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Shear Layer Cavitation Phenomena Behind A Sharp-edged Triangular Wedge

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Abstract

Experimental investigations have been carried out over a three dimensional (3-D) triangular wedge located inside the rectangular channel at a particular height from the bottom of rectangular surface to study both non-cavitating and different stages of cavitating conditions at a Reynolds number of 3.2×10^5. The main objective of the present study is to understand the 3-D visualization of shear layer cavitation over the wake zone in turbulent flow field. Two high speed cameras were used to record instantaneous cavity structure. Simultaneously, local velocity was measured using two components of flow velocity with the help of laser Doppler velocimeter (LDV). Cavitation is seen to occur in the two zones of shear layer: between the flows above the sharp crest of the wedge and free stream flow as well as between the flows which enters from the sides of the low pressure recirculating flow region and the recirculating flow. Velocity measurements (both mean and fluctuating components) carried out in 3-planes agrees qualitatively in identifying the shear layer.

1 Introduction

Cavitation is one of the major problems in all fluid handling units and its being a major concern for most of the researchers to deeply study the extent of its domain. It is a phenomenon of the formation of vapours-filled cavities in a liquid when local pressure falls below the vapour pressure. The bubbles, thus formed, grow in the low pressure region and subsequently collapse in the high pressure zones. Hydrodynamic cavitation can be broadly classified into travelling bubble, attached and vortex cavitation. One such example of vortex cavitation is seen in the shear layers in the jets, wakes or mixing layer. In the present work, flow past an isolated obstacle in the form of three dimensional triangular wedge is studied. This is an example of shear layer cavitation where vortex cores are likely to be zones where cavitation initiates. Before describing the work, a brief review of literature on shear layer cavitation is presented to contextualize the significance of the present work.

Numerical and Experimental works are carried out by many researchers to identify the interactions of cavitating structures and the turbulent wake region of bluff bodies over a range of Reynolds number. Holl (1960) had described the effect of isolated roughness on inception cavitation by taking constant cross-section of circular arc and triangular section and concluded that inception is mainly dependent on roughness height and boundary layer shape parameter. He also provided a correlation between minimum base pressure coefficient (C_{pmin}) and Reynolds number for different geometries. Katz and O'Hern (1986) studied the different stages of cavitation in the shear layer behind a 2-D sharp edged plate at Reynolds number ranges from 1.89×10^6 – 2.28×10^6. They had observed that the cavitation formed in vortex core and drifting both in streamwise and spanwise direction with the eddy structures though they did not correlate the inception cavitation with the flow Reynolds number and stated that is mainly dependent on the air content and population of free stream bubbles. O'Hern (1990) experimentally investigated the inception and developed phase of cavitation in the wake region of sharp-edged plate at Reynolds number ranges from 1.2×10^6 – 2.1×10^6 and described well the importance of coherent vortical structures in the cavitation inception process. He further found out that the strength of streamwise vortices is always less than 10% than that of spanwise vortices. Belahadji et al (1994) observed different types of vortices inside the turbulent wake zone of 2-D object when cavitation is moderately developed at Reynolds number ranges from 1.2×10^5 – 5.2×10^5. He also tried to forecast the information on incipient cavitation from rotational structures in the wake and explained the difference between mean pressure coefficient at the object and incipient cavitation number. In a recent study Liu and Katz (2013) have presented detailed studies on the interaction of unsteady pressure field with cavity corners in their two-dimensional cavity geometry at Reynolds number of 4×10^4. 2-D PIV measurements were carried out over entire flow domain surrounding the shear layer to obtain the velocity distribution and prediction of pressure fluctuation measurement.

The main motivation behind the present work is to study the interaction of flow field behind a three-dimensional (3-D) wedge with cavitating bubbles and in particular to study the effect of instantaneous velocity fields in the regions of bubble collapse since no such literature is available which predicts the three dimensional character of cavitation structures in relation to shear layer vortices behind the wake of an obstacle.

