Research on the equivalent relationship of torpedo penetrated by underwater supercavitation projectile based on energy consumption model

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Abstract. Supercavitation projectile is one of the research hotspots of underwater defence technology. The cost of underwater damage test is such high that equivalent test on land is often considered as a possible alternative. In this paper, the equivalent relationship between torpedo and related materials penetrated by underwater supercavitation projectile is studied. Firstly, a typical torpedo structure model consisting of the torpedo shell and 14 key components is constructed; Secondly, the process of underwater supercavitation projectile penetrating torpedo is divided into two stages, that is, the underwater motion of projectile before penetration and the projectile penetrating torpedo. And the energy consumption models of projectile penetrating water medium and the energy consumption models of projectile penetrating torpedo are established respectively, considering the influence of water medium on torpedo. Because the equivalent targets obtained by the vertical impact of the projectile are different at different positions of the torpedo, two typical penetration directions and typical cabin sections of the control section of the torpedo are considered in this paper. Finally, combined with the water medium model and torpedo structure model, and based on the principle of equivalent ultimate penetration velocity and equal minimum penetration energy consumption, the full torpedo equivalent simulation model of transverse penetration and longitudinal penetration torpedo control section under underwater penetration condition considering the influence of water medium is established.

1. Introduction
The threat of torpedo to warship is more and more serious. It is one of the most popular research of underwater defense technology to destroy torpedo by launching supercavitating projectile. Although it is the most authentic to use real target for damage test, the cost of underwater damage test is high, and the equivalent target test on land is a feasible alternative. Yan Zhou [1] and others put forward the equivalent relationship between shipboard structural target and homogeneous target on the basis of energy equivalent principle; Ran Xiong [2] and others studied the relationship between ceramics and homogeneous steel under the condition of rod penetrator penetrating armor target on the basis of residual penetration equivalent principle equivalent relation: Ting Liu [3] and others have obtained the
equivalent relation of torpedo, mine and homogeneous steel under the penetration of projectile on the basis of the equivalent theory of ultimate penetration velocity. However, their research is only limited to the shell of torpedo and mine, and they do not consider the penetration of projectile into the whole mine under the influence of water medium.

This paper studies the equivalent relationship between torpedo and relevant materials under the condition of underwater penetration of supercavitation projectile, constructs a typical torpedo structure model composed of shell and 14 key components, and establishes an underwater multi-layer target model under the consideration of the influence of water medium based on the equivalent theory of ultimate penetration velocity and the principle of equal minimum penetration energy consumption.

2. Structural model of torpedo

MK48ADCAP (MK48-5) torpedo in the United States is a typical heavy-duty anti-ship torpedo in active service. The torpedo is 5.85m in total length, 533.4mm in diameter, 1580kg in weight at launch, 60kn in speed, 46km in range, 1000m in depth and 350kg in charge. It is guided by inertial navigation, linear navigation and active passive acoustic homing. The power device is piston engine and the propulsion device is pump injection Thruster, energy system is Otto II fuel, fuse category is trigger proximity. In this paper, MK48 torpedo is selected as the research object, and the torpedo model is established [4].

There are two kinds of damage modes of supercavitating projectile to torpedo: one is that the projectile penetrates the key parts of torpedo in order along the penetration direction, resulting in the functional failure of key parts; the other is that the projectile produces secondary fragments when penetrating the shell of torpedo, resulting in auxiliary damage.

In the research of this paper, one of the preconditions for establishing the equivalent target of the simulation model is to determine which parts of the torpedo are damaged by the supercavitation projectile, so as to determine the key parts of the torpedo, and then establish the torpedo structure model. The mechanism of supercavitating projectile destroying torpedo is: through penetrating armor and then destroying the internal devices of torpedo, the torpedo can not complete its combat mission.

The cross section of MK48 torpedo body is round, the head of the torpedo is streamlined, the middle part is cylinder, the tail is frustum, The shell is a thin shell structure with ribs, and the thickness of the shell is uniform. The basic components are mainly composed of five parts, including the overall structure system, the guidance system, the warhead system, the control system and the power propulsion system. According to the components, the MK48-5 torpedo is divided into five sections, from the front to the back, which are the top section, torpedo war head, the control section, the bunker and the rear compartment. The schematic diagram of its size structure is shown in figure 1 [5].

