

Closure mechanisms of ventilated supercavities under steady and unsteady flows

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Abstract. The present work reports some interesting experimental results for ventilated supercavitation in steady and unsteady flows. First, a variety of closure modes obtained as a result of systematic variation in Froude number and air entrainment, are reported. The closure mechanisms were found to differ from the standard criterion reported in the literature. Further, the occurrence of a variety of stable and unstable closure mechanisms were discovered that have not been reported in the literature. Next, a hypothesis is presented to explain the cause behind these different closure mechanisms. The proposed hypothesis is then validated by synchronized high-speed imaging and pressure measurements inside and outside of the supercavity. These measurements show that the supercavity closure is a function of instantaneous cavitation number under unsteady flow conditions. (Research sponsored by *Office of Naval Research*, USA)

1. Introduction

Supercavitation is a technique for achieving high speeds underwater by enveloping a body in a gaseous cavity. It is of great practical interest owing to its advantages in the drag and noise reduction for high-speed underwater vehicles. A supercavity can be formed at lower speeds by injecting non-condensable gas, typically air downstream of the cavitator. This is commonly referred to as ventilated supercavitation. The parameters that characterize ventilated cavities are cavitation number, $\sigma = 2(P_\infty - P_C)/(\rho_w U^2)$; Froude number, $Fr = U/\sqrt{g d_c}$ and air entrainment coefficient, $C_Q = \dot{Q}/U d_c^2$, where P_∞ and P_C refers to the test-section pressure upstream of the cavitator and cavity pressure respectively, ρ_w , U and g correspond to liquid density, the free-stream velocity in the test-section and gravitational acceleration, respectively, d_c denotes the cavitator diameter, and \dot{Q} is the air ventilation rate. In understanding the mechanism of air entrainment, the study of supercavity closure, i.e. how a supercavity closes in the rear portion, is particularly relevant, since a majority of ventilated gas leaks from the closure region. The ventilation demand to form and sustain a supercavity is dependent upon the closure mode of supercavity under different flow conditions.

Four types of closure mechanisms have been reported in the literature. These include re-entrant jet, twin-vortex, quad-vortex, and pulsating modes. Three modes have been thoroughly reviewed by Franc and Michel (2005). Based on an empirical relation from Campbell and Hilborne (1958), the re-entrant jet mode should occur when the product $\sigma_c Fr > 1$ while the twin-vortex mode is expected to appear at $\sigma_c Fr < 1$. However, Kawakami and Arndt (2011) observed twin-vortex mode as the dominant closure mechanism in their experiments where $\sigma_c Fr$ was always much greater than one, where according to other authors the re-entrant jet regime would be expected. The third closure mechanism, i.e. quad-vortex mode, was first reported by Kapankin and Gusev (1982). This mode consists of four vortices situated in pairs, one pair above the other. According to Kapankin and Gusev (1982), this mode occurs when the cavitator angle of attack was less than some critical angle which is a function of U_∞ (Tunnel

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velocity), and the drag coefficient of the cavitator at zero cavitation number. Although the quad-vortex closure has been observed in the experiments at SAFL (Kawakami and Arndt 2011), the conditions of this closure did not match those predicted by Kapankin and Gusev (1982). Moreover, neither of the studies has provided clear physical explanations of the occurrence of quad-vortex closure mode. Finally, the pulsating mode refers to a particular unsteady closure phenomenon that occurs in a pulsating supercavity, which commonly occurs at extremely high ventilation flow rate (See details in §2.2.3).

Besides the existing inconsistency in the onset criteria for different closure mechanisms, a recent investigation on the closure mechanism at SAFL (see details in §2.3) reveals many new closure modes which are not readily interpreted and reconciled with prior literature based on existing empirical relations involving σ_c , Fr and C_Q . The lack of agreement among various studies is commonly attributed to the differences in experimental procedure such as the tunnel type and blockage ratio. These limitations on our ability to explain the observed physical phenomena, including the change of flow conditions leading to transition between different closure modes, indicates a deficiency in our current understanding of the supercavity closure. The present work is aimed at bridging this gap in the current understanding of supercavity closure.

