Researching acceleration and deceleration processes of supercavitating strikers under the conditions of hydroballistic track

A N Ischenko, V V Burkin, A S Diachkovskiy and A V Chupashev
National Research Tomsk State University, 36 Lenin Avenue, 634050, Tomsk, Russia
E-mail: ChupashevAV@gmail.com

Abstract: Laboratory researches of the processes accompanying high-velocity motion of supercavitating strikers under water, conducted under the conditions of a hydroballistic track imply the acceleration of a striker within a ballistic barrel to speeds exceeding 200 m/s and consequent partial or complete deceleration within a water tank. The results of experimental and theoretical researches concerning the acceleration and deceleration processes are considered in the given work as well as the estimation of the force and pressure values impacting the striker.

1. Introduction
High-velocity motion of bodies in water continues to be a central topic of investigations performed by scientific communities from different countries [1 – 5] as the result of the widest area of applications in different fields of human activities including the development of under-water deposits of hydrocarbon. Inert kinetic bodies – strikers can be used in the range of technical operations. They can continuously move under water preserving the initial rectilinear trajectory [6]. This is possible due to the phenomenon of supercavitation [7, 8] during which the interaction between a body and water takes place on the surface of a cavitator which “splits” the continuous volume of aqueous medium with the formation of steam-and-gas cavity. Therefore, the main part of a striker body moves in rare medium, due to this deceleration impact produced by water significantly decreases. If a striker body is made with allowance for the shape of a supercavity formed under water, the striker will preserve the initial trajectory of motion with its tail part periodically pushing off from the inner borders of a supercavity [9].

As a rule, a supercavity contour is drastically extended along the trajectory, therefore a striker obtains a significant extension. During acceleration and while a striker is moving under water some significant loading is expected which can cause both elastic and plastic deformation of an extended body of a striker.

In the given work considers consequent acceleration and deceleration processes of strikers under the conditions of throwing from a ballistic launcher to a track filled with water. The comparison of calculating relationships between a striker velocity and a distance covered and experimental data is conducted. Subsequently, on the basis of these data, particular force and pressure values realized at the ends of a striker during their acceleration and consequent motion in water are calculated.

In the first section of the work there is a description of a striker and a throwing assembly, the second section briefly describes an experimental facility, in the third represents the comparison between experimental and calculated data on a striker motion within the barrel channel of an accelerator. The fourth section describes the motion of strikers in water, calculated and experimental data are provided as well as the photographs of the process. In the fifth section the following features are considered:
forces and pressures impacting a striker during its acceleration and deceleration depending on the material a striker is made of.

2. Describing a striker and components of a sabot

Truncated cone-shaped subcalibre strikers with a particular extension of \( l \geq 10 \) (figure 1) were used. The top of the striker cone was truncated with the formation of a disc surface called a cavitator. The strikers used in work had similar forms and were divided into three groups according to the basis of the alloy they were made of: Al* – aluminum alloy (\( \rho = 2.8 \text{ g/cm}^3 \)), Fe* – the alloy on the basis of iron (\( \rho = 7.8 \text{ g/cm}^3 \)), W* – alloy on the basis of tungsten (\( \rho = 18.0 \text{ g/cm}^3 \)). The difference in the density of the material along with a similar shape of a striker body allowed to get throwing masses of 4, 11 and 26 g correspondingly.

For the purpose of accelerating a subcalibre striker with an intersection size smaller than the diameter of a barrel, centering petals and obturating pushing pallet which the whole sabot leans on are needed. The pallet is made from polymer materials by means of layer-by-layer fusing and has the form of two units which represent a cylinder. Master devices were also made from polymer materials. A thin steel disc-marker was placed between the pallet and the striker which allowed to prevent the piercing of the pallet by the base of the striker during acceleration and which formed synchronizing signal when passing a muzzle velocity sensor.

![Figure 1. Photographs of applied supercavitating strikers and the components of a sabot.](image)

When the throwing assembly leaves the accelerator channel and gets into the airstream, plastic parts of centering petals leave the trajectory and a steel marker significantly lags behind. That allows a striker to get into water easily.

3. The description of an experimental set up

Experimental part of the researches aimed at determining spatiotemporal relationships when strikers move under water and the character of the phenomena accompanying this process implies using devices and technologies for their initial acceleration up to required velocities.

The work was performed on a hydroballistic track (figure 2) [10] equipped with a smoothbore ballistic accelerator and recording equipment. The water tank represented a thick-walled horizontal tunnel more than 10 meters long, at the end of which a target was set up. Within the tank shockproof illuminators were provided through which a high-speed video-recording of the processes was made. Throwing strikers from a ballistic set up into water was performed horizontally through a thin polyethylene screen.