![Figure 1. MK48-5 Schematic diagram of torpedo dimensions.](image)

According to the materials commonly used in weapons at home and abroad, it is assumed that the torpedo shell is made of 7039 aluminum alloy, the warhead shell is made of titanium alloy, and the
other key parts are made of A356. According to the characteristics of torpedo structure, the size of key components is assumed as follows, as shown in the basic characteristics table of each key component.

Damage to the torpedo shell will result in holes, which will cause seawater to intrude into the interior and disable the sensitive parts. Its equivalent simulation model needs to be considered.

If the guidance system is damaged, it will not be able to send or receive signals, resulting in the torpedo to be unable to search and track the target, causing the torpedo to lose the target, or unable to operate the torpedo, causing the torpedo to lose control. The main key components of the guidance system and their characteristics are shown in table 1.

It is assumed that the origin of the coordinate system used for the central coordinates is established on the center point of the torpedo head, the 0X axis is the torpedo longitudinal, the 0Y axis is transverse along the torpedo, and the 0Z axis is perpendicular to the 0XY plane, in line with the right hand rule.

| Part                  | Dimensions          | Central coordinates |
|-----------------------|---------------------|---------------------|
| Transducer            | 39mm×156mm×156mm   | 39,0,0              |
| Transmitter           | 65mm×234mm×234mm   | 169,0,0             |
| Acoustic Homing Control Logic Component | 195mm×39mm×208mm | 455,91,0 |
| Receiver              | 195mm×39mm×208mm   | 455, -91,0          |
| Coil                  | 156mm×234mm×234mm  | 2600,0,0            |

Damage to the warhead system may result in either detonation of the warhead to disintegrate the torpedo or dud. The warhead system is mainly composed of the warhead shell and the detonating device, and its basic characteristics are shown in table 2.

| Part                  | Dimensions          | Central coordinates |
|-----------------------|---------------------|---------------------|
| Warhead Shell         | 585mm×208mm×208mm  | 1287,0,0            |
| Detonation Device     | 65mm×117mm×65mm    | 1469,0,0            |

Damage to the control system will prevent the torpedo from following instructions. The key components of the control system include sensor control components such as gyroscope, command control components and power supply components, whose basic characteristics are shown in table 3.
Table 3. Basic features of key components of control system.

| Part                                      | Dimensions        | Central coordinates |
|-------------------------------------------|-------------------|---------------------|
| Gyro and other Sensor Control Components  | 260mm×26mm×182mm  | 2158,0,0            |
| Command Control Unit                      | 260mm×52mm×182mm  | 2158,-104,0         |
| Power Supply Component                    | 260mm×39mm×182mm  | 2158,117,0          |

Damage to the power propulsion system will cause the torpedo to lack power and be unable to complete its function. The power propulsion system mainly consists of bunker, auxiliary pump, engine and pump jet thrusters, whose basic characteristics are shown in table 4.

Table 4. Basic characteristics of key components of power propulsion system

| Part              | Dimensions        | Central coordinates |
|-------------------|-------------------|---------------------|
| Bunker            | 650mm×247mm×247mm | 3432,0,0            |
| Auxiliary Pump    | 195mm×234mm×234mm | 4303,0,0            |
| Engine            | 390mm×195mm×195mm | 4914,0,0            |
| Pump Jet Thrusters| 260mm×260mm×260mm | 5590,0,0            |

To sum up, it is necessary to consider the equivalent simulation model of guidance system, warhead system, control system, key components of power propulsion system and torpedo shell.

According to the basic characteristics of key components in table 1 - table 4 [6] the torpedo structure model as shown in figure 2 and the torpedo structure diagram in figure 3 were established in combination with the shell of MK48-5 torpedo.

Figure 2. Structural model of torpedo.  
Figure 3. Schematic diagram of torpedo structure.
3. Equivalent modeling

3.1. Equivalence theory

There are two alternative theories for the study of equivalent targets: the ultimate penetration velocity equivalence theory [7] and the residual penetration equivalence theory [8]. The equivalent theory of ultimate penetration velocity is chosen in this paper. The principle of equal energy consumption through the principle [9], that is, after the supercavitation projectile penetrates the torpedo shell, the minimum energy consumption of the residual projectile penetrating the key components inside the torpedo is equal to the minimum energy consumption of the same projectile penetrating the equivalent target, or the residual kinetic energy after the residual projectile penetrating through the key components is equal to the residual kinetic energy after the residual projectile penetrating the equivalent target. Therefore, the equivalent theory of ultimate penetration velocity and the principle of equal penetration energy consumption are adopted in this paper.

