Experimental study on water-entry of body with buffer at high velocity

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Abstract. In order to study the buffering effect of the structure when it enters the sea at high speed in the air, an effective test method is established in this paper. The experimental method can effectively observe the motion state of the structure body and the deformation process of the buffer structure, and the impact response data collected by the acceleration sensor provides an important reference for the research. The results show that the cushioning device installed on the head of the structure can effectively reduce the overload at the moment of water impact, and the choice of protective material will affect the cushioning energy absorption effect.

1. Introduction
An air-launched structure, such as an air-dropped torpedo, is subjected to a very high peak pulse pressure when contact to the water surface with high velocity (about 100m/s) [1-2]. In the subsequent stage of water entry, the whole structure will experience high overload. If the peak pressure on the wet surface is too high, the head structure of projectile will fail, and even the internal structure and electronic devices will be damaged [3-6]. For the weak strength structure, high overload during water entry will lead to the failure of the whole structure, the loosening of internal devices and the electrical failure, which will eventually make the whole structure lose its function [7-8].

In order to prevent the above situation, energy absorption and peak overload limiting can be achieved by adding protective head cap to the air-drop structure. In order to verify the buffering performance of different headgear, this paper designs relevant tests for further analysis, and provides reference data for the design of protective headgear. This work is significant to headgear design.

2. Experiments
Because the normal pool test can not meet requirements of high speed entry, a new test method is applied in this paper. The schematic diagram of test system is shown in figure 1. The projectile with acceleration sensor inside will be shot into the water tank through the ballistic gun. High-speed camera will capture the whole motion process. Acceleration data will be collected by oscilloscope. Constant current power will be applied to supply power to the sensor. The parameters of sensors are shown in table 1.
The accelerator employed in this test is a smoothbore gun with 40mm caliber, as shown in figure 2. Since the projectiles tested in this work are over caliber but the required speed is very low compared with real missile, the projectile is loaded directly from the muzzle in this test.

A Phantom color high-speed camera was employed in this experiment, and the sampling rate was adjusted to 10000fps, which is equivalent to sampling every 100μs. The exposure and resolution of the image at this sampling rate can meet the needs of the experimental research.

The transparent, impact-resistant water tank was made of polycarbonate composite material, and there was no cover on the tank. The water tank is 1m long, 0.8m wide and 0.6m high, with a central hole diameter of 0.4m, as shown in figure 3. Two holes were cut in the front and the back pieces of the polycarbonate and were sealed by two pieces of diaphragms analogously to Guo Z, Zhang W, et al. [9]. The diaphragms were made of 0.2 mm thick acrylic sheets. The projectile was fired into the front hole to penetrate the fluid horizontally and it either left the tank from the back hole by itself or was manually unloaded. Before each run, water was replenished and the tank was sealed with fresh diaphragms.

### Table 1. Parameters of the accelerometer.

| Sensitivity (20 ± 5 °C) | Frequency range | Maximum acceleration | Thread | Nominal voltage | Rated current | Output mode |
|-------------------------|-----------------|-----------------------|--------|-----------------|---------------|-------------|
| 0.003 mV/(m·s²)         | 5–10000 Hz      | 5×10² m/s²            | M5     | 5 V (DC)        | 2–10 mA       | L5          |

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The buffer head used in the test was 150mm diameter, the projectiles are accelerated by the ballistic gun to a speed of about 100m/s, and measured the peak acceleration in the process of water entry. In order to meet the above requirements, the specimen is mainly divided into three parts: sabot, bottom support (sensor inside) and buffer head. The schematic diagram of the specimen is shown in figure 4. The sabot is made of nylon, and the length of sabot is 300mm, which is obtained from previous test experience. Grooves were dug in the rear of the sabot to seal up the gunpowder gas, and the diameter is 40mm, which is the same as the inner diameter of the ballistic gun. In order to make the impact velocity consistent, the mass of the specimen should be consistent. Therefore, the hole should be dug in the sabot to fine-tune the total mass of the specimen through the steel ball. The function to be realized in the bottom support is to connect the sabot and buffer head, fix the sensor inside, and should be water tight. Since the sensor needs to be reused, they need to be disassembled easily from the bottom support. The bottom support designed for this experiment is shown in figure 5. The buffer head is a cylinder with simple structure, as shown in figure 6. Two materials, polyurethane and aluminum foam, were used in this experiment. The density of polyurethane was 0.12g/cm$^3$, 0.18g/cm$^3$ and 0.25g/cm$^3$, respectively. The density of aluminum foam was 0.34g/cm$^3$. The actual specimen is shown in figure 7.

Figure 3. Axonometric drawing of water tank.

Figure 4. Specimen diagram.

Figure 5. Diagram of bottom support.
3. High speed photographic data and analysis

Figure 8 shows the water entry process of polyurethane head with a density of 0.25g/cm$^3$, showing the state at each time point after water entry. Figure 8(a) shows the initial stage of water entry, which will generate stress wave and peak acceleration. The buffer head will be squeezed and deform in large quantity to absorb energy, and the gap inside the material will be densified. The subsequent process is water invasion process. Due to the high density of 0.25g/cm$^3$ polyurethane, it is rapidly compacted in the water entry process, so a large number of pieces are broken in the water invasion process, which is conducive to the removal of the head in the water.

