The research of the dynamics and the form of supercavities during separate and simultaneous motion of strikers under hydroballistic track conditions

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Abstract. The research considers high-speed separate and simultaneous movement of an elongated metal strikers at supercavitation conditions. In the zone around a striker in water the high pressure area appears which makes the adjacent layers of water move. In case of a parallel high-velocity motion of a set of strikers, it is reasonable to assume the availability of the effects caused by their mutual close location.

1. Introduction

High-velocity motion in water has a lot of practical applications and therefore is actively investigated in a lot of countries [1–4]. Much of the attention is focused on studying the mechanisms of high-velocity motion of single strikers, underwater vehicles and the corresponding phenomena. Stable high-velocity motion of a set of supercavitating strikers under water launched simultaneously in a common assembly was shown in the research [5]. Until now, the data on the availability and the nature of interference of simultaneously moving bodies in a supercavitating regime haven’t been found. The objective of this research comprises studying the processes and phenomena appearing when two supercavitating strikers simultaneously enter water and propagate in it. Their longitudinal axes are parallel and are situated at a distance of 6÷35 cavitator diameters.

The research considers velocities under water with which the conditions of striker motion inside a steam-and-gas cavity (supercavity) are realized. A supercavity is created by a flat disc-shaped front part of a striker which is called a cavitator. A supercavitating regime usually implies that the interaction between the striker and water takes place only at the surface of the cavitator. The inner borders of the axisymmetric supercavity formed in an undisturbed flow restrict the value of the solid angle of the axisymmetric striker attack, therefore stabilizing its motion along the trajectory. It allows to preserve the initial direction of motion.

In the zone of a cavitator in water the high pressure area appears which makes the adjacent layers of water move. In case of a parallel high-velocity motion of a set of strikers, it is reasonable to assume the availability of the effects caused by their mutual close location.

2. Strikers and conditions description

The investigation of a supercavitating motion of a set of strikers and the corresponding phenomena was conducted at the horizontal hydroballistic track in the Research Institute of Applied Mathematics
and Mechanics of Tomsk State University [6]. The length of the water segment of the track from the entry into water to the target was 10.5 meters. The strikers were released from a 30 millimeter smoothbore ballistic test setup.

In the process of the experimental work, different configurations of throwing assemblies and strikers were used. In figure 1 photos of the throwing assemblies are shown. They comprise one or two strikers and additional units: a pallet, a disc marker and master devices. A steel disc marker was put between a pallet and a striker, it allowed to register the point in time when the throwing assembly passed the controlling intersections of the induction pickup of a muzzle velocity. Strikers of this series were made of steel or WNF alloy and had a cylinder foundation turning into a truncated cone.

![Figure 1. The photos of some applied strikers and parts of throwing assemblies.](image1)

In figure 1, a, a throwing assembly with a single striker made of WNF is represented. It’s 100 mm long, has a cylindrical foundation which is 9 mm in diameter, the weight is about 55 g, and its cavator has a diameter of $D_c = 3$ mm. Also, 185 mm steel strikers with same cavator diameter were used. A type of a throwing assembly shown in figure 1, b, has two strikers with a cylindrical foundation which is 9 mm in diameter. Peculiarities of the usage of a set of strikers with cavitators about $D_c = 2$ mm and the mass varying from 53÷63 g were investigated. Longitudinal axes of the strikers in an assembly were arranged parallel at a distance of 13 mm from each other.

The applied technology of throwing implies acceleration of strikers with a light master device in a throwing assembly along the channel of a ballistic setup. After the acceleration a throwing assembly firstly gets into a vacuum segment of the track, then it gets into an air segment of it where the parts of a master device are separated from the strikers. After that the strikers penetrate the water segment of the track which is separated from an air segment with a vertical polyethylene film.