2. Experimental Methodology

In this work, the variation of closure modes of ventilated supercavitation is investigated by systematically varying Fr and C_Q for a range of cavitator sizes. This experiment uses a backward facing cavitator model (Figure 1). In the backward facing model, the strut is placed upstream of the cavitator to avoid the interaction between the formed cavity and the strut body which was shown to affect the supercavity closure (Kawakami and Arndt 2011). The experiments were conducted with 10, 20, 30 and 40mm-diameter cavitators to investigate the variation of closure modes over a wide range of parameters with Fr varying in the range of 5-40 and C_Q of 0.001-10 and $B=5\%$, 9% , 14% and 19% . The experiments on unsteady ventilated supercavitation are conducted with the aid of a gust generator located upstream of the cavitator. The gust generator consists of two oscillating hydrofoils, which are placed upstream of the cavitator at a distance 180 mm. These two hydrofoils are oscillated in phase by the system's pivot arm to generate uniform gusts. This pivot arm is linked to a flywheel through a connecting arm, which extracts the periodic motion from the motor. An eccentric flywheel can allow for gusts of varying amplitudes. The detailed description of gust generator mechanism is provided in Kopriva *et al* (2008). High speed imaging is conducted and synchronized with pressure measurements inside the cavity and test section. The experiments were conducted at a fixed $Fr = 20$ and $C_Q = 0.03$ with a cavitator diameter of 10 mm to minimize blockage effects. The gust amplitude is kept fixed for all the experiments and the gust frequencies were varied between 1 – 10 Hz. The pressure measurements and high speed videos were captured at a sampling rate of 1500 Hz.

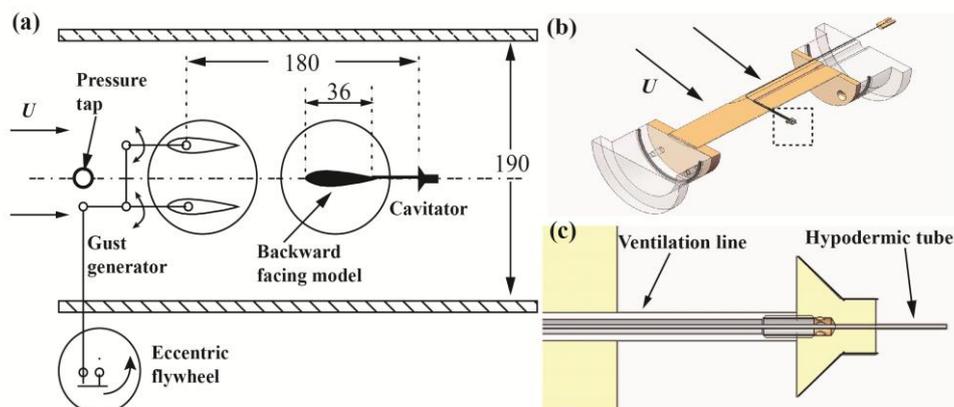


Figure 1: Experimental Setup

3. Results and Discussion

This series of experiments provided a rich array of different closure modes, including several modes that were not reported in the literature, as illustrated in Figure 2. In general, the closure modes are divided into stable modes and unstable modes. The four stable closure modes are Re-entrant Jet (RJ), Twin-vortex (TV), Quad-vortex (QV) and Foamy Cavity (FC) (Figure 2a - d). Note that FC is

strictly not a closure mode, but it is one of the states in which a supercavity might exist. The unstable closure modes include Hybrid QV-RJ (QVRJ), Hybrid TV-QV (TVQV), Pulsating Twin vortex (PTV) and Interacting Vortex (IV). These unstable closure modes were either observed at the transition of two stable closure modes or at extremely high ventilation rates. QVRJ closure, formed at the transition of QV and RJ closure has the features of both QV and RJ modes and the cavity has a foamy end with four vortices. TVQV closure refers to the transition between QV and TV modes and may have one to four vortices. It was found that the bottom two vortices were more stable than the upper two, however sometimes even one of the two lower vortices disappears. Similarly, a TVRJ closure, characterized as the supercavity with foamy rear and two vortices, was also observed. Finally, at very high flow rates, PTV could be seen, where both the vortices pulsate in longitudinal direction, and closure may intermittently break into elongated pockets of air because of severe instabilities on the cavity surface. At similar flow conditions, but at a higher blockage, IV mode was observed, where the two vortices would interact with each other to form one single thick vortex at the closure. In our experiments, TV and RJ mode does not obey the Campbell-Hilborne criterion. Also, QV is not observed at the condition reported by Kapankin and Gusev. Clearly, no empirical criterion for other observed closure modes have been reported in the literature.