Buffer head after test is shown in figure 9. The impact velocity of this group is 85-95m/s. As can be seen from the figure, the head of 0.12g/cm$^3$ has been completely broken and separated from the bottom support, which is an ideal process, but plays a limited role in impact protection. For the head of 0.18g/cm$^3$, the part with high stress closer to the edge detached from the bottom support, it has good protection and detachment effect. The head of 0.25g/cm$^3$ is broken and a small amount of foam is detached. Due to the high density, the deformation is limited and the protective effect is limited. The aluminum foam head of
0.34g/cm³ fell off a little, and the falling part almost did not deform, which proved that the density aluminum foam was rigid under this impact condition, and its buffering performance is poor in this test.

The purpose of this experiment is to study impact effect of water entry process, so only the first 3ms of water entry process is analyzed. In order to better describe the rupture position of buffer head, dimensionless penetration depth \( G = x/2R \) is introduced, where \( x \) is the penetration depth and \( R \) is the radius of buffer head.

![Buffer head images](image)

(a) 0.12g/cm³ polyurethane foam.  
(b) 0.18g/cm³ polyurethane foam.  
(c) 0.25g/cm³ polyurethane foam.  
(d) 0.34g/cm³ aluminum foam.  

**Figure 9.** Buffer head after test.

Velocity and displacement parameters were collected by high-speed camera. v-t curve and v-G curve are shown in figure 10 and 11. Due to the small mass of the specimen, it is sensitive to acceleration, and the velocity changes greatly during water entry. The velocity history of the specimen was significantly different from that of the rigid body. The velocity of the projectile with buffer head decreased significantly during the water entry process, and the deceleration process was obviously divided into two sections. This is because during the process of water entry, the buffer head is compacted in the horizontal direction, expanded in the circumferential direction, compressed into a flat shape and increased the water contact area, resulting in a fast decrease in velocity. When the buffer head is broken, the projectile body velocity decreases. The density of 0.12g/cm³ polyurethane head is too soft, so the velocity curve is basically the same as rigid projectile. The rupture time and location vary with the density, so in general the higher the density of the buffer head, the early the compaction happened. A low velocity water entry test was conducted (65-75 m/s) for polyurethane materials and compared with the previous velocity history, as shown in figure 12. The form of v-t curve almost the same. A certain amplitude of velocity attenuation fluctuation will occur during compaction and fragmentation.
Figure 10. v-t curve.

Figure 11. v-G curve.

(a) Projectile with 0.12g/cm$^3$ polyurethane foam.
(b) Projectile with 0.18g/cm$^3$ polyurethane foam.
(c) Projectile with 0.25g/cm$^3$ polyurethane foam.
(d) Projectile with 0.34g/cm$^3$ aluminum foam.

Figure 12. V-t curve of projectiles with the same buffer head at different impact velocities.
4. Acceleration sensor data and analysis

The acceleration sensor was used in the test to measure the peak overload at water entry. Due to the measurable range of the sensor, only polyurethane foam head was measured. Figure 13 shows the overload history of 0.25 g/cm$^3$ density. Because of the low response frequency of the sensor, only the peak point has reference value. The overload of the rigid head and the aluminum foamed head both exceeded the measurable range and were not obtained from the experiment. Table 2 lists the data obtained by the acceleration sensor and the overload data obtained by the numerical simulation under the same conditions, and compares the overload reduction rate. Figure 14 shows the relationship between peak acceleration and density under two impact velocities. It can be found that the head cap with a density of 0.18g/cm$^3$ has a better buffering effect than the other two under this condition.

![Figure 13. Overload history of 0.25 g/cm$^3$ density.](image1)

**Table 2. Test results of maximum deceleration.**

| Buffer density (g/cm$^3$) | Initial velocity (m/s) | Peak deceleration (G) | Reduction rate |
|---------------------------|------------------------|-----------------------|----------------|
| Rigid                     | 70.0                   | 92600                 | n/a            |
| 0.12                      | 98.4                   | 161300                | n/a            |
| 0.18                      | 69.8                   | 9600                  | 89.6%          |
|                            | 91.7                   | 48700                 | 69.8%          |
| 0.25                      | 71                     | 3400                  | 96.3%          |
|                            | 96                     | 12700                 | 83.9%          |
| 0.25                      | 70.4                   | 11400                 | 87.7%          |
|                            | 90.7                   | 22000                 | 86.4%          |

![Figure 14. The relation between peak overload and buffer head density.](image2)
5. Conclusion
This paper conducts an experimental study on the impact of the air-drop equipment when it enters water at high speed, and draws the following conclusions:

A set of feasible test methods is designed, which can be used to observe the buffering effect of projectiles with buffer head when entering water at high speed. By analyzing the high-speed photographic data, the motion of the projectile buffer into the water is understood. The cushioning effect of the headgear was verified by comparing the data of the acceleration sensor.

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