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The control of ventilated supercavity pulsation and noise

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ABSTRACT

A technique to control ventilated supercavity pulsation and noise is explored analytically and verified experimentally. The technique, which has its roots in parametric oscillators, changes the stiffness and, therefore, resonance frequency of the ventilated supercavity gas/water system by modulating or adding a sinusoidal component to the ventilation rate. This results in the ventilated supercavity effectively being driven off-resonance as the frequency of the interface waves which force the supercavity gas/water system remain largely unchanged. A wide range of ventilation rate modulation frequencies cause the pulsating supercavity to transition into twin vortex closure, typically within 0.25 sec of modulation initiation. Accompanying the transition from pulsation to twin vortex closure is a reduction in the radiated noise, to the continuum at the pulsation frequency, often by 35 dB or more. Other modulation frequencies do not suppress pulsation, but are effective at changing the supercavity pulsation frequency.

1. Introduction

Ventilated supercavities are generated by introducing gas into the separated flow region behind a cavitator placed at the nose of a body. The ventilation process provides control of the supercavity interior pressure and, therefore, its size. Supercavitation may significantly reduce the skin friction drag and result in an order-of-magnitude increase in speed compared with conventionally wetted vehicles (Kirschner et al., 2001; Vlasenko, 2003; Wosnik et al., 2003). Ventilated supercavities are typically classified according to their closure regimes as re-entrant jet, twin vortex, or pulsating. In a free-field environment, with a gravitational field transverse to the velocity vector, the Campbell–Hilborne criterion (Campbell and Hilborne, 1958) identifies the closure regimes that are likely to occur in terms of the product of the cavitation number, $\sigma = 2(p_\infty - p_c)/(\rho V_\infty^2)$, and Froude number, $Fr = V_\infty/(\sqrt{gD_n})$:

$$\sigma Fr < 1 \quad \text{Twin Vortex}$$
$$\sigma Fr > 1 \quad \text{Re} - \text{Entrant Jet}.$$

Here V_∞ is the freestream velocity, D_n is the maximum diameter of the cavitator (or equivalent disk diameter if the cavitator is not axisymmetric), p_∞ and p_c are the pressures in the freestream and in the supercavity, respectively, ρ is the water density, and g is the gravitational acceleration of 9.81 m/sec^2. It has been observed that a stability parameter, $\beta = (p_\infty - p_v)/(p_\infty - p_c)$, i.e., the ratio of the vaporous cavitation number to the supercavity cavitation number, must be greater than 2.645 for pulsation to occur in a free-field environment (Paryshev, 2003, 2006; Kirschner and Arzoumanian, 2008). During water tunnel testing, tunnel walls induce a blockage effect that can cause the above relations to deviate from their reported free-field values (Tulin, 1961; Brennen, 1969; Logvinovich, 1969; Kawakami and Arndt, 2011). Note that in this paper the terms "supercavity" and "cavity" will be used interchangeably.

Ventilated supercavity pulsation is an autoresonant phenomenon of the gas/water system (Silberman and Song, 1959, 1961; Song, 1961, 1962). It is characterized by the presence of traveling surface waves on the cavity interface that cause the cavity volume to change periodically and, in correspondence, the cavity pressure to change. The oscillating cavity pressure sets the air/water interface into an oscillating trajectory as it separates from the edge of the cavitator (viewed relative to the cavitator) (Skidmore et al., 2015a). The oscillating interface advects downstream to the cavity terminus. The "pinch off" or terminus of the cavity is considered to be the point where the local cavity diameter becomes less than that of the cavitator (Paryshev, 2003). This process results in a strong monopole sound source (Skidmore et al., 2015a; Pierce, 1989). A typical pulsating supercavity generated in the ARL Penn State 0.305 m diameter water tunnel is shown in Fig. 1.

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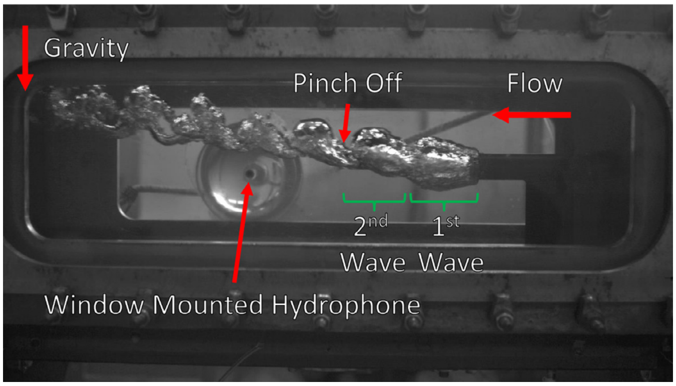

Fig. 1. Photograph of a second order pulsating supercavity in the ARL Penn State 0.305 m diameter water tunnel. This supercavity is classified as second order due to the presence of two waves on the cavity interface prior to pinch off.

Song (1961) modeled a ventilated supercavity as a mass-spring system without damping or forcing, deriving an expression for natural frequency, f_o, as:

$$f_o = \frac{1}{2\pi}\sqrt{\frac{2\pi\gamma p_c}{\rho K \mathcal{S}\ln\frac{R_o}{r_o}}}. \tag{1}$$

Here γ is the specific heat ratio of the gas inside the cavity, K is a constant for a given cavity, $\mathcal{S}$ is the mean cavity surface area, R_o is the tunnel radius, and r_o is the mean cavity radius. Previously, Eq. (1) was used to successfully predict the resonance/pulsation frequencies of ventilated supercavities (Skidmore et al., 2015a). Pulsation occurs when the interface instability induced wave frequency is equal to the ventilated supercavity gas/water system resonance frequency (Song, 1961).