Different positions of underwater supercavitation projectile hit torpedoes will cause different damage, which will result in the failure of different functions of torpedoes. Therefore, the equivalent target model obtained by different impact angles and impact directions of torpedoes is also different.

In this paper, it is assumed that the projectile impacts the torpedo vertically at different positions, and the study of the different impact angles of the projectile on the torpedo is not considered. The torpedo can be divided into transverse penetration and longitudinal penetration according to different impact directions. Because of the different direction of the underwater transverse penetration of the supercavitating projectile into the torpedo, the key components of the damage are different, and the equivalent target models obtained are also different. Therefore, the transverse penetration can be divided into five situations for analysis and research, which are: penetrating the top section of the torpedo, penetrating torpedo war head, penetrating the control section, penetrating the bunker and penetrating the rear compartment. In this paper, longitudinal penetration and transverse penetration control sections are selected for analysis.

When the underwater super-cavitation projectile penetrates the torpedo longitudinally, it is assumed that the projectile penetrates the torpedo head shell, transducer, transmitter, homing control logic assembly, warhead, control system, wire cluster, bunker, auxiliary pump, engine, pump jet propeller and the torpedo tail shell. The water medium and torpedo head shell are equivalent to a layer of equivalent target. The warhead includes the warhead shell and the charge, which are uniformly equivalent to a layer of equivalent target; The other key components are equivalent to a layer of equivalent targets. Therefore, when the underwater super-cavitation projectile penetrates the torpedo longitudinally, the torpedo and water medium can be equivalent to a 12-layer equivalent target, as shown in figure 4.

![Figure 4. Schematic diagram of equivalent target structure of longitudinal penetration.](image-url)
Underwater supercavitation projectile lateral penetration torpedo, depending on the direction of penetration, the water medium and torpedo equivalent to a multilayer target, as this article choose projectile penetration torpedo control transverse section, assumes that the projectile through the torpedo the upper shell, power components, such as gyro sensor control components, command control components and lower part of torpedo shell, a total of five parts, including water equivalent to a layer of the upper medium and torpedo shell equivalent target, the rest of the four components of each equivalent to a layer of equivalent target, so the water medium and torpedo equivalent to 5 layer equivalent target, its structure diagram as shown in figure 5.

**Figure 5.** Schematic diagram of equivalent target structure of transverse penetration.

In order to simplify the research, the following assumptions are made in this paper:

1) The projectile is rigid and impacts the target plate vertically;
2) The perforation deformation mechanism of elastic body is plastic deformation;
3) Neglecting thermal effect and wave effect;
4) The influence of projectile flow field after penetrating shell is ignored;
5) Ignoring the mass loss after the projectile penetrates the torpedo shell;
6) After the projectile penetrates the torpedo shell, the influence of redundant secondary fragments is ignored.

### 3.2. Energy consumption model

In this paper, the process of underwater supercavitation projectile penetrating torpedo is divided into two stages: projectile penetrating water medium and projectile penetrating torpedo.

#### 3.2.1. Energy consumption model of water medium

When the underwater super-cavitation projectile penetrates the torpedo shell, the kinetic energy lost by the projectile mainly includes the energy consumed by the projectile penetrating the water medium, the kinetic energy gained by the projectile, the energy consumed by thermal effect and wave effect, and the energy consumed by the projectile deformation. According to the hypothesis, the effects of elastic deformation, thermal effect and wave effect on energy dissipation are ignored. When the projectile penetrates the torpedo shell at the ballistic velocity limit $v_{50}$, the corresponding kinetic energy is the minimum penetrating energy $E$.

\[
\frac{1}{2}mv_{50}^2 = E - W_s + W_y
\]

\[
W_s = \frac{1}{2}mv_0^2 - \frac{1}{2}mv^2 = \frac{1}{2}mv_0^2(1 - e^{-0.108x})
\]
\[ W_y = \frac{1}{4} \pi \partial_1 H_y d^2 \left[ 1 + \mu / \tan \left( \frac{r}{2} \right) \right] \sigma_{y1} + 6.984 \left( \frac{H}{d} \right)^{2.256} \sigma_y d^3 \quad (3) \]

\[ W_1 = \frac{1}{4} \pi \partial_1 H_1 d^2 \left[ 1 + \mu / \tan \left( \frac{r}{2} \right) \right] \sigma_{y1} \quad (4) \]