3. Single striker motion under water

During the experiments photo and video data were received which illustrate single striker motion in water at velocities of 473 m/s, 553 m/s, 737 m/s, and 943 m/s. In figure 2 a supercavity is shown formed with a single 185 mm striker with $D_c = 3$ mm, which moves at a velocity of 553 m/s. The distance from the point of a striker penetrating water and the spot where the photos were taken was 3.2 meters.

![Figure 2. A single striker in a supercavity.](image2)
The formed cavern has precise contours which allows to plot its profile in a frame of reference using the figure. The graph in figure 3 shows the points represented by the dots which correspond to the contour of the upper part of a cavern profile shown in figure 2. The profile of the cavern at a 473 m/s velocity is represented by rhombuses. Triangles refer to the measured points of a cavern contour at a striker velocity of 943 m/s, squares refer to the ones at a striker velocity of 737 m/s. The contours of the strikers used are represented with crosshatched sections. Additionally, the calculated cavern contours are shown in the graph. They were received with the usage of an empirical formula from [7] for velocities of 473 and 943 m/s.

**Figure 3.** Experimental and calculated supercavity profiles behind single strikers at different velocities when moving under water.

The comparison of the data results in the following conclusion: in the range of velocities experimental and theoretical profiles of caverns are similar concerning their shape. The range of cavitation numbers [8] realized in the experiments is \( \sigma = 2.25 \cdot 10^{-4} \pm 8.95 \cdot 10^{-4} \). In the indicated range of cavitation numbers, the maximum difference in experimental cavern profiles within a 100 mm striker doesn’t exceed the highest value (10 \%) of a relative error of the measurements. When comparing estimated cavern profiles the difference in their radii at the point \( x = 100 \text{ mm} \) doesn’t exceed 0.07 mm. Based on these examples, one might make a further comparison of super cavern profiles in experiments with the velocity close to the mentioned above.

4. Two supercavitating strikers motion in water

Let’s consider the peculiarities of two strikers moving together and simultaneously released from a barrel of a ballistic track at a velocity of 1087 m/s. Strikers in an assembly were parallel one above the other at a distance of 13 mm (figure 1, b). The photo showing the motion of two strikers at a distance of 3.2 m from entry into water is represented in figure 4. Additionally, the points of measuring the radius of a profile of each of the cavity are marked in the photo. The profiles of a cavity boundaries are enumerated from 1-4 for further understandable exposition.

**Figure 4.** A photo of simultaneous motion of two strikers in water with markings on the spots where the cavern profiles were measured.
The spatial position of strikers and caverns along the trajectory was determined according to the markings on mylar screens put along the trajectory of motion. On the basis of this data, the absolute distance between central axes of strikers and caverns along the trajectory and the moment of taking a photo was determined (figure 5).

Figure 5. Dependence of an absolute distance between two strikers from a full distance travelled in water.

At the beginning of a trajectory $x/D_c=0$ the distance between the longitudinal axes of strikers when entering water corresponds to their initial position in a throwing assembly $\delta/D_c = 6.5$. At distance of $x/D_c = 350$ from entry into water the distance between the strikers is $\delta/D_c = 11.5$, which corresponds to the $0.82^\circ$ angle of deflection. Having overcome the distance of $x/D_c = 1200$ in water the strikers drifted apart with the value $\delta/D_c = 17.3$, which corresponds to the angle of $0.39^\circ$. Approaching the spot of photo registration $x/D_c = 1600$ the deflection between the strikers is $\delta/D_c = 20.0$. When reaching the full distance in water $x/D_c = 3350$ the distance between the strikers continues growing, but with the angle of $0.31^\circ$ and reaches $\delta/D_c = 29.0$. On the screen set at a distance of $x/D_c = 5250$ the biggest value of deflection is received $\gamma/D_c = 32.6$, along with that the angle between the strikers on this trajectory segment decreased down to $0.1^\circ$.

