides the option for low speed supercavities, where gas is injected behind the cavitator of the body and a supercavity forms. Ventilated supercavities, when formed in a gravity field roughly orthogonal to the direction of body motion, the condition of most interest, tend to obey

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three main closures: re-entrant jet (also known as toroidal shedding cavities), twin vortex, and pulsation [2]. It is a fundamental requirement for all regimes that the rate of mass ingress into the cavity must match the rate of mass egress out of the cavity in order for the cavity to remain stable; thus, the difference between closure regimes is the primary mechanism employed to allow gas to exit the cavity into the water.

Supercavity pulsation was first reported by Silberman and Song [3] who found that, as the cavity gas injection rate increased, the cavitation number decreased linearly up to a certain critical cavitation number; from this point, increased gas injection lead to the cavity walls vibrating in the manner described and little correlation between ventilation rate and cavitation number was observed. Silberman and Song identified this new closure regime by a wavy cavity surface where the cavity exhibits periodic changes in both length and internal pressure. These waves travel along the cavity interface until minima, on opposing sides of the cavity, approach one another sufficiently close for “pinch off” to occur [4]. That is, pinch off occurs where the surface wave influenced local cavity diameter becomes less than the cavitator diameter. The pinch off location effectively denotes the termination of the cavity. The gas ejected from the cavity is advected with the mean flow. Hence, large portions of the gas of the supercavity are periodically ejected by this pinch off process and carried downstream by the flow. The pulsation phenomenon is depicted schematically in Figure 1a.

The first notion of control of pulsation via harmonic forcing can be attributed to Semenenko in 1996. Semenenko discussed the possibility of driving a pulsating cavity with an external forcing frequency. When the forcing frequency is close to that of the natural frequency, the pulsation is said to be “reinforced” by the forcing frequency, and when forced at a frequency away from the natural frequency the periodic mode was said to be “chaotized” [5]. A related approach, that has its roots in parametric oscillators, is to modulate the ventilation gas flow rate at frequencies other than the pulsation/resonance frequency. This, theoretically, changes the supercavity resonance frequency from its constant ventilation rate value and, as a result, can inhibit resonance excitation from the interface waves. This approach was explored numerically by solving the appropriate form of Hill’s equation [6] and found it to be an effective means of shifting the supercavity resonance frequency, and thus, potentially mitigating pulsation.

3. Experimental Setup
The cavitator configuration used in this experiment is shown in Figure 1b; the system is similar to the one detailed by Skidmore [1]. It was installed in the test section of the ARL Penn State 0.305 m water tunnel. The cavitator itself was a truncated 15° cone with a maximum diameter of 3.175 cm and a thickness of 0.48 cm. The cavitator had a flush mounted Measurement Specialties XPM5-A1 static/dynamic pressure sensor on the downstream face for measuring the cavity interior pressure. The cavitator was oriented downstream of the sting configuration, a 14.13 cm long body with an elliptic nose that allowed for minimal flow disturbances upstream of the cavitator. The sting was, in turn, mounted to a strut with a hydrofoil cross section. The strut was bolted into the walls of the tunnel and kept the centerline of the cavitator concentric to that of the 0.305 m circular test section. A Kelly Pneumatics KPS-10-A0-4 high speed butterfly valve was used to modulate the cavity ventilation rate. A Celesco LC-10 hydrophone mounted onto the tunnel test section was used to measure the near-field noise radiated by the cavities. A Casio F1 camera was used to record images of the cavities at 600 frames per second.
3.1. Experimental Procedure
The tunnel velocity was set to 2.05 m/s (for the cavities discussed in this paper) and a pulsating supercavity was established with the high speed butterfly valve fully open. This baseline condition was established for successive tests such that a nominally fixed pulsation frequency was observed. The pulsating supercavity was given approximately 20 seconds to stabilize before the high speed butterfly valve was employed to modulate the ventilation rate. After initiating modulation of the gas ventilation rate, the cavities were observed for 30 seconds or more in order to quantify what changes, if any, occurred to the cavity.

4. Results
Two pulsating cavities were generated at identical test conditions and were pulsating at 38.8 Hz (±0.06 Hz) prior to modulating the gas ventilation rate. The gas ventilation rate to the first cavity was then modulated at 32.0 Hz, and within 0.3 seconds of initiating modulation, the pulsation frequency increased to 41 Hz and the amplitude of both the cavity interior pressure and the radiated sound pressure decreased 4 dB as shown in Figure 2a. The cavity was initially a 2nd order pulsating cavity (i.e. two waves on its surface prior to pinch-off) and the spectral changes occurring 0.3 seconds after initiating modulation were accompanied by the cavity transitioning to 3rd order as shown in Figure 2b. These results indicate that modulating the gas ventilation rate was effective at shifting the supercavity resonance frequency but not enough to mitigate pulsation.

The gas ventilation rate to the second cavity was modulated at 28.0 Hz and within 0.1 seconds of initiating modulation, the cavity ceased pulsating. When modulation was initiated, the 38.8 Hz surface traveling waves disappeared and 49.0 Hz surface traveling waves appeared. The 49.0 Hz surface traveling wave amplitude, however, decayed to a non-observable level over 1.5 seconds, at which time the cavity transitioned to the twin vortex closure regime. The internal cavity pressure and near-field noise spectra shown in Figure 3a were recorded over an approximate 23 second window prior to initiating gas ventilation modulation and 33 second after. The spectra show that the effect of modulation was to reduce the cavity pressure and radiated noise spectrum level, at the pulsation frequency 35 dB to the continuum (a near two order-of-magnitude reduction in both interior pressure and radiated sound pressure). The cavity before and after modulating the gas ventilation rate is shown in Figure 3b.
Figure 2: Subfigure 2a shows pressure spectra measured by the interior cavity pressure sensor and near-field hydrophone before and after gas modulation. Subfigure 2b shows images of the cavity before and after gas modulation.

Figure 3: Subfigure 3a shows pressure spectra measured by the interior cavity pressure sensor and near-field hydrophone before and after gas modulation. Subfigure 3b shows images of the cavity before and after gas modulation.

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