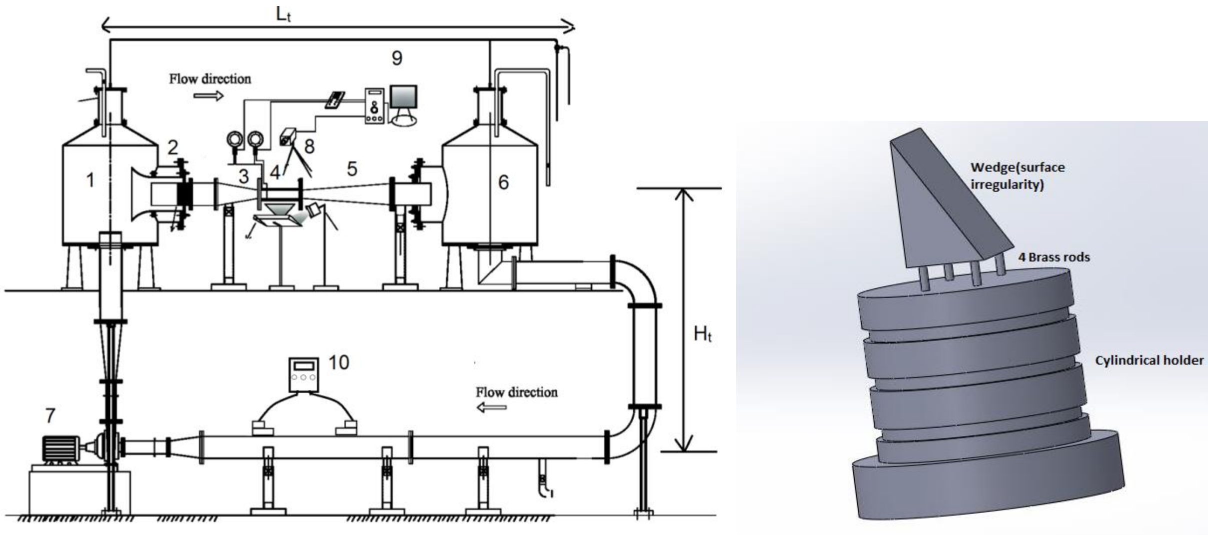
The paper is organized as follows. In the next section, experimental setup and methodology is presented. That is followed by the presentation of results and discussions. Salient observations are listed in the concluding section.

2 Experimental setup and methodology

The present experiment is carried out in a closed loop high speed water tunnel test facility of IIT Madras (Fig.1a). The overall test facility consists of two large identical tanks (1.52m in diameter and 1.52m in height), a honeycomb screen in order to reduce the level of turbulence in the flow domain, a settling chamber, a convergent portion (25º contraction angle and 6.25 contraction ratio) followed by a test section having transparent acrylic (perspex) windows and a divergent portion (10º expansion angle). The test section is 565mm long × 130mm wide × 130mm high rectangular duct. Obstacle used is a three dimensional triangular wedge (Fig.1b) made of acrylic and having a configuration of 50mm long × 30mm wide × 50mm high. The wedge is inserted at an upstream distance of 165mm from duct inlet. The wedge is located 10 mm above the bottom surface of channel by means of 4 small brass rods in order to avoid the interaction of boundary layer flow on the test section window and the flow past the wedge.

The flow is driven by means of centrifugal pump with the help of variable frequency drive and the experiment is carried out for a Reynolds number of 3.2×10^5 based on characteristic length of 50mm roughness height and inlet test section velocity of 6.5 ms^{-1} which is estimated from the flow rate measured using pre-calibrated ultrasonic flow meter (UFM, Fluidyne). Test section pressure was maintained with the help of a vacuum pump. Test section static pressure measurement is carried out by means of Honeywell pressure transducer (Model: STD130-E1H-00000-AN). Two high speed cameras (Photron

Fastcam SA4 and Photron Minicam) was used to capture the images of cavitating structures in front and top views at a frame rate of 3600 fps in the presence of LED lighting. Fastcam SA4 camera was used to trigger the other camera in order to ensure synchronization of the images captured. Local flow velocity was measured using a two-component laser Doppler velocity measurement (mini-LDV from Measurement Science Inc.).



a) *b)*

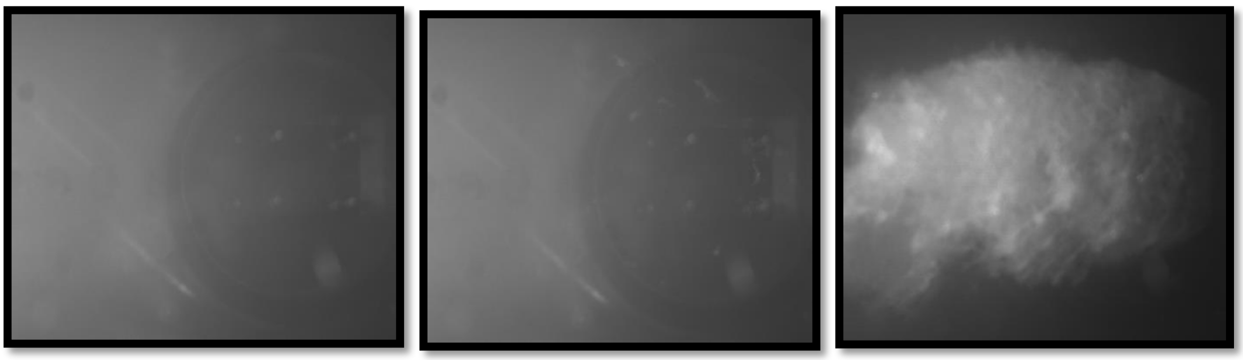
Figure 1: a) Schematic of cavitation test setup with component and b) Geometrical model of wedge supported on cylindrical holder. In (a) legends are 1- Upstream tank, 2- Honeycomb, 3- Convergent portion, 4- Test section, 5- Divergent portion, 6- Downstream tank, 7- Centrifugal pump, 8- High speed camera, 9- NI-card with PC, 10- Ultrasonic flow meter, H_t = 3940mm, L_t = 5990mm.(Kumar et al 2014).