It is possible to transition from the pulsating closure regime to either the twin vortex or re-entrant jet closure by adjusting the ventilation rate, pressure/depth, or velocity (Skidmore, 2013). However, when these parameters are fixed or limited, an alternate means for mitigation of pulsation is desired. There exists a wealth of experimental data (Michel, 1973; Laali and Michel, 1984; Michel, 1984; Semenenko, 2001) and theoretical models (Kirschner et al., 2001; Paryshev, 2003, 2006; Kirschner and Arzoumanian, 2008; Song, 1961; Hsu and Chen, 1962; Woods, 1966; Spurk, 2002) of pulsation of ventilated supercavities. However, physical demonstration of a means for pulsation control has not been reported. It is noted that consequences of pulsation are an adverse effect on vehicle stability and significant radiated noise. For these reasons, a means to suppress pulsation are desired. One such a method is proposed and numerically analyzed in Section 2. This is followed by a physical means to implement the method proposed in Section 3. Experimental results of the methodology are given in Section 4 before concluding on the methodology in Section 5.

2. Model for the control of ventilated supercavity pulsation

Semenenko (1996) presented a brief numerical investigation on the effect of external periodic pressure perturbations on ventilated supercavity pulsation. He found that certain frequencies could suppress pulsation but did not elaborate on how such perturbations could be induced in a practical setting (i.e., outside of a simulation or laboratory). It also seems plausible that practical pulsation control could be achieved with active/adaptive control of the ventilation rate. This, of course, would require some compatible instrumentation and an appropriate numerical controller. An alternative, simpler approach is to modulate or add a sinusoidal component to the ventilation rate at a frequency away from the pulsation/resonance frequency. This, theoretically, changes the supercavity resonance frequency from its constant ventilation rate value and, as a result, inhibits resonance excitation from the interface waves, whose frequencies remain largely unchanged. This approach, in keeping with the analysis of Song (1961), can be simply modeled with a modified form of Hill's equation (Teschl, 2012), as:

$$\frac{d^2s}{dt^2} + 2\pi b f_o\frac{ds}{dt} + 4\pi^2 f_o^2[1 + h\sin(2\pi f_{mod}(t+\tau))]s = \mathcal{F}_o \sin 2\pi f_o t. \tag{2}$$

Here s is the unsteady cavity area, t is time, f_o is the (constant ventilation rate) resonance frequency, b is a damping parameter based on cavity bulk modulus, and $\mathcal{F}_o$ is the fluctuating external pressure amplitude, $\widetilde{P}_a$, divided by the $\frac{\rho}{2\pi}\ln\frac{R_o}{r_o}$ term of Song (1961) and driving the surface area oscillations at f_o. The terms h, f_{mod}, and τ are parametric amplitude, frequency, and phase variables, respectively, that are used to modulate the stiffness and, thus, resonance frequency in a time-dependent manner. Note that for an undamped ($b = 0$), unforced ($\mathcal{F}_o = 0$), and unmodulated ($h = 0$) oscillator, Eq. (2) reduces to the expression derived by Song (1961). Also, note that for the case of $h = 0$, Eq. (2) is that of a damped harmonic oscillator being driven at its resonance frequency, f_o.

Eq. (2) was solved numerically using the fourth order explicit Runge–Kutta solver, ode45, of MATLAB (2013), for the case of a cavity pulsating between 10 and 70 Hz at 0.25 Hz intervals, with modulation frequencies between 10 and 70 Hz at 0.25 Hz intervals, and without damping ($b = 0$). The amplitude of the forcing function, $\mathcal{F}_o$, was estimated to be 11.63 m^2/sec^2. This assumes that the fluctuating external cavity pressure amplitude is equal to the fluctuating internal pressure amplitude, which was typically 3.5 kPa for a pulsating cavity with an average radius of 2.3 cm inside of the 0.305 m diameter water tunnel (Skidmore et al., 2015a). Modulation strength values range from 0.10 to 0.25, which correspond to oscillations about the constant ventilation rate resonance frequency from 4.9% to 11.8%, respectively. Such oscillations in the resonance frequency appear to be feasible without prohibitively large oscillations in the ventilation rate. This stems from the shallow slope of typical dimensionless ventilation rate, $C_{\dot{Q}} = \dot{Q}/(V_\infty D_n^2)$, versus σ curves in the re-entrant jet flow regime where, as with pulsation, it is relatively difficult in this regime for air to escape from the cavity (Spurk, 2002). The phase variable, τ, was given a random value between 0 and 2π sec for each numerical solution.

Typical plots of unsteady cavity area, s, versus time are shown in black in Fig. 2. Fig. 2 also depicts the growth of unsteady cavity area in time of the forced but unmodulated system in magenta. Note that, depending on values of f_o, f_{mod}, and h, the unsteady cavity area may range from exhibiting stability with time, as shown in Fig. 2a, to resonant instability, as shown in Fig. 2d, where it grows at a rate much faster than that of the unmodulated but forced system. The growth rate envelope of the unsteady cavity area was regressed to $s = \exp(\alpha t)$ and contours of α are plotted in Fig. 3 for all values of f_o, f_{mod}, and h considered. The value of α for the unmodulated ($h = 0$) but forced system is denoted by the magenta "†" on the color bar in Fig. 3. Values of α denoted by white in Fig. 3 correspond to regions of stability (i.e., as depicted in Fig. 2a) where red corresponds to instability, with s growing much more rapidly than for the unmodulated but forced system (i.e., as depicted in Fig. 2d). Regions of green in Fig. 3 correspond to s growing in time, as shown in Fig. 2b, but not as rapidly as for the unmodulated but forced system; while regions of orange correspond to growth rates above that of the unmodulated but forced system (i.e., as shown in Fig. 2c) but below that of Fig. 2d. Note the increase in white or region of stability as the modulation strength increases from 0.10 to 0.25.