Finite Volume Computation of the Mitigation of Cavity Pulsation

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Abstract. Finite volume based modeling of ventilated supercavity pulsation and its mitigation via a priori modulation of ventilation flow was investigated. Simulated pulsation was numerically achieved, as was mitigation of pulsation via sinusoidal modulation of the ventilation flow. In addition to confirmation that the numerical approach is sufficient to capture mitigation, it was found that modulated ventilation, without altering the mean ventilation mass flow rate, results in altered cavity size, pressure, and closure condition.

1. Introduction

Due to their potential and proven hydrodynamic applications to high speed drag reduction and facilitation of high speed marine lifting surfaces, ventilated gas supercavities are of particular interest. The pulsation of ventilated supercavities, generated by axisymmetric cavitators, was reported by Song [1], Michel [2], and has been studied extensively by Paryshev [3], among others. Due to his contribution, and his widely cited modeling, pulsating modes of the supercavity are frequently referred to as the Paryshev Instability.

Control of pulsation via harmonic forcing can be attributed to Semenenko [4]. Recently, Skidmore et al. [5] conducted an investigation into potential strategies for the mitigation of cavity pulsation. This work focuses on a priori modulation of the ventilation flow. Tests were completed in a closed-loop water tunnel. Modulation was achieved using a butterfly valve. Results indicate that this strategy may, under proper application, induce the cavity to transition away from pulsation into a twin vortex condition. Although not comprehensive, the current investigation is an attempt to computationally complement those physical experiments.

2. Computational Physics

The computational fluid dynamics software, StarCCM+ [6], is employed as a physical modeling tool. Lindau et al. [7] have previously applied StarCCM+ to capture cavity pulsation with a finite-volume, Navier-Stokes approach. It was found that a time dependent finite volume discretization with incompressible liquid flow and isothermally compressible gas flow, without rigorous turbulence modeling, was sufficient to capture the salient physics of cavity pulsation. A standard volume of fluid approach supported by the HRIC scheme was employed (e.g. [8]). Care was taken to ensure that local convective Courant numbers were within the bounds prescribed for best use of the scheme. In [7], asymptotic numerical mesh convergence to a pulsation condition was demonstrated, supporting the current approach. A complete model (computational domain, time step size, and all numerics and physical models) found to be convergent in [7] is applied here, albeit with modulated ventilation flow.
3. Computational Results

Here, scaling parameters typically applied to ventilated supercavitation are used. They are the cavitation number \( \sigma \equiv \frac{2}{cav}(p - p_{cav}/\rho U_{\infty}^2) \), the Froude number \( Fr = U_{\infty}/(gD_{cav}^2) \), and the ventilation flow coefficient \( C_Q = Q/(U_{\infty} D_{cav}^2) \). For completeness, the Reynolds number based on cavitation diameter and free stream quantities was held constant \( Re_D = \rho U_{\infty} D_{cav} / \mu = 573,000 \). For the envisioned conditions, the Thoma or (vaporous) cavitation number at the modeled condition was also a constant \( \sigma_c = 2(p - p_{cav})/\rho U_{\infty}^2 = 0.97 \). It should be clear that \( p_{cav} \) is much less than \( p_{cav} \) for all presented results. The quantity \( p_{cav} \) is the pressure inside the ventilated cavity, \( D_{cav} \) is the diameter of the disk cavitator, and \( Q \) is the ventilation gas volume flow rate. In addition, time scales are nondimensionalized by the quantity \( D_{cav}/U_{\infty} \). A Detached Eddy Simulation approach based on the Spalart-Allmaras turbulence model was applied [6].

In figure 1, the computational mesh is shown. The computational domain is a cylindrical tunnel with diameter of 52.5 and length 78.7 \( D_{cav} \). Tunnel walls are modeled as inviscid. The wetted face of the cavitator is concentric with the tunnel, 26.2 \( D_{cav} \) downstream from the inlet. The mesh is illustrated with a plane bisecting the computational domain and on the inlet and outlet boundaries. The mesh on the cavitator surface, is also shown. Computational ventilation gas is issued via mass flux boundary conditions around the cavitator aft side and perimeter. (Isothermally compressible standard air at a reference temperature of 300K is used. The mean absolute pressure at the tunnel centerline under static conditions is 110.8kPa.) The liquid is treated as incompressible water. Water density \( \rho = 1000 \text{kg/m}^3 \).

![Flow Direction](image1)

Figure 1. Computational grid.