In the formula, \( W_y \) is the energy consumed by the projectile penetrating the water medium [10]; \( W_y \) is the energy consumed by the projectile penetrating the torpedo shell [11]; \( \sigma_y \) is the quasi-static yield stress; \( v \) is the projectile penetrating speed; \( x \) is the displacement of the projectile in the water medium; \( d \) is the projectile diameter; \( r \) is the projectile cone angle; \( H \) is the torpedo shell thickness.

Based on the equivalent theory of ultimate penetration velocity and the principle of equal energy consumption, combined with equations (1) and equations (4), the water medium and the torpedo shell are equivalent to a layer of duralumin target plate.

3.2.2. Torpedo energy consumption model. After the projectile penetrates the torpedo shell, it continues to penetrate the key internal parts. In this paper, each key part penetrated is equivalent to a layer of duralumin target plate. Due to the different penetration directions of projectiles, the types and quantities of key internal components of projectiles are also different, so different multi-layer targets should be selected according to the specific penetration directions of projectiles.

The following is the energy consumption model and equivalent relationship of a key component equivalent to a layer of duralumin target plate.

\[ \frac{1}{2}mv_r^2 = W_s + W_{ls} \quad (5) \]

In the formula, \( W_s \) is the energy consumed by the projectile penetrating into the key parts of the torpedo, and \( W_{ls} \) is the energy consumed by the equivalent target. \( v_r \) is the remaining speed. Among them:

\[ v_r = \sqrt{v_0^2 - v_5^2} \quad (6) \]

\[ W_s = \frac{1}{4} \pi \partial_1 H_s d^2 \left[ 1 + \frac{\mu}{\tan \left( \frac{r}{2} \right)} \right] \sigma_{ys} + 6.984 \left( \frac{H}{d} \right)^{2.256} \sigma_y d^3 \quad (7) \]

\[ W_{ls} = \frac{1}{4} \pi \partial_1 H_{ls} d^2 \left[ 1 + \frac{\mu}{\tan \left( \frac{r}{2} \right)} \right] \sigma_{ys} \quad (8) \]

According to the equivalent theory of ultimate penetration velocity and the principle of equal energy consumption, by combining equations (5), (7) and (8), the equivalent relationship between key components and the equivalent target plate can be obtained as follows:

\[ \partial_1 H_{ls} = \partial_1 H_s \frac{\sigma_{ys}}{\sigma_{ys}} + \frac{6.984 \left( \frac{H}{d} \right)^{2.256} \sigma_y d^3 - 2m(v_0^2 - v_5^2)}{\pi d^3 \left[ 1 + \mu / \tan \left( \frac{r}{2} \right) \right] \sigma_{ys}} \quad (9) \]
3.3. Equivalent simulation target

One of the key to establish multi-layer target is to determine the gap between adjacent targets. Assuming that the material and thickness of key components are uniform, the relative gap between key components is the distance between their geometric centers, and the gap between adjacent target plates is the relative gap between the corresponding key components.

3.3.1. The equivalent target of projectile penetrating torpedo longitudinally. Since the head of the shell of the top section of the thunder is curved, considering the strike probability, it is assumed to be a layer of duralumin target plate with a slope of 60°. Similarly, the tail shell of the tail-section of the rear cabin is equivalent to a layer of duralumin target plate with a slope of 30°. In order to simplify the calculation, the warhead shell and charge are uniformly equivalent to a layer of duralumin target plate.

