Experimental Study of the Inertial Motion of Supercavitating Models

N.S. Fedorenko, V.F. Kozenko, and R.N. Kozenko

Abstract
The paper gives a brief overview of various types of available facilities for the experimental study of the high-speed inertial motion of supercavitating bodies in water. The paper reports the procedure of the experimental studies of high-speed supercavitating models which have been conducted at the Hydrodynamics Laboratory of the Institute of Hydromechanics of the National Academy of Sciences of Ukraine under the direction of Yu.N. Savchenko since 1990. The design philosophy of the electrochemical-catapult model firing system and the motion parameter recording system is described. The paper gives examples of model firing and reports the values of the initial parameters, video-recording data on the motion of a supercavitating model, and motion parameter values for models moving with a system of shock waves.

1 Introduction

Models can be put in high-speed motion through water in a number of ways [1, 2]. The types of existing facilities differ in the method of production of the energy delivered to the model to speed it up.

Thus, a controlled-pressure ballistic chamber was built at the Naval Ordnance Test Station, Pasadena, the USA, in 1951. It serves to study the water entry, water exit, and underwater motion of engineless projectiles. A pneumatic piston catapult system fires models of diameter 50.8 mm and mass up to 530 g from a tube into the chamber with water entry and exit speeds up to 36 and 24 m/s, respectively. The 0.9 m square chamber of length 2.4 m has glass windows on three sides and can be set at an angle of 5–90° to the horizontal. The gas pressure in the chamber

N.S. Fedorenko (✉)
Institute of Hydromechanics of the National Academy of Sciences of Ukraine, Kyiv, Ukraine
e-mail: inesteruk@yahoo.com

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over the water surface can be varied from the vapor pressure to 1.5 atm. Observations are made using stroboscopic photography. To measure the variation of the projectile angular velocity in water entry, use is made of a special camera with optical scanning to compensate for the motion of the image relative to the film.

The more recent ballistic chamber at the California Institute of Technology has an electromagnetic catapult system with controlled atmosphere and allows one to study water entry and exit at different angles with waves on the free surface. Model projectiles of diameter 25.4 mm can be fired (at the center of the chamber) transverse to the water–gas interface up and down. Stainless steel models of diameter 25.4 mm are fired underwater at a speed of about 27 m/s, the speed-up distance being 50 mm. Increasing the energy to 54,000 W·s increases the speed to 130 m/s. The speed-up time can be varied by varying the circuit parameters, and an oscillatory motion can be imparted to the model.

The largest controlled-pressure ballistic chamber is installed at the Naval Ordnance Laboratory in White Oak, Maryland, the USA, and it serves to test engineless models. One powder gun fires into the water models of diameter 76.2 mm and mass 5.05 kg at 900 m/s. The other gun has a barrel of caliber 102 mm. Models of diameter up to 76 mm are loaded in a strong titanium cartridge. The tray is stopped by an aluminum braking nozzle of diameter 80 mm at the end of the barrel while the model continues to fly. All operations: model firing, speed calculation, and photography with the use of flash tubes – are performed automatically by a preset program. The chamber length and width are 30 and 10.5 m, and the water depth is 19.5 m.

The Hydrodynamics Laboratory at the California Institute of Technology has a centrifugal catapult system mounted inside a sealed reservoir with water and a gaseous atmosphere over it. Models are fired in a vertical plane at any desired angle with any angle of attack in the range $\pm 10°$ at any speed up to 75 m/s. The water surface has area 3.6×9.16 m, and the water depth is 3.05 m. This special-purpose facility makes possible a variety of experiments both with self-propelled projectiles and with projectiles moving on inertia.

Experimental facilities to test high-speed inertial models have been built and are currently being built in a number of European and Asian countries too. Some results of foreign experimental studies of supercavitating bodies moving at high speeds are presented in [3–5]. At the Institute of Hydromechanics of the National Academy of Sciences of Ukraine, a firing bench has been in service since 1990.