The velocity-time function of a throwing assembly within the barrel channel was determined by means of the Doppler sensor in a microwave range of radio-frequency [11]. At the end of the accelerator channel an induction sensor of muzzle velocity was set [12] which allowed to synchronize measuring and photo-video recording equipment of a hydroballistic track with a point when the assembly leaves the barrel. As the result of a skin-effect, a velocity of a striker under water cannot be measured.
by means of the Doppler sensor, therefore the measurements under water are made according to the data of photo and video-recording systems. A relative error of motion measurements with a video-recorder in the experimental series is not more than 3 %.

Figure 2. The scheme of major units of a hydroballistic track.

4. Striker motion along the channel of an accelerator

In order to determine loading parameters, the ingredients of a throwing load and its quantity, the calculation of inner ballistic characteristics is performed on the basis of the suggested mass of the assembly and the intended velocity. We used a programming complex on the basis of a mathematic model of inner ballistic processes in barrel gas-dynamic throwing devices for calculating. The model is based upon the principles of mechanics of mutually penetrating continuums applied for gas-and-powder mixture motion along the channel of a cross-section [13]. The usage of a programming complex also allows to determine non-metering parameters during shooting, for example, the distribution of pressure along the length of a barrel or in the area of combustion products.

It is considered that during motion along a channel, the acceleration of a striker and other components of a throwing assembly are similar. Integrating the velocity-time function of a throwing assembly received with the Doppler sensor allows to go to a more comfortable velocity-distance relationship of a striker and covered distance within a barrel channel. In figure 3 there is a quantitative comparison of an experimental velocity-distance function (a curve) of a striker and the distance covered within the barrel with the range of muzzle velocities from 450 to 1200 m/s for 45…100 g throwing assemblies.

Figure 3. Calculating and experimental velocity-distance relationships of a striker and distance covered within a barrel: — experiment; --·-- calculation.

Fine correspondence of relationships at the initial stage of major acceleration of the assembly is observed. That concerns the first meter covered by the moving assembly and its further motion within a barrel. Value mismatch of a calculating and muzzle velocities didn’t exceed 1 % which allows to design calculating dependencies of velocity within a barrel for throwing assemblies similar in masses and velocities without conducting any additional experiments.
For quantitative estimation of the force applying the end of a striker it is considered that acceleration of all parts of a throwing assembly is similar, therefore there comes the equation:

\[
\frac{F_s}{q} = \frac{F_b}{m},
\]

in which \(F_s\) is the force impacting the bottom of a throwing assembly, \(q\) – the mass of the throwing assembly, \(F_b\) – the force impacting the end of the conic striker, \(m\) – the mass of a striker. Therefore, we get the force impacting the surface of the base of a striker and realized during acceleration:

\[
F_b = F_s \frac{m}{q}.
\]

5. Striker motion under water

When a striker moves under water, let’s consider its water engagement surface be limited only by the area of a cavitator, contacting the inner surface of a supercavity during gliding is not taken into consideration. In this case, water resistance force \(F_c\) which decelerates a striker moving in a supercavitating mode is defined the following way:

\[
F_c = C_s \frac{\rho V^2 S_c}{2},
\]

in which \(\rho\) – water density, \(V\) – striker motion velocity, \(S_c\) – the area of a striker cavitator, \(C_s \approx 0.82\) – coefficient of resistance (\(\sigma\) is about 10\(^{-4}\)) [7, 14].

In the series of experiments strikers of different masses made from the three mentioned alloys were thrown into water at the velocity range of ~ 450…1200 m/s. In figure 4 the comparison of calculating and experimental velocity-distance relationships of a striker and the distance it covered are represented.

As far as we can see from the relationships (figure 4), the calculation represents the slope of the velocity change curve. For relatively solid and firm strikers made of tungsten alloy with masses of 26 grams (figure 4, a) a wide range of initial velocities is typical. They stably enter water, move along a straight trajectory and hit the target at the end of the track. Along with that, maximum mismatch between a calculating value for velocity and the value received during the experiment was not more than 3 \%. For 11 gram strikers made of iron alloy (figure 4, b) the mismatch was not more than 6 \%.

