Experimental Study of Ventilated Cavities on Dynamic Test Model

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Abstract

A series of experiments were conducted to examine ventilated cavity physics. Over 200 hundred test runs were performed. Tow tank tests were conducted to examine the stability of ventilated cavities. The tests were performed on three different models at speeds up to 55 feet per second. One 6.25-inch diameter model allowed body motion with 3 degrees of freedom. The model also employed a cavitator that could be pitched to +/- six degrees angle of attack. The models allowed the examination of ventilation data at a variety of length scales and for a number of cavitator shapes and sizes. Some tests also incorporated simulated rocket exhaust. High frequency solid-state pressure transducers were used to determine the stability of the cavities. The tests confirmed that the dominant cavity frequency was correlated with cavity length and towing speed. Dynamic model motion and the rocket exhaust both tended to enhance overall cavity stability. The impact of free shear instability on cavity stability was negligible at these speeds.

1. Background

Supercavitation is a revolutionary means to achieve drag reduction of up to 90% on an underwater body. This level of drag reduction will have dramatic effects on the operation of naval forces. The high level of drag reduction is achieved by enveloping the body within a gaseous cavity. Only small areas at the nose and on the afterbody remain in contact with the liquid. The nose contact region called the cavitator, produces a wake in which the gaseous envelop exists and the body travels. The aft section (usually fin-like control surfaces or a planing body section) support vehicle weight and provide stability. The wetted forces determine vehicle speed and vehicle stability. The wetted forces must be specified and understood to determine vehicle maneuverability. Because the wetted contact area is small, unwanted changes in the wetted contact arising from local cavity breakdown area may results in large destabilizing forces and moments for a supercavitating vehicle. Thus to insure control authority a supercavitating vehicle must remain in a well-defined cavity. Cavity instabilities may give rise to local disturbances that result in local cavity breakdown and loss of control authority. Several different mechanisms act on the cavity interface that could cause instabilities. Three of these mechanisms are ventilation forced instabilities, free shear instabilities and bubble oscillation.

The cavity boundary is defined by a constant pressure surface. The boundary is known in the case of vaporous cavitation. The basic geometry of a cavity is roughly elliptical as detailed by several formula listed in May 1975. Expressions for the maximum diameter, d_{max}, and length, l, of a cavity as functions of cavitator length scale, d, drag coefficient and cavitation number, σ are available. The cavitation number and drag coefficient then determine the cavity geometry. The determination of cavitation number and hence cavity structure in ventilated cavitation is more complicated.

Ventilation is the pressurization of the cavity from within. An examination of empirical data shows that pressurization of the cavity (at a fixed speed) lowers the cavitation number and increases the cavity size. The level of understanding about ventilated cavities however is not complete. Pressurization is obtained by pumping gas into the cavity. The level of pressurization that may be obtained in the cavity ultimately depends on the outflow of gas from the cavity. Complicated flow structures and unsteady cavity closures govern the outflow of gas from the cavity. Empirical relationships between the ventilation coefficient, $cq = Q/(d^2U)$, the cavitation number, σ, and the cavity Froude number, F, have been obtained (May, 1975). Here cq is the volumetric gas flow into the cavity and U is the vehicle speed. The experimental data shows considerable scatter among different experimental studies and it is difficult a prior to quantify a required volumetric flow needed to generate a cavity of a specific size.

The ventilation system used to develop and sustain a ventilated supercavity can be a source of instabilities. The mechanism initiating the instability is the locally non-parallel flow from the ventilation system interacting with the wall of the cavity. Results obtained in a 1998 series of ventilated cavity tests performed at the NUWCDIVNPT Research Water Tunnel and are shown in Figure 1.

(a) **(b)**

Figure 1. Effect of normal ventilation flow on cavity stability (a) low normal gas flow results in stable glassy cavity (b) high normal flow results free surface cavity waves.