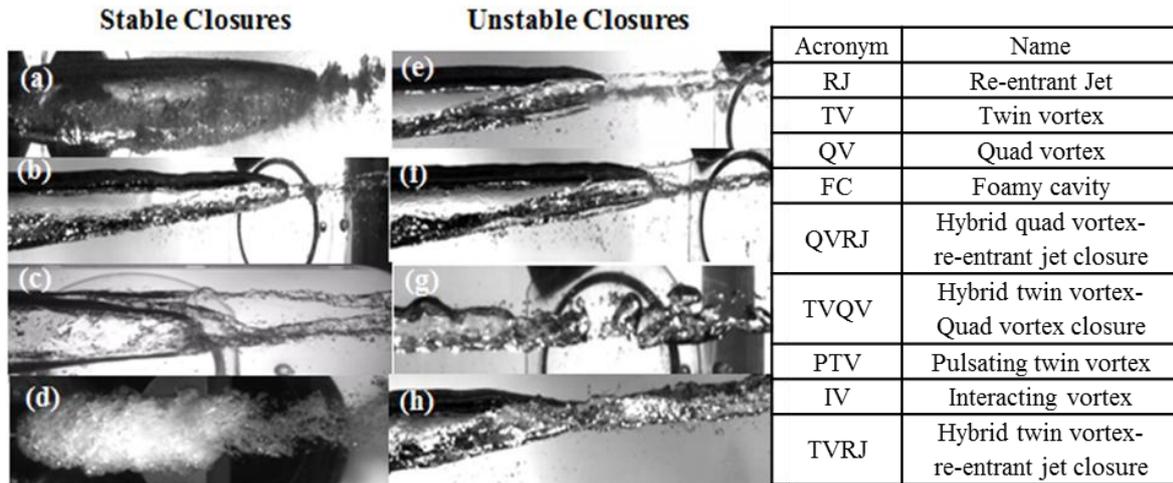


Figure 2: Assembly of different closure modes observed: (a) RJ (b) TV (c) QV (d) FC (e) TVRJ (f) QVRJ (g) PTV (h) IV.

A hypothesis on the physical mechanism that determines the closure modes of a ventilated supercavity is proposed as follows in order to interpret the above-mentioned observations. The hypothesis posits that the closure mechanism is mainly determined by the pressure difference ($\Delta\tilde{P}$) across the gas-liquid interface at the cavity closure. The pressures are normalized as follows: $\Delta\tilde{P} = (P_C - P_{TS}) / P_d = \tilde{P}_C - \tilde{P}_{TS}$, where $P_d (= 0.5\rho U^2)$ is the dynamic pressure in the test section of the water tunnel, \tilde{P}_C is the pressure inside the cavity at the closure and \tilde{P}_{TS} represents the pressure just outside the cavity closure. It is worth noting that P_C is not necessarily equal to the mean cavity pressure due to the possibility of pressure gradients due to internal flow circulation within the supercavity. The formation of a stable closure is a result of a balance among pressure difference, gas/liquid phase momentum across the interface, and other factors such as surface tension, which could contribute to subtlety of different vortex-based closure mechanisms. We hypothesize that the change of Fr , C_Q , B or type of experimental facility leads to $\Delta\tilde{P}$ resulting in the variation of different closures. Spurk (2002) notes that the opening of the cavity (and thereby, cavity closure) is determined by the change of streamline curvature and the free streamline at the cavity closure. Our experiments reveal that the radius of curvature (R) of the streamlines at the supercavity closure follows this general trend: $R_{TV} > R_{QV} \gg R_{RJ}$. Using this radius inequality, we hypothesize that the criterion to obtain different closure follows this general trend: $\Delta\tilde{P}_{RJ} \gg \Delta\tilde{P}_{QV} > \Delta\tilde{P}_{TV}$. RJ is formed when \tilde{P}_{TS} is significantly higher than \tilde{P}_C . As $\Delta\tilde{P}$ reduces to a critical value when it is no longer sufficient to sustain a re-entrant jet, the closure region transitions from RJ characterized by chaotic mixing flow pattern to vortex-based