2 Firing Bench at the Institute of Hydromechanics of the National Academy of Sciences of Ukraine

At the Institute of Hydromechanics of the National Academy of Sciences of Ukraine (IHM of NASU), inertial models are fired using a $2{,}100 \times 2{,}100$ mm water tunnel entrance channel of length 35 m. It has ten pairs of windows for optical observations, which are mounted perpendicular to the model trajectory. To keep the model from flying out of the channel, the windows are recessed and protected by the strong walls of the channel, thus assuring test safety. At the end of the test distance, the model is stopped using a metal shield or an obstacle filled with a soft material such as sand, wood, etc. so that the model may not be damaged in stopping.

Models are fired using an electrochemical catapult, which uses ecologically clean components: water, compressed air, hydrogen, and electric current and provides high firing energy at transonic speeds (the sound speed in water at $T = 6°C$ is 1,440 m/s). The action of the electrochemical (gas–vapor) catapult is described and estimates of firing efficiency are given in [6]. The firing bench comprises a hydraulic, a pneumatic, an electric, and a measuring system.

2.1 Hydraulic System

The hydraulic system (Fig. 1) serves to fill the water tunnel channel 10 with water from a basin 7 through a pressure pipe 6 using a pump 2 and to empty the channel 10 through a drain pipe 5 after the experiment. Valves 3 and 4 control the pressure and the drain pipe, respectively.

2.2 Pneumatic System

A schematic of the pneumatic system is shown in Fig. 2 where: 1, 2, 3, 4, 5, 7 – valves, 6 – pressure gage, 8 – gas release to the atmosphere, 9 – compressed-hydrogen

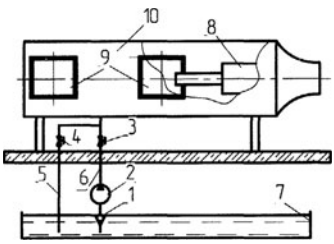

Fig. 1 Schematic of the hydraulic system of the firing bench:.1 – check valve; 2 – pump; 3, 4 – valves; 5 – drain pipe; 6 – pressure pipe; 7 – water basin; 8 – catapult; 9 – observation windows; 10 – water tunnel

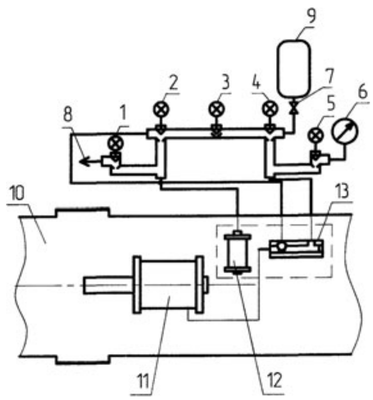

Fig. 2 Schematic of the pneumatic system of the firing bench

bottle, 10 – water tunnel section, 11 – catapult, 12 – electrolyzer, and 13 – check valve block.

2.2.1 Operational Procedure for the Pneumatic System

Before filling the catapult combustion chamber with the products of electrolysis, blow through the system, for which purpose close the valve 1 with the valves 2, 3, 4, 5, and 7 open. Then close the valve 7 and open the valve 1 to complete the blow-through. In doing so, check the pressure on the pressure gage 6.

To fill the catapult combustion chamber with the combustible mixture, close the valve 1 with the valve 2, 3, 4, and 5 open and the valve 7 closed. Turn on the electrolyzer 12 and raise the pressure in the catapult combustion chamber to its working value; in doing so, check the pressure on the pressure gage 6. Once the working pressure is reached, turn off the electrolyzer 12, open the valve 1, and close the valve 5. When the whole of the pneumatic system is vented to the atmosphere 8, the pressure in the catapult combustion chamber remains unchanged due to the check valve 13.