The tests demonstrated how ventilating the cavity through a narrow slot could induce a localized disturbance at the gas-liquid interface, which would then propagate downstream. If the ventilation flow rate was sufficiently localized and strong, a disturbance could be induced which would de-stabilize the entire cavity. This was easily observed by the transition of the cavity from a clear transparent interface, to a blurry somewhat opaque surface, which broke down into a frothy flow downstream. Thus care must be taken in the design of an experimental ventilation ports to ensure the introduction of ventilation gas itself is not responsible for cavity instabilities.

Free shear instabilities may occur when two nonimmersible fluids are in contact across an interface. The instability mechanism is called the Kelvin –Helmholz instability. For the case of two parallel streams of fluid, linear stability theory yields an exact expression for the conditions required to initiate a disturbance on the fluid boundary. An estimate of the stability of the cavity boundary may be may be constructed using this analysis. The curvature of the cavity is not modeled, as is the variation in local pressure gradient. In general, a favorable pressure gradient will significantly dampen destabilizing ripples. The linear stability theory was applied using the properties of water and air to result in the maximum allowable velocity difference between layers and is listed below:

$$\Rightarrow \left| u_{water} - u_{gas} \right| > 6.6 \tfrac{m}{s} \qquad (1)$$

Bubble oscillation (Parishev instability) may also be present in ventilated cavities. Changes in ambient pressure result in a local migration of the cavity free surface. This in term leads to a volume change in the ventilated cavity. The volume change effects the cavity pressure, which in term effects the cavity shape throughout the cavity. Pressure information in the liquid may propagate at different speeds than in the gas cavity. The cavity response lags the pressure response in the liquid. The result of this phase lag is that the cavity shape and pressure may oscillate. The oscillations of the artificial cavity will be a function of forced changes in the artificial cavity shape arising in the liquid, the time lag between the liquid and gas mediums, as well the volume and length of the artificial cavity. The artificial cavity pressure will also be affected by ventilation gas inflow and outflow across cavity boundaries. The mathematical description of the cavity bubble oscillation is extremely complex. Parishev (1978) developed the basis for a simplified model to describe the bubble oscillation problem. The Parishev analysis relied on the Logvinovich "principle of independence" to describe the cavity as a series of independent cross sections. The cavity inflow and outflow was assumed to be in balance. The pulsations in the cavity were small in the analysis. The results of the analysis showed that a single parameter T_0 dictates the cavity stability T_0 is a function only of the Euler number, the cavitation number and the polytropic exponent of cavity gas.

2. Experimental Hardware

The vehicle itself could affect the cavity surrounding a supercavitating vehicle. The propulsion system and vehicle motions, which determine cavitator position, are coupled with cavity dynamics. This experimental study was conducted to determine how vehicle motions and cavitator migrations would impact cavity stability and provide ventilated cavity data on a large-scale model at moderate speed. Three basic model configurations were constructed and tested at the Langley Towing Tank. The overall dimensions of the towing tank are 12-ft deep by 24-ft wide by 2880 ft long, with maximum speeds of 40 knots.

The first test model was a strut mounted two-inch diameter model. The two-inch model was tested in both the NUWC water tunnel and at the Langley Towing Tank. The model employed two independent internal conduits for cavity ventilation and simulated rocket plume exhaust gases. A drawing and a photograph of the model are shown in FIGURE 2. The brass model basically consists of a cylindrical body with dual plenums and a leading edge cavitator assembly. The model was designed to be modular so that several cavitators and tail cones of different shapes and sizes could be attached. A typical model configuration produced an overall vehicle length of 19 inches. Bottled Nitrogen to ventilate the cavity and steam for thrust generation, are passed through separate conduits through the strut. The gas used throughout the experiment was bottled nitrogen, which was injected through forward facing, azimuthally distributed holes immediately behind (downstream) of the cavitator plate. In the water tunnel test steam or Nitrogen was vented through the tail cones to simulate rocket exhaust. In the tow tank test, nitrogen or carbon dioxide was vented. The model was instrumented with an Assurance Technology 12/4 Nano 6 component load cell and seven pressure taps. The static pressure tap locations along the model are indicated in Figure 2.

