THE ROLE OF VORTEX RING FORMATION ON THE DEVELOPMENT OF IMPULSIVELY INDUCED SUPERCAVITATION

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Supercavitation refers to a single gas or vapor bubble that envelope a translating body. The development of supercavitation is a multi-stage process where initially microscopic air bubbles naturally present in water rapidly expand once a critical tensile stress is reached [1]. The inception of cavitation due to streamwise and spanwise vortices, such as those encountered in hydrofoils, has been studied in the past ([2],[3],[4]). However, we find no mention in the literature on a mechanism for supercavity development over impulsively started translating bodies. This is because most supercavitation research is conducted in water tunnels and as such the impulsive nature of the flow field is not studied. This paper explores the mechanics of supercavitation development for a body that is accelerated from rest and illustrates the role of vortex ring formation in this process.

Gharib et al ([5],[6]) have studied vortex ring development, in particular the governing time scale at which the starting vortex will pinch off from its feeding jet. Subject to a number of assumptions they concluded that the nondimensional formation time (Equation 1) scales the amount of circulation that the vortex ring can contain before pinching off from the feeding jet.

$$\frac{L}{D} = \frac{\overline{U_p} t}{D} \qquad 1$$

Here L is the stroke length, D is the bore diameter, t is time, and is the running mean piston velocity, which was driven down a cylinder bore to generate the vortex ring. They concluded the formation time ranges between $3.6 < L/D < 4.5$ under certain assumptions.

An impulsively started blunt projectile behaves very much like a piston where the displaced fluid rolls into a starting vortex ring that convects downstream towards the aftbody. In this paper we will demonstrate how the critical time scale for vortex ring formation governs the corresponding time scale for the explosive growth of the cavitation nuclei into a fully developed supercavity.

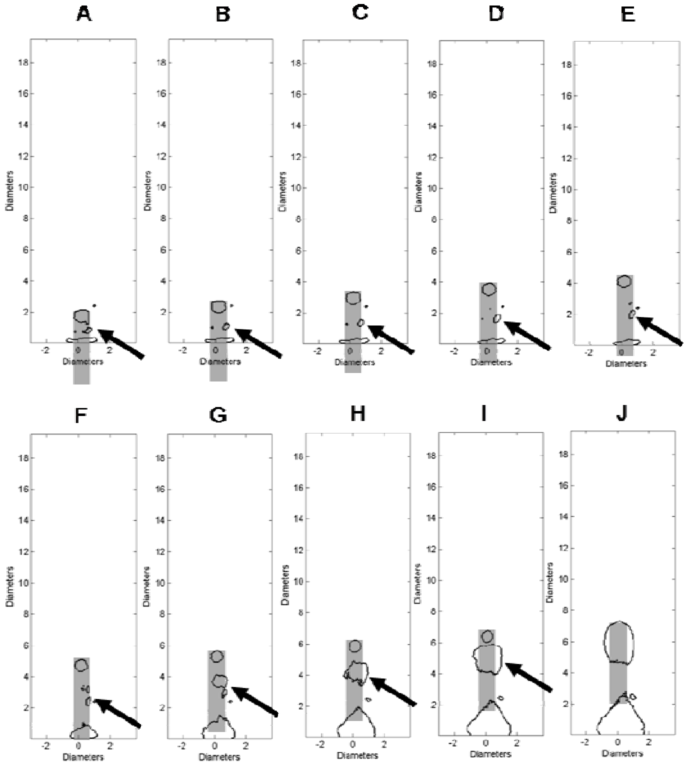

Figure 1. Supercavity development over aspect ratio 5 blunt projectile with maximum speed of 20.6 m/s (σ=0.34). The images are shown at 0.24 ms intervals.

To study the supercavity development over accelerating bodies, projectiles were shot vertically into a water tank with quiescent ambient flow conditions using a modified gas gun. Blunt unguided circular cylindrical projectiles were fired at initial velocities that ranged between 19 m/s to 40 m/s. A Phantom IV high speed digital camera was used to image the test section that was illuminated by either 500 Watt halogen lamps or a planar laser sheet. Images were digitally recorded with sampling rates between 1900-6000 Hz and were post-processed and analyzed with in-house developed image processing software.

An example of the prototypical supercavity formation process is shown in Figure 1 for a blunt projectile with aspect ratio 5 and initial speed of 20.6 m/s (σ=0.34). The images correspond to 0.24 ms intervals. In image A, the barrel is seen centered about position (0,0) and the first small cavity appears downstream of the projectile forebody. A gray estimated projectile position is superimposed over the images. The two initially small cavities remain stable for some time (images A-F) until they spontaneously grow into the fully developed supercavity (image J). We term the nondimensional time that signifies this spontaneous cavity growth as Critical Supercavity Growth Time (CSGT) and is based on Equation 1, however $\overline{U_p}$is now the running mean projectile speed.

The typical governing parameters that describe supercavity development are the cavitation index and the Reynolds number. In order to determine the dependence of the CSGT against viscous and pressure effects the ratio of these parameters was plotted for all test cases and is shown in Figure 2 against the CSGT. We see that CSGT is practically independent to this dimensionless parameter that scales the pressure, inertia and viscous effects. The bulk of the test cases had a CSGT between 3.5 and 4.5, similar to the results reported in the literature for pinch-off of the vortex ring. Figure 2 suggests there is a limiting characteristic of the vortex ring generated during projectile launch that governs the CSGT.

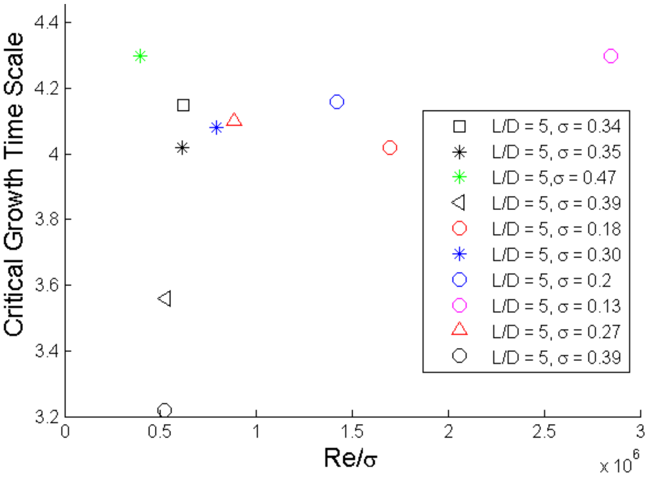

Figure 2. The critical time of the supercavity development process over the range of parameters tested.

The vortex ring generated during impulsive launch of the projectiles plays a key role in the supercavity development. As flow stagnates on the forebody of the projectile and separates from the sharp corner small nuclei are entrained in the resulting vortex ring. As the circulation in the vortex ring increases, cavitation inception occurs and a stable bubble appears in the core of the vortex ring. This is an equilibrium state until a critical vortex circulation is exceeded inducing a pressure drop higher than the Blake critical pressure threshold. Above that point the bubble is unstable and grows non-linearly in response to the external pressure field [7]. Figure 1, images A-E show observations of these events. The initial cavitation bubble remains stable in its size over this period, after which a rapid growth of the bubble is seen. The time of the abrupt growth of the cavitation in the core of the vortex as shown in image G corresponds to the CSGT as shown in Figure 2. The final presentation of this work will provide detailed experimental and theoretical analysis of the processed summarized above.

References

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