closures, from QV to TV gradually as $\Delta\bar{P}$ keeps decreasing. To get an insight into the physical mechanisms that cause the change in cavity shape and closure, we conducted simultaneous pressure measurements both inside and outside the cavity in synchronism with the high-speed imaging of cavity behavior under different gust frequencies. To quantify the effect of unsteadiness, the pressure data are recorded at steady state ($Fr = 20$, $C_Q = 0.03$), under which RJ closure is present. The flapping of the gust generator causes fluctuation of test-section pressure which in turn leads to an oscillation in cavity pressure. Figure 3 shows the frequency response analysis of cavity pressure data and it is observed that the cavity pressure oscillates at a frequency close to the gust frequency, although sometimes a minor frequency mode can be seen.

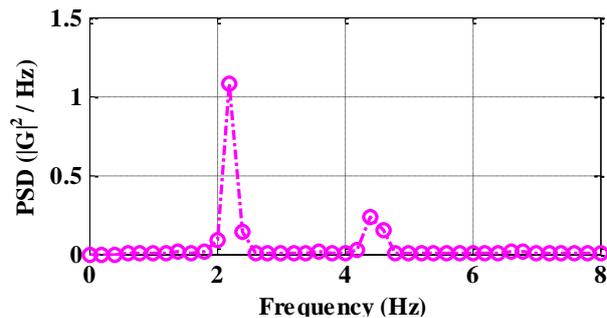
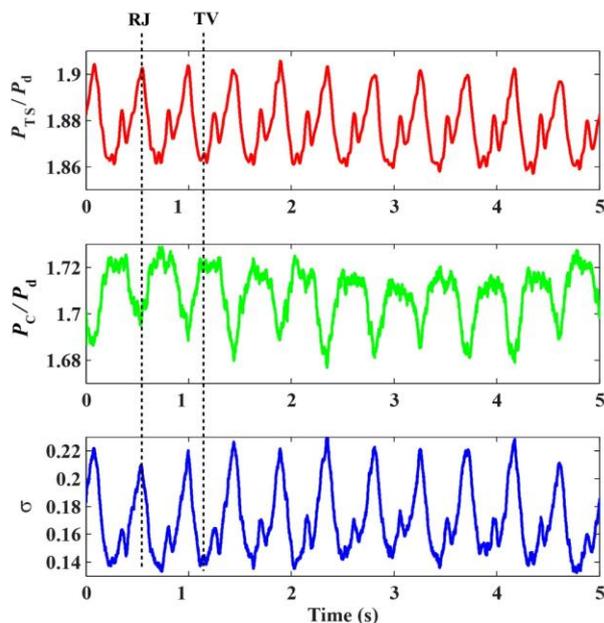


Figure 3: Power spectral density of cavity pressure data at a gust frequency of 2.2 Hz.



4. Conclusions

In this paper, a variety of supercavity closures have been obtained by a systematic variation of Froude number and air entrainment. It is found out that the supercavity closure is also dependent upon the path taken. Further, a hypothesis is presented to explain the cause behind these different closure mechanisms. The proposed hypothesis is then validated by synchronized high-speed imaging and pressure measurements inside and outside of the supercavity. These measurements show that the supercavity closure is a function of instantaneous cavitation number under unsteady flow conditions.

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Figure 4 shows the periodic variation in normalized test-section pressure, normalized cavity pressure and their difference (i.e. cavitation number) over many gust cycles. Pressure information in the liquid and gas propagate at different speeds, resulting in a phase lag between the measurements of test-section and cavity pressure. This difference in phase of the test-section pressure and cavity pressure leads to the oscillating nature of cavitation number. Synchronized high-speed video and pressure measurements reveal that the cavity closure alternates between RJ and TV modes, with the RJ mode forming at instants when the cavitation number attains its maximum (0.2 - 0.22), while the TV mode is obtained when the cavitation number attains its minimum (~0.14). Thus, our experiments have demonstrated that cavity closure is dependent upon the pressure difference at the rear end of supercavity and can undergo transition even when none of the steady-state non-dimensional parameters, viz. C_Q , Fr or blockage etc. in the flow has been altered. Simultaneous measurements of internal and external pressure at the rear portion of the cavity for different supercavity closure modes is required to further substantiate our proposed hypothesis.

Figure 4: The periodic variation of normalized test-section pressure, cavity pressure and cavitation number at a gust frequency of 2.2 Hz.