Study on Buffering Performance of Aluminum Foam during Water-entry Process

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Abstract. The structure will suffer a huge overload, when it enters into water. The buffer head cap can effectively reduce the overload, and the buffer material in the cap is the key to its load reduction performance. In order to study the buffering ability of aluminum foam, an effective numerical simulation method is established in this paper. The numerical simulation method can effectively observe the motion of the structure and the energy absorption process of aluminum foam. It is found that the aluminum foam has strong capacity of buffering and reducing load by comparing with the structure without buffer head cap under the same conditions. In the process of energy absorption deformation, it can effectively protect the projectile from buckling deformation.

1. Introduction

With the rapid development of weapon science and technology, many countries are developing or equipping intelligent mine, torpedo or other intelligent water ammunition of air-drop type, canister shot type, long-distance launching type. In addition, a variety of intelligent water-launching devices are being developed to perform tasks such as information collection, signal relay, and underwater monitoring in inaccessible waters. The above water injection equipment has complex internal structure and a variety of electronic devices. When entering water, the wet surface of the head will encounter transient pulse pressure and overload with quite high peak value, and the dynamic response of the structure aroused will lead to problems such as shell buckling failure and electronic device function disorders.[1] The common problems of water entry equipment are large impact load, intense dynamic response of structure, and difficult to guarantee the motion state and trajectory after water-entry, which seriously affect the development of high reliability and intelligence of water entry equipment.

At present, the solution to the high overload in water-entry is to install a buffering cap on the head of the projectile and fill it with energy absorbing material. Wu Siyu and Shao Zhiyu et al. studied the polyurethane foam material, studied the buffer capacity of polyurethane foam in the water impact, and established the corresponding empirical model.[2] This year, foam aluminum materials have been widely used. Aluminum foam is a kind of light porous material. The foaming mechanism is to inject gas or add foaming agent into aluminum melt. With the continuous formation and growth of bubbles, it further acts with aluminum melt to form a cellular structure, namely aluminum foam. Compared with other porous materials, it has a high opening rate and large pore size, the opening rate is usually more than 60%, up to 95%. Its density is generally between 0.2-1.2g/cm³. During compression, there is a long horizontal phase in the compressive stress-strain curve as shown in Figure 1, so it has a good absorbing and cushioning effect.
In this paper, we manage to use numerical simulation method to study the buffer performance of aluminum foam in the water impact, and compare it to the structure without buffer head, so as to provide engineering guidance for the buffer of air-launched under water equipment.

2. Simulation Set Up

2.1. Simulation Model
In this paper, LS-DYNA is used for numerical simulation analysis, and the missile body, protective material and water area are respectively established. The air has little influence on the maximum impact force, so the air domain is ignored in this modeling. Adopt quarter model, unit system is cm·g·μs. A steel cylinder with a diameter of 11cm and a height of 55cm is adopted to simulate the missile body. The protective material is a half sphere with a diameter and a cube with water as 60*60*60cm size. Lagrange algorithm and vertical entry method with the worst force condition are selected. The model view is shown in Figure 2.

2.2. Material Model of Steel
The material model selected for steel material is *MAT_JOHNSON_COOK, which is suitable for most metal materials with high strain rate. This model is suitable for metal explosion, forming trajectory, penetration and impact. The material parameters are shown in Table 1.

![Stress-strain curves of typical buffer materials](image1.png)

**Figure 1.** Stress-strain curves of typical buffer materials

![Model for numerical simulation](image2.png)

**Figure 2.** Model for numerical simulation.
The state equation of steel is Gruneisen’s state equation:

\[
p = \rho_0 C_P a \left[ 1 + \left( 1 - \frac{\gamma_0}{2} \right) \frac{\mu - \frac{\alpha}{2} \mu^2}{\mu + 1} \right] \left( \nu + a \mu \right) E
\]

(1)

Where \( P \) is pressure, and \( \mu = \rho / \rho_0 - 1 \). The values of state equation are shown in Table 2.

### Table 1. Material parameters of steel.

| Property                          | Value     |
|-----------------------------------|-----------|
| Density (g/cm³)                   | 7.83      |
| Failure stress (Mbar)             | -9.0      |
| Shear modulus (Mbar)              | 0.77      |
| Constant A (Mbar)                | 7.920 × 10⁻³ |
| Elasticity modulus (Mbar)         | 0         |
| Constant B (Mbar)                | 5.100 × 10⁻³ |
| Poisson’s ratio                   | 0         |
| Constant C                        | 1.03      |
| Melting temperature (°F)          | 1793      |
| Constant n                        | 0.260     |
| Normal temperature (°F)           | 294       |
| Constant m                        | 0.0140    |
| Specific heat (cm²/k)             | 0.477 × 10⁻⁵ |
| Constant D1–D5                    | 0         |

### Table 2. Values of state equation of steel

| Variable | C(cm/μs) | S₁ | S₂ | S₃ | γ₀ | a |
|----------|----------|----|----|----|----|---|
| Value    | 0.4569   | 1.49 | 0  | 0  | 2.17 | 0.46 |

### Table 3. Material parameters of water

| Property                          | Value     |
|-----------------------------------|-----------|
| Density (g/cm³)                   | 1.02      |
| Cutoff pressure (N)               | 0         |
| Coefficient of kinetic viscosity  | 0         |
| Relative volume                   | 0         |
| Young’s modulus (Mbar)            | 0         |
| Poisson’s ratio                   | 0         |

