Supercavitation Phenomenon during Water Exit and Water Entry of a Fast Slender Body

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1 Introduction

The direct applications of water exit and water entry study are submarine launched ballistic missile and anti-submarine missile [1],[2]. This study is also related to underwater high-speed torpedo which moves in a supercavity and is designed to confront aircraft carrier [3]-[4]. Previous research has suggested that when an underwater body moves close to the free surface, cavitation may become important[5],[6]. However, due to its transient and non-linear nature, water exit is a rather complicated process and many problems remain to be solved.

We have conducted systematic research on water entry problem of a blunt body [7]-[12]. Now, we extend our research activity into water exit problem. Meanwhile, we will also examine the water entry process of a slender body. It is known that the equation of motion for an underwater body is [12]

$$m\frac{dV}{dt} = mg - \frac{1}{2}\rho_w A_0 C_d V^2 \quad (1)$$

where t, g, ρ_w, A_0, m, V, C_d are time, gravity, density of water, the projecting area of the body, body mass, body velocity and the drag coefficient, respectively. The effect of gravity is usually allowed to be ignored. Let

$$\beta = \frac{\rho_w A_0 C_d}{2m} \quad (2)$$

It is easily to get the following equation by integrating Eq. 1,

$$V = \frac{V_0}{\beta V_0 t + 1} \quad (3)$$

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where V_0 is the initial velocity of the body. Thus we know that the velocity of an underwater body decays with time. This paper's experiments will also confirm this law.

2 Experimental Device and Method

Figure 1 shows the schematic drawing of the experimental devices for conducting water exit/entry experiments. A water tank 2 is located on the support 12. The water tank is made from 5 mm thick stainless plate and the size of $60 \times 60 \times 100$ cm. It also has four observation windows 4 on the four sides, which is made from 5 mm thick plexiglass plate and has the size of 30×80 cm. The testing slender body 9 is a metal nail that is shot into the water tank from its bottom or from its top. An air nail gun 8 fires the slender body. The air compressor 11 provides pneumatic power for the nail gun. The slender body travels through ball valve 5 and connection flange 6 and penetrates through the 10 μm thick tin foil 7 that is fixed by a press ring 18. Then the slender body becomes an underwater body 10 that moves towards the water surface 17. A projectile catcher 3 is designed to catch the body after water exit. A high speed photographic system which consists of camera 13, monitor 14, computer 15 and controller 15 is applied to visualize the flow field. The illumination is provided by light source 1. Before the experiment, the bottom of the water tank

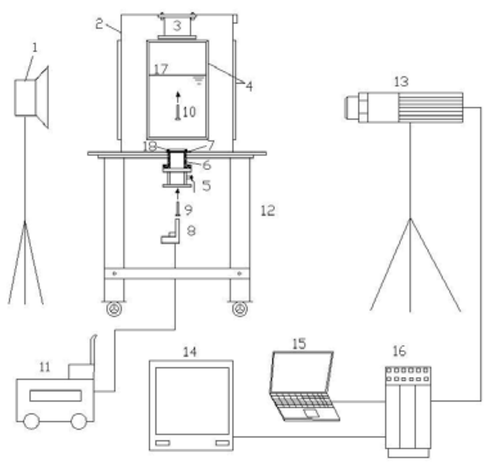

Fig. 1 Schematic of the experimental system for water exit/entry experiments. 1 - Light source, 2 - Water tank, 3 - Projectile catcher, 4 - Observation window, 5 - Ball valve, 6 - Connection flange, 7 - Tin foil, 8 - Air nail gun, 9 - Slender body in air, 10 - Slender body in water, 11 - Air compressor, 12 - Support, 13 - High-speed camera, 14 - Monitor, 15 - Personnel computer, 16 - Controller, 17 - Free surface, 18 - Press ring

is sealed by the tin foil 7 and the ball valve 5 is open. After every experiment, close the ball valve. The geometry of the slender body is given in Fig. 2. It has an apex angle of 84 deg and its total length is about 48 mm.