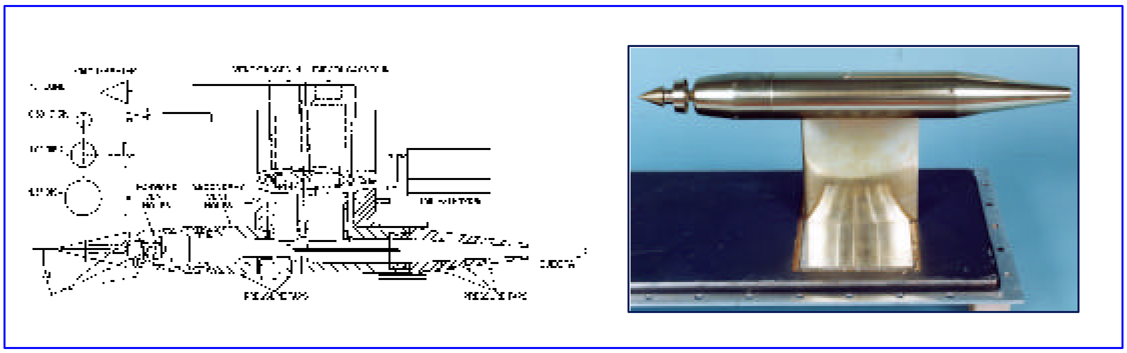

Figure 2 2 Inch Diameter Water Tunnel and Tow Tank Model.

The second test model was a sting mounted model shown below in Figure 3. This “ventilation” model was used to examine a ventilated cavity with a narrow clearance point in the absence of effects from the test model geometry.

(A)

(B)

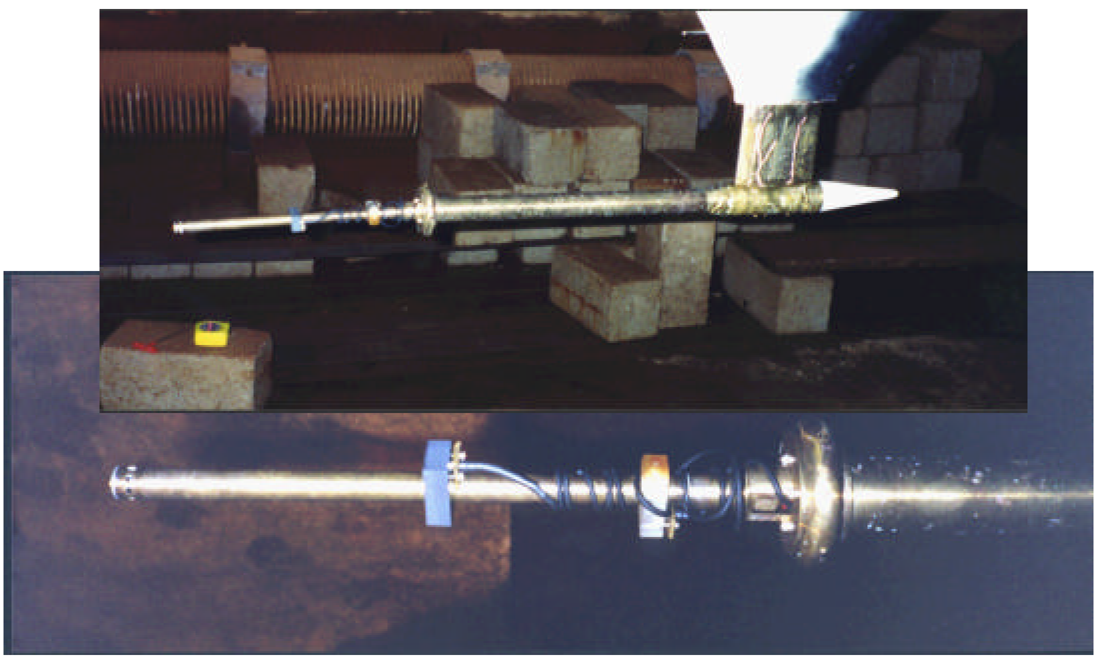

Figure 3 Strut Mounted Ventilation Model
(a) Model in Langley Dry Dock
(b) Pressure Sensors and Choke Point