### Table 4. State equation value of water

| Variable | C(cm/μs) | S₁ | S₂ | S₃ | γ₀ | a |
|----------|----------|----|----|----|----|---|
| Value    | 1.65     | 1.92 | -0.096 | 0 | 0.35 | 0 |

### Table 5. Material parameters of aluminum foam

| Property                          | Value     |
|-----------------------------------|-----------|
| Density (g/cm³)                   | 0.17      |
| E (MPa)                           | 377       |
| γ (MPa)                           | 1.87      |
| \( \varepsilon_D \) (MPa)         | 2.77      |
| \( \alpha_2 \) (MPa)              | 93.5      |
| β                                 | 5.79      |
| \( \sigma_p \) (MPa)              | 1.15      |
| \( \varepsilon_c \)               | 0.02      |
| 0.286                             | 73.1      |
| 0.34                              | 1516      |
| 0.51                              | 5562      |
| 5.37                              | 1.67      |
| 66.9                              | 2.99      |
| 14.82                             | 0.02      |
3. The Buffering Performance

The water entry model of unprotected projectile was established, as shown in Figure 3. The simulation results were compared with the model of protective material with a density of 0.34g/cm$^3$, and the buffering performance of aluminum foam was analyzed from four aspects: velocity, acceleration, energy absorption and buckling deformation.

![Figure 3. Simulation model of unprotected projectile.](image)

Figure 3 shows the velocity curves of water entry in two cases. It can be seen from the figure that the variation of velocity can be reduced with protective materials, and the motion of the projectile body tends to be more stable. Without protection, the velocity drops instantly at the beginning, and the velocity changes rapidly. The time-velocity curve of the unprotected water entry projectile in the initial stage was enlarged, and only the velocity change of the first 100μs was observed, as shown in Figure 5. It is observed that there is a significant decrease in velocity at the beginning, lasting about 10μs.

![Figure 4. Velocity curves of water entry in two cases.](image)

![Figure 5. Zoom in on the first 100 milliseconds.](image)

Figure 6 shows the acceleration curves of water entry in two cases. The acceleration changes significantly at the beginning, and then gradually stabilizes. The acceleration curve for the unprotected projectile in the initial stage was enlarged, and only the acceleration change of the first 300μs was observed, as shown in Figure 7. It is observed that there is a significant decrease in acceleration at the beginning, lasting about 300μs.

![Figure 6. Acceleration curves of water entry in two cases.](image)

![Figure 7. Zoom in on the first 300 milliseconds.](image)
Acceleration changes in the two cases are shown in Figure 6. It can be seen that the two cases are obviously different. In the case of no protection, the acceleration-time curve rises at an instant with a maximum value of $3.1 \times 10^{-5} \text{cm/μs}^2$, while in the case of protection, the maximum value of acceleration is $3.6 \times 10^{-7} \text{cm/μs}^2$. There was a 98.84% reduction compared with no protection. Focus on the acceleration changes of the first 300μs, as shown in Figure 7. When the projectile body enters the water without protection, there will be a moment of great hydraulic invasion. This stage is the key stage of research on protection. The force at this stage may exceed the yield strength of the material and cause damage to the function and structure of the projectile body. It can be seen that this stage disappears after the addition of protective material.

![Figure 8. Energy absorption over time.](image)

![Figure 9. Percentage of failed units.](image)

The buffer mechanism of buffer materials such as aluminum foam is that they can absorb a large amount of energy when they are impacted. The change of energy absorption over time is shown in Figure 8. At the beginning, the energy absorption efficiency is high, and at the end, the absorbed energy tends to be flat about 7000J, which can be seen that buffer materials absorb a large amount of energy and achieve a good buffer effect.

Figure 9 shows the percentage of failed units in the total units in two cases, where the solid black line is the model without protection and the dashed red line is the model with protective head and cap. It can be seen that in the case of no protection, the proportion of failed units appeared a peak at about 50μs, and about 17% of the units failed. It can be seen that at this time, the projectile body was subjected to great water intrusion, and then there were continuous failure of units. After adding the protective device, it can be seen that the maximum unit failure ratio is reduced to 0.0366%.

4. Conclusion

Through the comparison of velocity curve, acceleration curve, energy absorption curve and buckling deformation curve, the following conclusions can be drawn:

1. After adding protective materials, the velocity change of projectile body is reduced by 39%.
2. The peak acceleration of the protected structure when entering water is reduced by 98.84%.
3. The cushioning effect of aluminum foam is obvious, and the maximum stress on the structure is reduced by 92.98%.
4. By comparison, the yield unit ratio of the projectile body with buffer head is reduced by 99.78%.

Table 6 shows the comparative results of the four aspects. It can be seen that the protective material has obvious buffering effect and effectively protects the missile body.
Table 6. Comparative results of the four aspects.

| Aspects                  | Unprotected       | Protected        | Reduction rate |
|--------------------------|-------------------|------------------|----------------|
| Velocity(cm/μs)          | $2.3 \times 10^{-3}$ | $1.4 \times 10^{-4}$ | 39%            |
| Energy absorption(J)     | -                 | 7000             | 98.84%         |
| Max acceleration(cm/μs²) | $3.1 \times 10^{-5}$ | $0.036 \times 10^{-5}$ | 92.98%         |
| The maximum stress on the projectile body(Mbar) | $1.502 \times 10^{-3}$ | $0.1055 \times 10^{-3}$ | 99.78%         |
| Maximum yield element ratio | 17%              | 0.0366%          |                |

5. References

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