In figure 5 there is a footage of the motion of the tungsten striker with the initial velocity of entering water of 1180 m/s (the upper line in figure 4, a). After overcoming the 3.2 m distance under water its velocity reduced to 985 m/s. There are no deformations of the striker body observed in the footage. The borders of a cavern except the area of gliding have even and transparent contours.
Strikers made from aluminum alloy (figure 4, c) didn’t overcome the whole distance of water area of the track as some of them became deformed after overcoming the border of water surface, notwithstanding the fact that the initial velocity of a striker entering water was reduced on purpose. In the experiments during which a striker was moving until reaching full deceleration under water, experimental values of velocities could be up to 13 % less than represented in the calculation. The footage of high-velocity video-recording (figure 6) shows that while moving in water at the velocity of 356 m/s the body of the striker made of aluminum alloy is exposed to elastic deformation, as the result of which the cavitator of the striker periodically fluctuates in the observed area. That leads to wavelike distortion of supercavity borders. The distortion of the supercavity borders makes a striker body over-step the borders in the areas of inflection (figure 6, b), therefore this distorts the trajectory of a striker motion and increases the interaction frequency of a side part of a striker body with water. The observed phenomenon most likely is the reason of premature deceleration of a striker under water. Further motion of a striker to a 2.3 m distance is accompanied by velocity reduction to 189 m/s, along with that the deformation of a striker and the borders of a supercavity is no more observed (figure 6 c, d).

Figure 5. Photographs of the striker made of tungsten alloy moving under water at the velocity of 985 m/s.

Figure 6. Photographs of a striker made of aluminum alloy moving under water.
Registered elastic deformations of strikers during motion show that there is a formation of forces close to critical ones for the construction of a striker made of aluminum alloy under the conditions of an experiment.

6. Calculation of force action on a striker during experiment

Let’s consider the process of the experiment from the point of view of forces acting along the long axis of a striker. The whole process of the experiment is conceptually divided into two stages: the acceleration of a striker within the barrel and its deceleration under water. In figure 7 there are calculated force-distance relationships of the force applied to the strikers and the distance covered across the track at the starting speed of 473 m/s (the motion of the light 4-gram striker corresponds to the experiment represented in figure 6). The force applied to strikers during their acceleration within a barrel increases with the growth of the mass. Top value of propulsive force for the striker made from Al*, Fe* и W* alloys is 660 N, 1380 N and 2450 N correspondingly. Along with that, the top force of resistance impacting the strikers and coming from water remains the same for all considered strikers – it is 290 N.

![Figure 7](image_url)

**Figure 7.** The diagram of force-distance relationships of a striker and the distance covered on a track during the acceleration up to 473 m/s and entering and moving in water: —— 26 g (W*); —— 11 g (Fe*); —— 4 g (Al*).

In figure 8 calculated velocity-distance relationships of strikers with different masses and the covered distance are shown, they were designed according to the data given in figure 7. Velocities less than 100 m/s aren’t considered in the diagram as a supercavitating motion mode may not be realized completely at velocities less than that [14, 15] and the consequent motion of a striker along this trajectory is difficult to predict. In the given experiment (figure 6) the striker was found in 6 meters under water without any visible signs of plastic deformation which indicates its insignificant further propagation after a supercavitating mode was ceased (<0.5 m).

On the basis of this relationship it’s evident that for the 4-gram striker made of aluminum the period of achieving a minimum velocity and deceleration under water with the supercavitating mode takes place within an approximately similar distance. Strikers made of steel and tungsten alloys seem to be more perspective than the ones made of aluminum alloy: after overcoming a 10 meter track a Fe* striker has the velocity of about 150 m/s, a W* striker – 290 m/s.
Figure 8. Velocity-distance relationship for strikers with different masses and made of different alloys at \( V_0 = 473 \text{ m/s} \): \( \bullet \) – 26 g (W*); \( - \) – 11 g (Fe*); \( -- \) – 4 g (Al*).

End surfaces of a striker have different areas: the diameter of the base of a striker is more than the diameter of a cavitator, therefore the values of pressures realized at the ends of a striker depending on the stage of experiment are different. In figure 9 there are pressure-distance relationships of pressure realized at the ends of a striker and the covered distance for the strikers of different masses, made of various alloys.

Figure 9. Pressure-distance relationships for the pressure impacting the ends of a striker and the distance covered on a track: \( \bullet \) – 26 g (W*); \( - \) – 11 g (Fe*); \( -- \) – 4 g (Al*).

According to the features of the relationships received in figure 9, it turns out to be that the pressure realized on the surface of a cavitator (90 MPa) exceeds the pressure on the base of the strikers made of different alloys (17, 36, 63 MPa) during their acceleration within a barrel not only with top values but also with an integral quantity. Along with that the top pressure value realized on the surface of a cavitator of each striker when entering water doesn’t depend on the mass of a striker. All these factors along with less solid material of a striker can be the reason for the observed resilient fluctuations of a striker made of aluminum alloy in figure 6 at the beginning of its trajectory in water.