The ventilation model consists of a cavitator affixed to a strut. Different shaped and sized cavitators could be used. A choke point was built on the model to produce a prescribed narrow cavity clearance at a fixed distance from the cavitator. The length of the distance from the fixed choke point could be varied from a minimum of 6 to a maximum of 24 inches. The model and the choke point were equipped with low (Static ports) and high frequency dynamic transducers to measure global and local cavity pressure fluctuations. The solid-state dynamic sensors were mounted on the blocks shown in Figure 3B. The model also allowed simulated rocket ejection behind the choke point. Over 60 tow tank runs were completed with this model.

The motivation behind the construction of the third model was the need for experimental data in conditions that approach free-range conditions as closely as possible. The effects of cavitator and vehicle motion on cavity stability were studied with this model. The velocity and length scale were also both important considerations. 6.25 inches diameter was selected. A schematic of the main features of the model and a photograph of the model are shown in Figure 4.

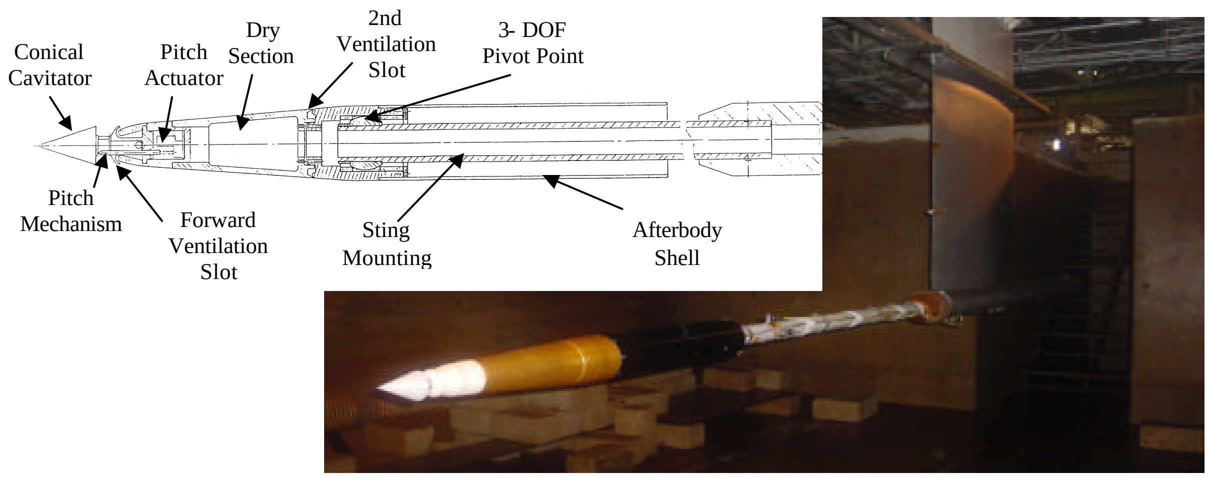

Figure 4 6.25 inch Dynamic Model.

The model is equipped with ventilation slots behind the nose and at two points along the forecone. The ventilation flow was supplied through two instrumented lines. The ventilation flow was measure with Porter fast response Series 100F and 200F mass flowmeters. The model was instrumented with static pressure ports and high frequency dynamics pressure transducers. PCB Model 103A02 and Model 103A12 were used to take the dynamic pressures. The three dynamic sensors were flush mounted; two approximately 11 inches from the cavitator at 180 degrees to each other and a third at approximately 16 inches.