2.3 Electric Circuit

The electric circuit of the bench is shown in Fig. 3 where: 1 – personal computer; 2 – control panel; 3 – video camera; 4 – power unit; 5 – DC generator; 6 – fuse wire; 7 – electrolyzer; 8 – catapult; 9 – window; and 10 – lighting.

The electric system serves to accumulate the firing energy by water electrolysis, fire the gas mixture, start the catapult, and record the test data.

2.3.1 Operational Procedure for the Electric System

To fire a model, fill the catapult combustion chamber with the electrolysis gas. To do so, apply to the electrolyzer a stable working direct current of 80–100 A and a stable working voltage of 11 $\div$ 14.2 V using the power unit 4 and the DC generator 5. Once the required pressure in the catapult chamber is reached, stop the electrolysis. The model is fired and the data are recorded using the control panel 2, the video camera 3, the lighting 10, and the personal computer 1.

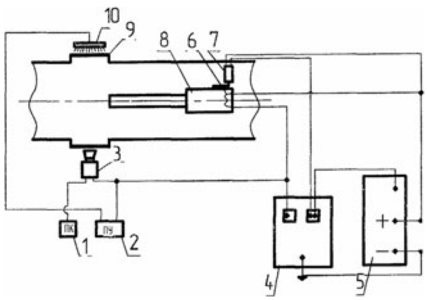

Fig. 3 Electric circuit

The current and the voltage are checked on the amperemeter and voltmeter of the control panel 2. The electric circuit also provides for the synchronous operation of the personal computer 1, the control panel 2, the video camera 3, and the lighting 10 when recording the test data.

The energy is accumulated using the electrochemical process of water decomposition into oxygen and hydrogen by the familiar chemical reaction [7]:

$$2H_2O \rightarrow H_2 \uparrow + O_2 \uparrow .$$

In the process, oxygen is liberated at the anode, and hydrogen is liberated at the cathode. According to Faraday's law, the mass of the oxygen and hydrogen produced at the electrodes will be

$$M = Z \cdot I \cdot t,$$

where $Z_H = 0.0376$ g·/(A · h) and $Z_o = 0.2984$ g·/(A · h) are the electrochemical equivalents of hydrogen and oxygen; I is the current (A); and t is the electrolysis time (h).

Since the produced gases are compressed to pressure P_0 in the combustion chamber, the amount of the accumulated energy can be estimated as

$$E = M_{H2O} \cdot \Delta H_{289}/18.02 + P_0 V_0,$$

where $\Delta H_{289} = 241.83$ kJ/mole is the water formation heat [kJ/mole] at 289 K (25°C) [8]; M_{H2O} is the water (water vapor) mass in grams; V_0 [m^3] is the combustion chamber volume; and P_0 [Pa] is the combustion chamber pressure prior to firing.

The consumed energy will be

$$E_\Sigma = I \cdot U \cdot t,$$

where I is the circuit current, U is the circuit voltage, and t is the chamber charging (electrolysis) time.

2.4 Measuring System

The measuring system allows one to check the catapult charging parameters. They are the electrolysis current, voltage, and time and the chamber pressure prior to and after electrolysis. The measuring system also records the model motion in the channel using a system of sensors and high-speed photography. Initially, SKS-1 M and Pusk-16 high-speed 16-mm movie cameras with a frame frequency up to 5,000 frames/s were used for this purpose. Now we use an X-Sheam XS4 video camera (Integrated Design Tools, Inc.) with a frame frequency of 1,000–20,000 frames/s.