The data of diagrams in figure 8 and 9 show that applying strikers made of heavier alloy W* seems to be more perspective. Due to a bigger mass such a striker decelerates slowly and the maximum pressure for a cavitator remains the same as for a striker of a smaller mass.
Conclusion

Laboratory researches of processes accompanying high-velocity motion of supercavitating strikers in water at velocities from 180 to 1180 m/s were conducted on a hydrobaltic track. The strikers were made from three types of alloys on the basis of aluminum, iron and tungsten. It is obtained that the strikers of the considered design made of aluminum alloy are able to maintain integrity when entering water at velocities up to 550 m/s. Stable motion of iron alloy strikers in water was registered at velocities up to 800 m/s, those made from tungsten alloy – 1180 m/s.

During experimental work it was shown that the front parts of striker bodies made of aluminum alloy perform resilient cross-section fluctuations when entering water at velocities of 300 – 550 m/s. The fluctuations slow down as the velocity decreases. It has been noted that the presence of these fluctuations facilitates the deceleration of strikers. When a striker made of tungsten alloy moves under water at velocity of 985 m/s, no fluctuations of the front part are detected.

Experimental and theoretic researches have been made, they concern the acceleration and deceleration of strikers; values of forces impacting a striker and pressures impacting its ends are estimated. In the considered example it is stated that the absolute value of a maximum quantity of the force impacting the strikers within the barrel is more than when they move in water – 8.4 times more for tungsten alloy, 4.8 times more for iron and 2.3 – for aluminum.

It was determined that when strikers of the investigated form enter water at 473 m/s velocity the pressure realized on the surface of a cavitator (90 MPa) exceeds the pressure on the base of the striker when it accelerates within a barrel not only according to the integral quantity but also according to the top value, 1.4 times more for tungsten alloy, 2.5 times for iron, 5.3 times more for aluminum. Along with that the top value of pressure realized on the surface of the cavitator of each striker the time they enter water doesn’t depend on the mass of a striker. There is a greater perspective of using strikers made of heavier tungsten alloy as evidenced by the experiments. Due to its bigger mass such a striker loses velocity more slowly and maximum pressure on a cavitator of a striker remains the same as for a striker of a smaller mass. This diminishes the possibility of resilient fluctuations of the front part which facilitate the deceleration of a striker.

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Abbreviations

Al* – aluminum-based alloy (ρ = 2.8 g/cm³)
Fe* – iron-based alloy (ρ = 7.8 g/cm³)
W* – tungsten-based alloy (ρ = 18.0 g/cm³)

References

[1] Arad Ludar L and Gany A 2020 J. Mar. Sci. Eng. 8(1) 28
[2] Yang D, Xiong Y and Guo X 2017 Int. J. Naval Architect. Ocean Eng. 9(1) 35–44
[3] Guo Z, Zhang W, Xiao X, Wei G and Ren P 2012 Int. J. Impact Eng. 49 43–60
[4] Ahn S 2007 An integrated approach to the design of supercavitating underwater vehicles PhD Thesis (Georgia Institute of Technology)
[5] Vlasenko Y 2003 Proc. In Fifth Int. Symp. on Cavitation (Osaka, Japan) Cav03-GS-6-006
[6] Zhao C, Wang C, Wei Y and Zhang X 2015 J. of Phys.: Conf. Series vol 656 012175
[7] Logvinovich G 1969 Hydrodynamics of flows with free boundaries (Kiev: Naukova Dumka) p. 208.
[8] Persol I 1972 Cavitation (London: Mills and Boon)
[9] Hrubes J 2001 Experiments in fluids 30 57–64
[10] Diachkovskii A, Ishchenko A, Burkin V, Zykova A, Korolkov L and Chupashev A 2016 Proc. 18th Int. Conf. on the Methods of Aerophysical Research (ICMAR) (Perm) Vol. 1770, 030011
[11] Korolkov L, Burkin V, Diachkovskii A, Ishchenko A, Maystrenko I, Rogaev K, Samorokova N and Chupashev A 2016 *Conf. Fundamental and applied problems of modern mechanics* (Tomsk) p. 140–141 (in Russian)

[12] Diachkovskii A, Sidorov A, Korolkov L, Moiseev D and Egorov L 2015 *Int. Conf. Tech. Sci. − «From theory to practice»* (Novosibirsk) p. 111–120 (in Russian)

[13] Ishchenko A and Kasimov V 2015 Mathematical model and software package for the theoretical study of intraballistic processes in stem systems (Tomsk: Publishing House of TSU (in Russian)

[14] Savchenko Yu, Semenenko V, and Putilin S 1999 *Appl. Hydromechanics* 1 (73) p. 79–97 (in Russian)

[15] Zhao X, Lyu X and Li D 2019 *Math. Problems in Eng.* 2019 1290157