According to the data received, on the spot where photos were taken (the crosshatched section in figure 5) the distance between the strikers was $40 \text{ mm}$, and the angle of deflection was $\sim 0.39^\circ$ which shows the interaction between the strikers. In figure 6 the construction of cavern profiles during the striker motion in a frame of reference is shown, which is connected with the cavitators of the corresponding strikers according to the photo shown in figure 4. The velocity of strikers when reaching the photo spot decreased down to $976 \text{ m/s}$.

Figure 6. The comparison of profiles of super cavern borders during parallel striker motion.
The difference in the form of contours of the upper borders of the upper 1 and lower 3 caverns is observed. Within the length of a 100 mm striker the maximum radius of a profile 3 is 2.4 mm (27%) less than the maximum radius of profile 1. Within the area between the front section of a striker and the end of the measured area (x = 100÷232 mm) the radius of a profile 3 is averagely 30% less than the radii of the profile 1. The contours of the profiles 2, 4 are similar in their shape, however, they are averagely 21% different from profiles 1 and 3 according to the value of radii, regarding the maximum radius of the corresponding cavern. This indicates the asymmetric form of the caverns regarding the cavitator motion axis. As geometrical features of strikers and their velocities are similar, the given data can be used as a quantitative estimation of a cavern mutual influence.

5. Computer modelling of a process
As far as the most evident deflection of strikers according to the experimental data (figure 5) is observed at the first stage of motion, computer modelling of strikers entering water was made. An elastic-plastic model of environment was used to describe the motion of a solid body, a hydrodynamic model was used for a water segment, the models are represented by a looped system of major conservation equations and the corresponding determining proportions considering both disconnection and shearing mechanisms of fracture of solids [9]. The initial experimental conditions were reproduced in the calculations. During the experiment two similar steel strikers entered water at a velocity of 563 m/s. The radii of striker cavitators are 1 mm, the distance between the longitudinal axes is 13 mm. In figure 7 the chronogram of two strikers entering water is shown. It represents the distribution of mass velocity vector related to the velocity of a striker center of mass (in the left half-plane) and the distribution of pressure (in the right half-plane).
Figure 7. Chronogram of a numerical simulation of two strikers entering water: \( a \sim 6 \) ms; 
\( b \sim 180 \) ms; \( c \sim 300 \) ms; \( d \sim 360 \) ms.

At the first stage of entry into water (figure 7, \( b \)) asymmetric cavity formation is observed, with the flank of a striker body interacting with the cavity boundaries. That results in a striker rotating through a certain angle within an observed plane. In the area between the strikers a local pressurization is registered forming side force. The impact of these factors by 300 ms point in time (figure 7, \( c \)) significantly draws apart the strikers.

Numerical simulation of two strikers entering water qualitatively confirms that at the first stage of motion with minimal distance between them the appearance of forces and points facilitating the increase of distance between the longitudinal axes of strikers is possible.

6. Conclusion

In the result of the research the peculiarities of two supercavitating strikers moving in water with the range of velocities from 400 to 1000 m/s were illustrated. It’s experimentally shown that cavern contours from two similar strikers when moving simultaneously close to each other (about 20 cavitator diameters) are asymmetric in relation to the axis of motion of the corresponding striker.

The maximal difference in radii of the upper borders of profiles of two caverns within a 100 mm striker length was 2.4 mm (27 \%). Within the segment behind the front section of a striker and the end of a measured area \( x = 100 \pm 232 \) mm profile radii are 30 \% different from each other. The difference between the upper and the lower profiles for each cavern with two strikers simultaneously moving at 40 mm distance from each other was 21 \% on average.

When two 50 gram strikers simultaneously entered water at a velocity of 1087 m/s at \( \delta/Dc = 6.5 \) distance between each other, the initial divergence angle was 0.82°. During their motion along the trajectory the decrease of the initial divergence angle is observed. When \( \delta/Dc = 29.0 \) distance is reached between the strikers, the angle between them decreases down to 0.1°, which means their motion pattern tends to become parallel.

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6