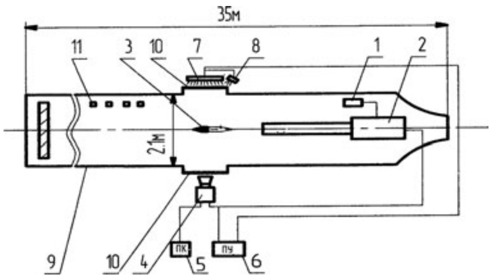

Fig. 4 Schematic of the experimental setup with a video recording

The rather large illuminated area (0.8 × 0.8 m) requires a high lighting power of about 10 kW. Figure 4 shows a schematic of the experimental setup with video recording where: 1 – gas generator; 2 – catapult; 3 – moving model; 4 – video camera; 5 – personal computer; 6 – control panel; 7, 8 – lighting; 9 – water wind channel; 10 – window; and 11 – sensors. The instantaneous speed of models is measured by two methods:

- From the recorded video frames by the technique described in [9]
- By measuring the time it takes for the model to travel the distance between two measuring planes

3 Model Design

Test models must be designed to suit the following basic requirements:

- A model must fit into the supercavity contour over a distance of 35 m
- Stable motion of a supercavitating model over a distance of 35 m
- Minimum deviation of a model from a straight-line trajectory over a specified distance
- Strength sufficient to withstand the accelerating pulse in firing and the longitudinal impact load in water entry
- Strength and stiffness sufficient to withstand the side forces caused by hydrodynamic interaction between the model and the cavity walls (Fig. 5)

To fit a model into the supercavity contour, use is made of the SC_Design program developed at the IHM of NASU [10, 11]. The program constructs the supercavity contour from given parameters: the speed V_x, the hydrostatic pressure P_0, the vapor pressure $P_к$ ($P_к(t) = 2{,}337$ Pa at $T = 20°$C), and the cavitator diameter D_n and fits the model contour into it with some gap between them.

The inertial force F_i and stresses σ_i acting on a model during its acceleration in the barrel to speed V_0 can be estimated as

$$\sigma_i = \frac{4F_i}{\pi D_m^2} = \frac{4ma}{\pi D_m^2} = \frac{2mV_0^2}{\pi D_m^2 L},$$

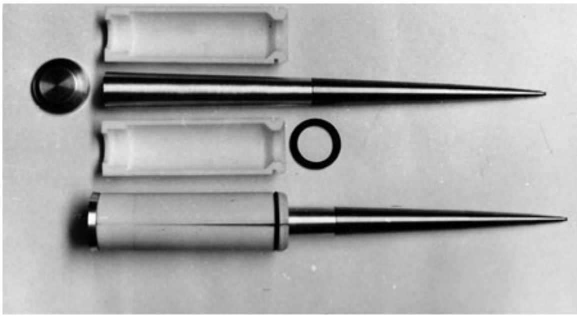

Fig. 5 High-speed supercavitating model

where m is the model mass (kg); $a = \frac{V_0^2}{2L}$ is the acceleration; L_c is the barrel length; and D_m is the model aft diameter.

The test results listed in Table 1 show that in acceleration the model bottom develops stresses of 235–785 MPa. Such high stresses call for special steels with ultimate stresses of the order of 500–800 MPa.

The hydrodynamic drag force F_n and stresses σ_n acting on the cavitator of a model can be estimated as

$$\sigma_n = 4F_n/\pi D_n^2 = C_x \cdot \rho V_0^2/2$$

where $C_x = 0.82$ is the drag coefficient of a disc in a supercavity flow, ρ [kg/m^3] is the water density, V_0 is the model speed, and F_n is the drag force. According to the attained speeds (Table 1), the cavitator stresses will lie in the range 400–910 MPa, which also calls for special high-strength steels.

4 Test Results

Systematic tests on the IHM of NASU's firing bench have been conducted since 1990. Over this period, the following has been investigated:

- The unsteady processes of high-speed water entry and supercavity inception
- The mechanisms of interaction of high-speed supercavitating models with various obstacles
- The features of interaction between high-speed supercavitating models in group motion

Starting in 1993, the obtained results have been published in Refs. [12–20]. Below are some of the test results obtained on the IHM of NASU's upgraded firing bench (see Table. 1). Table 1 gives the catapult charging parameters and the model speeds calculated from the recorded video data for a series of tests. Among the firings shown in the table, of especial interest is firing No 6 because in this case the water sound speed $a = 1{,}422$ m/s at water temperature $T = 4$°C was exceeded.