A free running vehicle experiences dynamic forces that typically result in low frequency oscillations of the cavitator. These motions may impact the ventilated cavity stability. In addition to steady flight, a maneuvering vehicle also experience commanded cavitator positions as well. To assess the impact of these effects on basic cavity stability and ventilation requirements, the model was mounted on a ball joint with free rotation with plus and minus three degrees of freedom in the pitch and heave planes and 180 degrees in roll. The model was sting mounted. The sting and model were instrumented with accelerometers to measure model motion in a known reference frame. A small electric motor was positioned in the forecone to actuate the cavitator. The cavitator could be moved to +/- 6 degree from the level position at a rate of approximately 1.5 degrees per sec. A number of different sized disk and cones were built and tested. Some are shown in Figure 5. The narrow cone is a 20-degree half angle. The towing carriage was fitted out with sufficient lighting so that several video cameras would provide visualization of the cavity's motion throughout each run. Approximately 90 runs were conducted at speeds from 25 to 55 feet per second.

3. Results

The tow tank tests first examined ventilation forced instabilities with each of the three models. The testing with the 2-inch diameter model in the towing tank produced identical results to earlier test results outlined in a water tunnel when the blockage correction outlined in Wu (1971) was used. The two-inch model and the ventilation model produced large cavities compared to model radius. Both the tow tank and water tunnel tests showed that ventilation forced waves could be created by poor ventilation design. In the unstable case, the overall average cavity pressure and hence cavitation number of the cavity was not affected by the presence of the ventilation forced waves. These cases had the same measured ventilation coefficient. The waves were caused by the local ventilation flows only. The local flow was controlled by providing the same mass flow through different size slots and thus only varying the local velocity. The ventilation forcing is simply a function of the magnitude of the jet that contacts the boundary. Hence, the angle of the jet to the boundary, the distance of the jet from the boundary and the velocity of the jet determine this forcing function. At speed up to the maximum tow carriage velocity of 55 ft per second all three models could be enveloped in a stable cavities that weren't limited by the ventilation slot design.

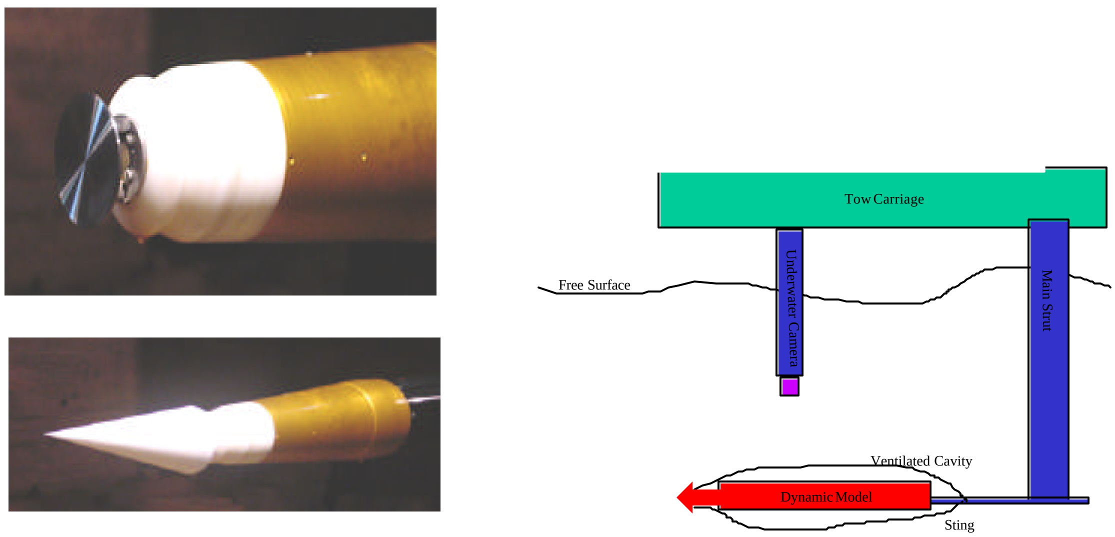

Figure 5 Cavitator Configurations and Test Schematic.