Fig. 2 Geometry of the slender body

3 Results

Figure 3 shows high-speed photographs of water exit of the slender body. The body appears in the scope of the picture in Fig. 3(1) and its tip starts to exit the water surface in Fig. 1(5). The body has completely left the water surface from Fig. 3(8). The body velocity between Figs. 3(1) and 3(2) is about 43 m/s. The labels S, N and W in the figure mean supercavity, nail and wake respectively. In Figs. 3(4) and 3(7), the label N marks the slender body in water and in air respectively. If comparing the cross-sectional sizes of the slender body in water and air, it is found that the body in Fig. 3(7) is much thinner than that in Fig. 3(4). This means that the underwater slender body has completely surrounded by a supercavity. On the other

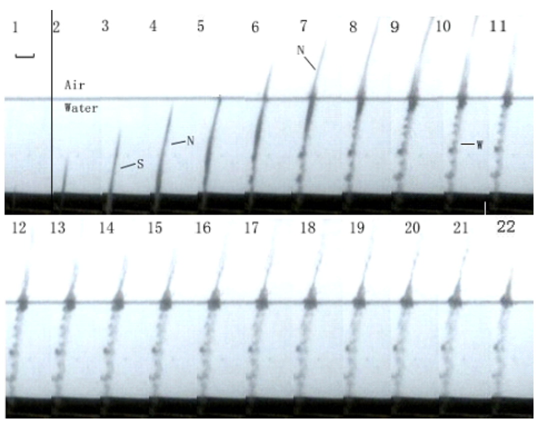

Fig. 3 Sequences of water exit. The water depth is 25 cm. The labels S, N and W mean supercavity, nail and wake. The photograph scale is given in (1) using a horizontal bar, which represents 15 mm. The interframe time is 1 ms.

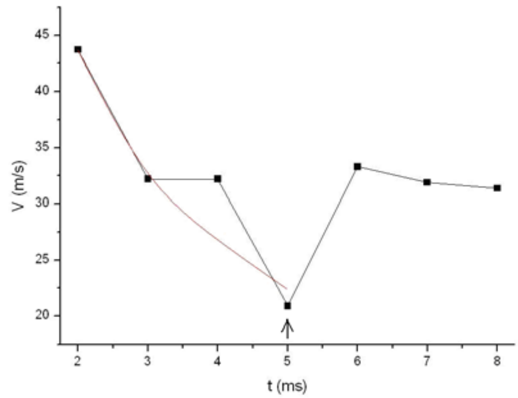

Fig. 4 Variation of slender body velocity with time in water exit. The arrow shows the time when the body starts to exit the free surface. The black square symbols are experimental data.

hand, the well observed wake flow is another evidence of showing the existence of a supercavity because bubbles are stripped from the body tail and play a role of tracing particles in the Karman vortex street. Significant features are that the supercavity is stripped off the body by the free surface (Figs. 3(7)-3(10)) and it merges into an upwards moving splash (Figs. 3(11)-3(14)). The so-called cavitation phenomenon near free surface [5],[6] is not found. This may be attributed to that since the pressure in a supercavity is negative [8], once it meets the open air it will absorb air and surrounding fluid into the cavity. This prevents the supercavity to keep its cavitation characteristic. The velocities of the slender body in Fig. 3 are measured and are given in Fig. 4. The curve in the left of the figure is the correlation curve of the body velocity until water exit, that is

$$V = 69.16t^{-0.6586}, (m/s) \tag{4}$$

where the units of time t and velocity V are ms and m/s respectively. Equation 4 correctly describes that the velocity of underwater body decreases with time, as shown in Eq. 4. In Fig. 4, an arrow at time of 5 ms marks the time when the body stars to exit the water surface. It must be noted that just after water exit, there is a significant velocity increase. From the time of 5 ms to the time of 6 ms, the velocity suddenly increases from 26 m/s to 34 m/s. Experiments at different conditions all show this tendency [13]. The mechanism for this is rapid decrease of the drag coefficient and added mass during the body crossing the free surface from water into open air [1],[2]. The sudden velocity increase will exert extra force and moment to the exiting solid body. Therefore, it is inevitable to consider this effect in designing underwater vehicles.