Prior to obtaining the presented results, an initial pulsation condition was obtained based on unsteady integration with steady ventilation; the ventilation mass flow was maintained \( (m_0 = 2.985 \times 10^3 \rho U_{\infty} D_{cav}^2) \) such that the mean ventilation rate was \( C_Q = 0.28 \). This same mass flow, \( m_0 \), is maintained as the mean value for all results presented here. Results from four model integration cases are presented. All cases were integrated, beginning with the same initial state, at \( \Delta t = 0.0787 D_{cav}/U_{\infty} \) for a total integration time of 2.362 \( D_{cav}/U_{\infty} \). This was adequate to obtain a final stationary condition. For all cases, \( Fr = 24.5 \). An interesting observation is that despite maintaining the same mean ventilation mass flow when modulation is introduced, the frequency content, the cavitation number, and (sometimes) the closure condition change. In other words, when modulation is begun, a transient occurs and eventually a stationary, constant mean but time varying, condition is found with a new mean cavity pressure and cavity size, often with a new closure condition. In the first of the four cases, ventilation is not modulated and the steadily pulsing condition is maintained. In the second, third, and fourth cases, different modulations are applied to the ventilation mass flow. In these modulated cases, the amplitude of modulation, \( A \), is determined relative to the mean total ventilation mass flow. For instance, the ventilation mass flow modulated at \( A = 0.2 \) varies sinusoidally between 80 and 120% of the mean ventilation mass flow.

The location of the numerical probe for determination of instantaneous cavity pressure is shown in figure 1, on the tunnel centerline and 0.66 \( D_{cav} \) downstream of the cavitator face.

In figure 2, snapshots of cavities resolved with CFD, without modulation and with three different modulation conditions, from two views, port and below, are shown. In figure 3, pressure time histories and spectra from the numerical probe pictured in figure 1 are presented. The time range chosen for representation in figure 3 is sufficient to allow appreciation of the character of the pressure signal, mean
value and frequency content, for each case. The snapshots in figure 2 illustrate both the general character of the pulsing cavity as well as the effect of modulated ventilation on cavity size and shape. A review of the snapshots together with the pressure histories and spectra give a fairly complete picture of the final stationary conditions. In all cases, the mean ventilation gas mass flow rate is the same and (in figure 2) $2.126 D_{\text{cav}}/U_\infty$ of simulation time has elapsed since numerical time integration was initiated from the common initial condition.

In the case with no modulation, the cavity continues to pulse at the nominal resonance frequency, $f_0 = 0.07493 U_\infty/D_{\text{cav}}$, and periodically toroidally ejected gas pockets, convected downstream, are clearly visible. The reentrant jet is clear in the translucent view from below. The mean cavity size and pulsation frequency and magnitude change little for the duration of the time integration. The pressure history, black lines in figure 3, clearly shows the nature and magnitude of the pulsing condition. It is nearly regular. The pressure spectral decomposition of the unmodulated case is also shown with solid black lines in figure 3. The peak frequency, $f_0$, is indicated with the dashed black line.

| No modulation: Pulsing at $f_0$ | Modulation: $f=0.79f_0$, $A=0.2$ |
|--------------------------------|------------------------------------|
| Port                           | Port                               |
| Below                          | Below                              |

| Modulation: $f=2.76f_0$, $A=0.2$ | Modulation: $f=2.76f_0$, $A=0.5$ |
|----------------------------------|-----------------------------------|
| Port                             | Port                              |
| Below                            | Below                             |

Figure 2. CFD resolved cavities, viewed from the port side and below (opaque isosurface from the side and translucent from below, both at liquid volume fraction, $\alpha_L=0.5$) with steady and modulated ventilation. All snapshots are at $2.126 D_{\text{cav}}/U_\infty$ after initial modulation.

With ventilation flow sinusoidally modulated, the final mean state is strongly dependent on the character of the modulation. With chosen modulation amplitude $A=0.2$, the final state can be larger and more steady, as with modulation frequency, $f=0.79f_0$ (red dashed lines, figure 3). Here, the closure appears to be twin vortex. However, with $A=0.2$ and $f=2.76f_0$ (blue dash-dot, figure 3), the cavity is reduced to a smaller, reentrant state. Re-running with $f=2.76f_0$ and $A=0.5$ (green dotted, figure 3), the cavity evolves to another pulsing state and appears to be approaching a twin vortex closure-with a smaller amplitude than the unmodulated cavity. It is noteworthy that although with $f=0.79f_0$ and $A=0.2$, the dominant pressure spectrum coincides with the modulation frequency, this is not the case at either of the higher frequency modulation conditions. The modulation frequency is discernible in the pressure
spectra, but it is not dominant. In all cases, even those with apparent twin vortex closure, there is some pulsation evident in the pressure history. Also in all cases, the regular nature of pressure pulsation history is sporadically broken by disruptive events. Typically this is due to water splashing in the supercavity as gas is shed. The strongest disruptor is associated with the nearly regular reentrant jet (modulation set to $f=2.76f_0$ and $A=0.2$).

4. Conclusions
A computational investigation of the physical concept of pulsation mitigation via a priori modulation of ventilation flow has been presented. The nature of cavity pulsation can be strongly altered by a priori modulated ventilation flow. This was determined with water tunnel experiments by Skidmore et al. [5], and the results here confirm and expand somewhat on those findings. It was computationally demonstrated here, that a simple sinusoidal modulation of the flow can drive the pulsating cavity to either a larger twin-vortex condition or a smaller reentrant condition. It also appears that both the frequency and amplitude of the modulation have a strong effect on the final state. To further extend this kind of modeling to a specific engineering application, an in depth validation study must be done.

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