For each test condition several parameters were recorded. The basic parameter nondimentional groups, cavitation number, ventilation coefficient and cavity Froude number were determined for each run. In addition to the basic cavity pressure and volumetric gas injection, the accelerometers were used to measure model and sting oscillations. For all test conditions the cavity dynamics were not well correlated with model oscillations. Data was sampled at 1000 Hz. In addition to the 19 channels of recorded data standard VHS video and visual observation were made for each run. Underwater video was also used with the dynamic model. The sequence of events during a typical carriage run is shown in figure 6 for data taken with the ventilation model. The ordinate is time in thousandths of a second.

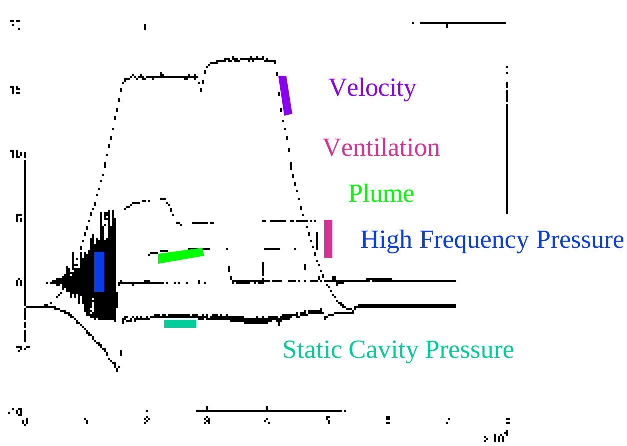

Figure 6 multiple test conditions during a single carriage run.

This run consisted of a ramp up to a steady velocity and then a change in speed to a second velocity. The drag of the ventilation model effectively has no impact on the carriage speed. The ramp up in speed takes approximately 10 seconds. The first speed of 50 feet per second was held constant for approximately 12 seconds. The acceleration to a steady speed of 52 feet per second took approximately 3 seconds. The 52 feet per second speed was held constant for approximately 13 seconds. As the model accelerates the dynamic (high frequency pressure transducers experiences dramatically larger forces and response accordingly. The static pressure owing to the local pressure coefficient along the body drops as the model accelerates. Ventilation gas flow is initiated at approximately 1.5 on the time scale and rise from zero to a higher initial value and levels near 2.5 seconds. The cavity formation occurs at the advective speed if the gas supply is sufficient, as it was in this run. As such within one tenth of asecond the cavity enveloped the location of both pressure sensors. The response of the high frequency probe occurs within a few thousands of a second of the cavity passage. The amplitude of the pressure fluctuations decreases markedly from water to cavity gas as seen in the figure. The high frequency sensor could then by be used to identify the position of local cavity passage. The response of the static sensor occurs with response times on the order of a fifth of a second. This response was longer in part because of the length of the lines from the pressure port and the transducer. During the run ventilation flow rate and nozzle flow rate were both varied. The static pressure remains near the cavity pressure (nominal values of the cavitation number for this run varies are 0.055 and CQ of 0.44). Because of the relatively high CQ the overall cavity size and cavitation number are insensitive to the introduction of additional gas flow or plume flow. The amplitude of the fluctuating pressure within the cavity however changes in response to the initial, termination and subsequent initiation of plume flow. For an undisturbed aft cavity, the pressure fluctuations in the cavity gas in the fore cavity are near zero .The visual observation of the cavity during this transient indicated that free surface wave were not excited by changes in gas flow rates. Two different dynamic pressure sensors record virtually identical amplitude and frequency information (there of course is a phase difference as the relative position of the sensors changes) regardless of their position within the gas cavity. No evidence of cavity gas recirculation was observed in any conditions. Two additional dynamic sensors were mounted within the narrow clearance ring. The ring sensors recorded near identical frequency information but the local amplitude of the pressure fluctuation was less than the upstream sensors in cases were the cavity clearance at the ring was small. No pressure sensors were located downstream of the narrow clearance point. This data suggests that changes in cavity termination conditions may change overall cavity stability.