Figure 5 shows high-speed photographs of water entry of the slender body. The body begins to enter the water between Fig. 5(1) and Fig. 5(2) and the entry velocity is about 53 m/s (see Fig. 6). It is seen that a supercavity is well formed. In

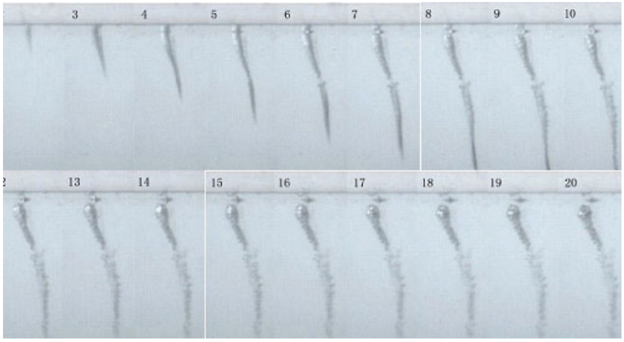

Fig. 5 Sequences of water entry. The interframe time is 1 ms. The height of each picture is 23.16 cm.

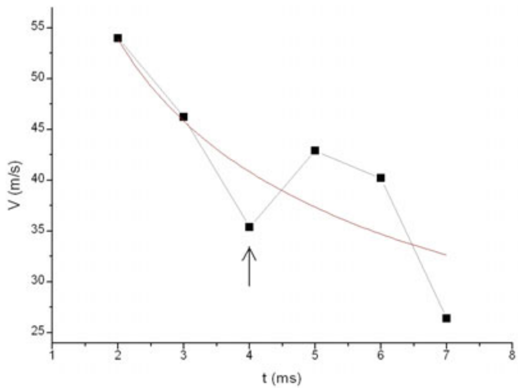

Fig. 6 Variation of slender body velocity with time in water entry. The black square symbols are experimental data. The curve is the correlation curve expressed by Eq. 5.

Figs. 5(4) and 5(5), the supercavity is twisted because the interaction between the slender body and the cavity wall. Because of its long length of a slender body, this kind of interaction often occurs[14]. Then supercavity starts to be broken into two parts (Figs. 5(6)-5(7)). The upper part of supercavity is finally pulled away from the free surface in Figs. 5(10)-5(14). The lower part of supercavity begins cavitation process from Fig. 5(8) to Fig. 5(20). The velocities of the slender body in Fig. 5 are measured and are given in Fig. 6. The curve in the figure is the correlation curve of the body velocity after water entry, that is

$$V = 71.10t^{-0.4003}, (m/s) \tag{5}$$

where the units of time t and velocity V are ms and m/s respectively. Similar to Eq. 4, Eq. 5 also shows the decreasing tendency of the velocity with time. However, it must be understood that Eq. 5 only gives an overall tendency of the velocity variation. From the time of 4 ms in Fig. 6 (marked by an arrow), the slender body starts to be fully surrounded by a supercavity. Because of the drag reduction effect of a supercavity, the velocity of the slender increases to 46 m/s at 5 ms from 35 m/s at 4 ms.

4 Conclusions

1. In water exit, the supercavity of a slender body stops at free surface. Considering the transient nature of the process, even if cavitation occurs near free surface, the solid body would have already left the water surface. Further research is been undertaken using high-speed underwater blunt body.
2. During exiting water surface, due to rapid decrease of the drag coefficient and other factors, the body velocity will increase suddenly. This will certainly exert extra force and moment to the solid body.
3. In water entry experiment, it is confirmed that a supercavity can be generated around a slender body. However, due to its long length of the body, the body may often impact on the cavity wall, which subsequently causes break-up of the supercavity and deflection of the body trajectory. When the slender body is fully covered by a supercavity, its velocity is increased.

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