3 Results and Discussions

High speed imaging is carried out to observe various cavitation events at the wake region of the object for given range of σ/σ_i values from 0.40 to 1. Fig.2 shows the snapshots of the instantaneous cavity structures for three cavitation numbers.

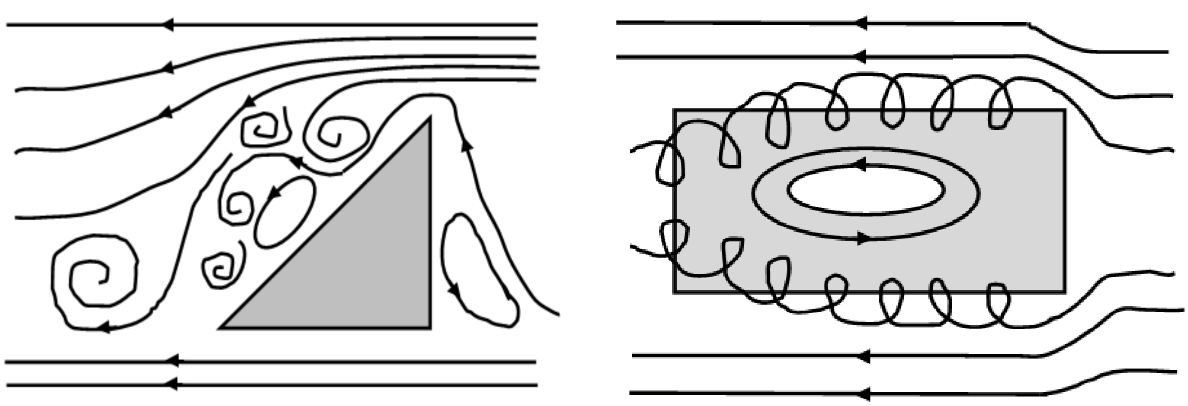
Cavity originates at inception in the shear layer away from the wedge (Fig. 2a). As σ/σ_i decreases further, extent of cavitation zone increases, cavity length becomes larger in the wake region (Fig. 2b), extending from the slant edge because there the local static pressure is reduced abruptly and small sized-bubbles are formed from the top trailing edge of the wedge and drifting away from it. With a further reduction of σ/σ_i value the extent of cavity length increases resulting in supercavitation (Fig. 2c). Two zones of cavitation could be seen: one in the shear layer above the wedge and one due to the flow entering the wake from the sides. This is shown schematically in Fig.3. The interaction of the two flows, one from the sides and another past the wedge, leads to a cyclic variation of the cavity structure and its shedding. This cyclic variation is shown in Fig.4.

a) b) Front view c)



a’) b’) Top view c’)

Figure 2: Snapshot of front (a-c) and top (a’-c’) views of cavitating wake indicating the extent of cavity at different cavitation numbers. (a) and (a’): $\sigma/\sigma_i \approx 1$, (b) and (b’): $\sigma/\sigma_i = 0.75$, (c) and (c’): $\sigma/\sigma_i = 0.4$. Flow is from right to left.



a) Front view b) Top view

Figure 3: Schematic diagram of turbulent eddy vortices when the flow passes over 3-D wedge

a) Cavity formation b) Cavity growth c) Cavity contraction

d) Cavity collapse

Figure 4: Time history of cavitation activity for $\sigma/\sigma_i = 0.75$ from bubble formation to collapse phase.