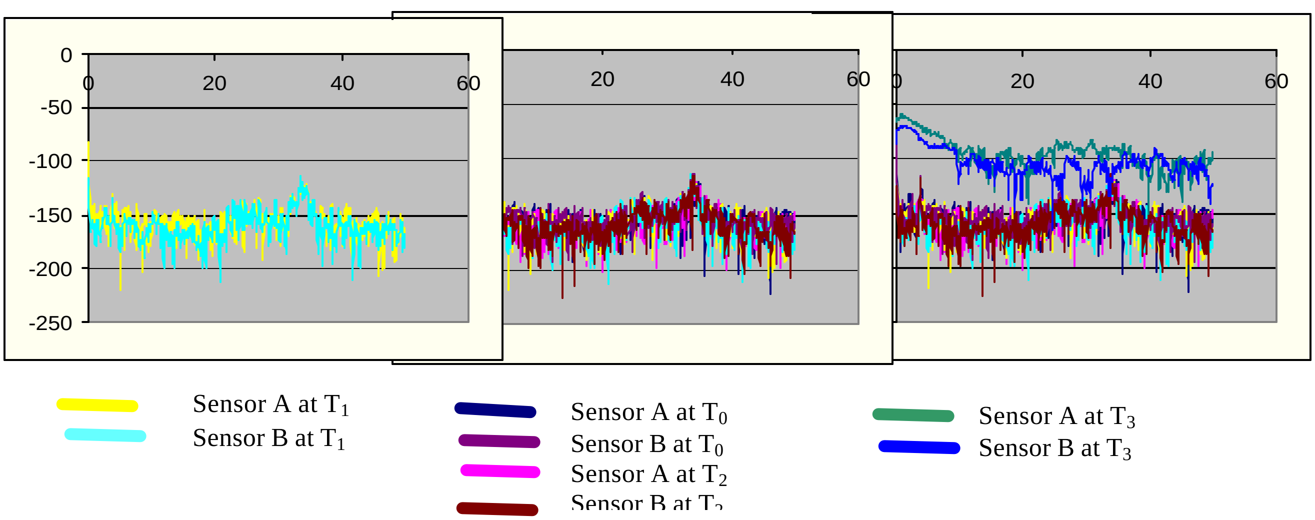

Figure 7 Persistence of Cavity Oscillation (Relative Amplitude as a function of Frequency)

Data from the dynamic model is shown in figure 7. The data is taken from two sensors on the dynamic model that are at the same axial location. The spectrum was windowed in sequential 10 seconds intervals beginning 1 second after the initiation of ventilation gas. The conditions for the run were Cq= 0.32 Froude number = 15.1 and a cavitation number 0.59. Conditions were held constant for 33 seconds. The leftmost plot shows the frequency response of the two sensors during the second 10-second time window (Time T_1). Both the amplitude and frequency of the response are nearly identical. The second plot overlays these results with data from the previous and following time windows. Again the amplitude and frequency of the sensors are nearly identical at each time. The peaks and relative amplitude are also similar for different time windows as well. The oscillation frequency was universally constant for data sets in which the cavity geometry was head constant by maintaining a uniform ventilation rate at constant carriage speed. There was some evidence of the oscillation dampening with time but no evidence of intensification of the oscillation. The cavity oscillations were at frequencies noncoincident with model or sting motions as measured by the accelerometers. At the latest time T_3 the cavity gas was shut off and the cavity had collapsed. The sensors were thus exposed to wetted flow. We observe the quantum leap in transitioning from gas to liquid flow, no evidence of frequency coherence in the signal and different responses because of different local wetted pressure coefficients. A steady cavity length at a constant velocity was seen to produce persistent frequency response. In cases with changes in cavity length that result from velocity or ventilation changes, the frequency response of the cavity is flat.

During several runs the ventilation gas flow was shut off to measure cavity persistence. The test runs also showed that free shear instabilities were not a concern for model up to eight feet long at speeds up to 55 feet per second. As cavity gas flow was shut off the relatively mean velocity difference across the cavity interface was maximized. In every case the cavity boundary became optically clearer to both visual and video observation. There was not observed at free shear transition location anywhere on the cavity boundary. The fact the cavity boundary was somewhat clearer after the ventilation flow was shut indicated that some ventilation forcing of the cavity was present. As each successive model was built, more care was build into ventilation design. The best results were obtained with introduction of ventilation gas a nearly parallel to the cavity boundary as possible.