Figure 6 shows video frames of the motion of the supercavitating model, wherein the supercavity shape and shock waves can be seen.

Table 1 The catapult and the model parameters in experiments

No	Model mass, m_1,kg	Charge mass, m_2, kg	Pressure P, MPa	Time t, s	Current I, A	Voltage, V, V	Power, N, kW	Speed, V_1, m/s	Acceleration, a, m/s^2	Barrel length, L, m	Kinetic energy, E_k, J
1	0.015	0.032	18	6,60	80	11.0	1.51	1,210	366,025	2.0	2,412.8
2	0.015	0.035	17	6,28	90	11.5	1.78	1,205	363,006	2.0	2,577.8
3	0.015	0.035	17	9,78	90	11.5	2.8	1,205	363,006	2.0	2,577.8
4	0.035	0.035	18.7	6,78	80	10.8	1.65	1,170	344,176	2.0	8,552.8
5	0.014	0.032	17	7,80	100	11.0	2.76	0,955	227,380	2.0	
6	0.015	0.065	11	4,80	100	12.7	1.69	1,550	600,625	2.0	8,028.8
7	0.015	0.068	13	6,90	100	12.8	2.45	1,330	442,225	2.0	6,137
8	0.015	0.068	15	6,00	100	12.7	2.16	1,240	384,400	2.0	5,334.5
9	0.015	0.066	11	5,10	100	12.0	1.7	1,380	476,100	2.0	6,412.8
10	0.015	0.071	11.5	5,10	100	13.1	1.85	1,350	455,65	2.0	6,573.9
11	0.014	0.075	11.5	5,10	100	13.0	1.84	1,205	363,006	2.0	5,593.3
12	0.015	0.072	11.5	5,40	100	13.0	1.95	1,300	422,500	2.0	663.4
13	0.015	0.033	11.5	2,28	100	13.0	0.82	1,200	214,925	3.35	2,424.5
14	0.015	0.060	11.5	4,80	100	14.2	2.08	1,350	272,015	3.35	5,625.5
15	0.016	0.084	11.5	4,95	100	14.2	1.96	1,375	282,183	3.35	8,102.6
16	0.015	0.103	11.5	4,50	100	13.3	1.65	1,230	226,806	3.35	8,053.3
17	0.036	0.080	12.7	5,46	100	13.0	1.97	1,320	260,060	3.35	7,111.8
18	0.015	0.123	11.5	4,80	100	13.0	1.73	1,270	240,731	3.35	10,1217

Fig. 6 Record of supersonic motion through water (video frames)

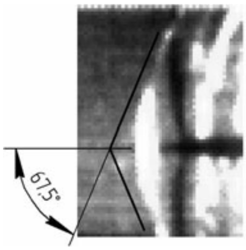

Fig. 7 Mach angle determination

The experiment was conducted under the following conditions:
Ambient parameters:
- Water temperature $T = 4°C$
- Water sound speed $a = 1{,}422$ m/s
- Model immersion depth $H = 0.5$ m

Model parameters:
- Cavitator diameter $D_n = 1.2$ mm
- Model length – 85 mm

Recording parameters:
- Frame frequency 25,000 frames/s
- Exposure time 1 μs
- Graticule scale spacing 50 mm

The model speed can be found from the recorded frames (Fig. 6) [9] and from the shock wave shape (Fig. 7) [20].

The model speed measured from the frames was $V = 1{,}550$ m/s, and the attained Mach number was:

$$M = \frac{V}{a} = \frac{1550}{1422} = 1.09.$$

From the shock wave shape in Fig. 7, the Mach number was estimated as [19]

$$M = \frac{1}{\sin\ 67.5^{\circ}} = 1.082.$$

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