The reason for cavitating flow can be understood from the knowledge of mean velocity distribution as well as velocity fluctuations are related with local pressure fields. These velocity distributions gives information of turbulent eddies at the wake of the object and also explain about the large velocity gradients at the shear layer interface. A typical velocity contour is shown in Fig. 5. It is clear from the above figure that the streamlines gets separated from top edge of wedge and shear layer provides large velocity gradients for the flow which is the initiation of cavitation zone to develop from the near wake and further it spreads along the streamwise direction and the bubbles oscillates at the wake zone due to large turbulent eddy distribution over the entire recirculation zone.

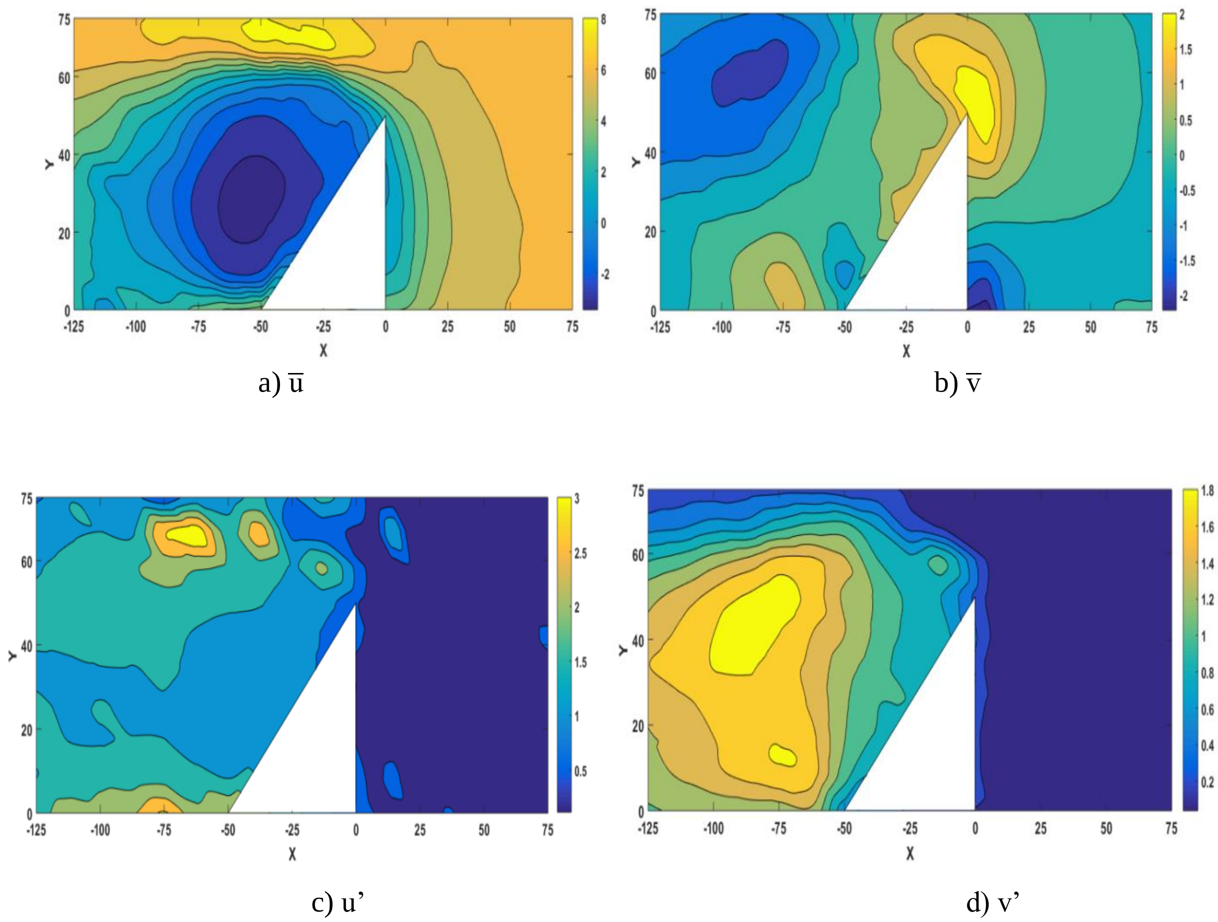


Figure 5: Mean velocity field: u is along flow direction (a) and v is along perpendicular direction (b). (c) and (d) show fluctuating components. Flow is from right to left. $\sigma/\sigma_i = 0.75$.

4 Conclusions

Incipient cavitation condition is dependent not only on geometrical configuration of model and flow Reynolds number but also on 3-D characteristics of obstacle placed in the direction of fluid flow. It is found that inception starts just few distances away from test body. As cavitation develops, the zone of cavity occurrence increases and at the lowest cavitation number of $\sigma/\sigma_i = 0.40$, supercavitation is seen when the vapour pocket engulfs the wedge.

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