Figure 8 shows a comparison of data from the dynamics model performed to compare the effect of model motions on cavity dynamics. The results of three equivalent drag cavitators are compared for test runs at velocities of 45 feet per second. There was an unexpected result in the use of different equivalent drag cavitators. The cone cavitator produced cavities that were slightly narrower than predicted by existing empirical relations. The cones thus produced cavities with narrow clearances over the model forecone. The cavities were on the order of millimeters thin. The experiment was not designed to provide an accurate measure of cavities this thin and as such an exact dimension is not yet known. Much lower cavitation numbers were obtained for the cones than for the disks. The model was completely enveloped in either case. While the blunt cone was in free oscillation the overall cavity physics were unaltered as compared to holding the cavitator fixed.

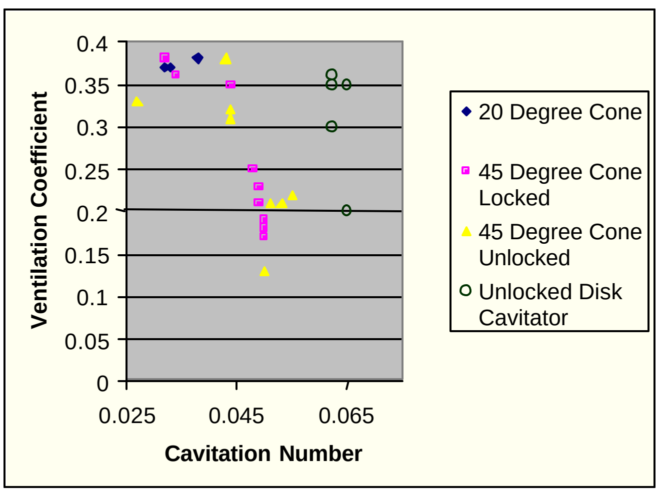

Figure 8 Comparison of Cone and disk cavitators for locked and unlocked models.

The "Parishev" instability of the cavity was affected by narrow or wide cavity clearances. In the case of a wide gap; the cavity was observed to oscillate at a characteristic frequency (Figure 7) that could be correlated to the free stream velocity and the cavity length. This frequency as predicted by the theory was valid for small and large models over the range of speeds tests. In the case of narrow cavities, the characteristic frequency of the cavity was absence even for cavities of constant length held at steady velocity. The narrow cavities then appear to behave differently than the "wide" clearance cavities.

The cavitator was also actuated during the test series. The effect of the cavitator motions was to produce a series of cavities that were similar to the quasi-steady cavities produced by positioning the cavitator at a series of steady angle of attack. The force ventilation, free shear, and parishev instability were unaffected by the actuation of the cavitator at speeds of 1.5 degrees per second. The cavities maintained similar cavitation number for the same ventilation rates as well.

4. Conclusions and Directions for Future Study

Analysis of test data with the various hardware lead to some general conclusions:

(1) The analysis of Parhesev accurately predicts the oscillation frequencies of a ventilated cavity produced by cavitators on the order of 1-3 inches in diameter over speeds ranging from 15-55 feet per second.
(2) Overall cavity dimensions are relatively insensitive to vehicle oscillations.
(3) Vehicle and cavitator motions as well as significant changes in ventilation rate tend to limit bubble oscillations.
(4) Modest actuation of the cavitator changes the body contact location but do not change the cavity interface stability significantly.
(5) Cavities with narrow clearance behave differently than cavities with large clearances.
(6) Overall cavity stability may be significantly impacted by cavity closure conditions.

Additional investigation is needed to understand the sensitivity of cavity stability to model accelerations and rapid changes in ambient pressure. The cavities remained stable for all cavitator sweep rates for every cavitator tested. The limits of this stability need to be explored with faster cavitator actuator. The quantification of the narrowness of the "narrow cavities need to be quantified and the phenomena explored in more detail.

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