Combined with the energy consumption model and the table of basic characteristics of key components, according to the equivalent structure diagram of the projectile longitudinal penetration torpedo in figure 4, the equivalent model structure table of the underwater supercavitation projectile longitudinal penetration torpedo is made, as shown in table 5.

| Part             | Equivalent material | Equivalent thickness | Relative clearance |
|------------------|---------------------|----------------------|--------------------|
| Water Medium and Shell | duralumin           | 8mm                  | 0mm                |
| Transducer       | duralumin           | 2mm                  | 39mm               |
| Transmitter      | duralumin           | 4mm                  | 130mm              |
| Self-directed Control Logic Component | duralumin | 2mm | 286mm |
| Warhead          | duralumin           | 30mm                 | 845mm              |
| Control System   | duralumin           | 6mm                  | 885mm              |
| Coi              | duralumin           | 2mm                  | 442mm              |
| Bunker           | duralumin           | 4mm                  | 832mm              |
| Auxiliary Pump   | duralumin           | 8mm                  | 871mm              |
| Engine           | duralumin           | 12mm                 | 611mm              |
| Pump Jet Propeller | duralumin       | 10mm                 | 676mm              |
| Shell            | duralumin           | 6mm                  | 260mm              |

According to the above content, the equivalent simulated target of underwater longitudinal penetration torpedo of the supercavitation projectile can be obtained, as shown in figure 6.
3.3.2. The equivalent target of projectile penetrating into the control section of torpedo. According to the torpedo structure diagram in figure 3, when the supercavitation projectile penetrates the torpedo control section horizontally under water, it is assumed that the projectile penetrates the torpedo shell, power supply component, gyroscope and other sensor control components and command control components horizontally, and the projectile penetrates the torpedo control section horizontally is equivalent to 5 layers of duralumin target plate.

Combined with the energy consumption model, the equivalent structure diagram of the projectile transverse penetrating torpedo in figure 5 is used to make the equivalent structure table of the transverse penetrating torpedo in table 6.

| Part                      | Equivalent material | Equivalent thickness | Relative clearance |
|---------------------------|---------------------|----------------------|--------------------|
| Water Medium and Shell    | duralumin           | 8mm                  | 0mm                |
| Power Supply Component    | duralumin           | 6mm                  | 149.7mm            |
| Gyroscope and other Sensor Control Components | duralumin | 6mm | 117mm |
| Command Control Unit      | duralumin           | 6mm                  | 104mm              |
| Shell                     | duralumin           | 6mm                  | 162.7mm            |

According to the above, the equivalent simulation target of the underwater transverse penetration of supercavitation projectile into the torpedo control section is obtained, as shown in figure 6.

**Figure 6.** Equivalent simulation target of projectile penetrating torpedo laterally.

4. Conclusions

In this paper, the underwater penetrating torpedo of the supercavitation projectile is equivalent to a multi-layer target. By considering the influence of water medium and the typical direction and typical section of the torpedo and the vertical penetrating projectile, the following conclusions can be drawn:

1) The equivalent target of the projectile longitudinally penetrating torpedo is 12 layers of duralumin target plates, and the clearance between the target plates of each layer is the relative clearance between the corresponding key parts. Considering the curvature of the torpedo head shell and the taper of the tail shell, the head shell is equivalent to with a slope of 60° duralumin target
plate, and the tail shell is equivalent to with a slope of 30° duralumin target plate.

2) The equivalent target in the control section of the projectile transverse penetration torpedo is 5 layers of duralumin target plates, and the clearance between the equivalent target plates in each layer is the relative clearance between the corresponding key parts.

References

[1] Yan Zhou, Ping Tang, Jin-Zhen Chang and Jian-Ming Jin 2008 Journal of Ballistic 20 30-4
[2] Ran Xiong, Xin-Bao Gao, Jun-Kun Zhang and Xing-Chun Xu 2013 Journal of Missiles and Guidance 33 102-04
[3] Tin Liu and Yi Liu 2014 Mine Warfare and Ship Protection 22 8-12
[4] Shao-Ping Yin and Rui-Sheng Liu 2011 Overall torpedo technology Beijing: National Defense Industry Press
[5] Xiu-Hua Shi and Xiao-Juan Wang 2005 Introduction to underwater weapons torpedo catalogue Xi’an: Northwestern Polytechnical University Press
[6] De Kang 2014 Study on the evaluation method of damage effectiveness of supercavitation projectiles on typical torpedoes Wuhan: Naval engineering university
[7] Bing Cao 2003 Journal of missile and arrow guidance 4 122-3
[8] Yu-Lin Yang, Guo-Zhi Zhao and Zhong-Hua Du 2003 Journal of Ballistic 4 32-5
[9] Guo-Zhi Zhao and YuLin Yang 2003 Journal of Nanjing University of Science and Technology 27 509-14
[10] Xiao-Jun Wang and Xin Zhao 1992 Explosion and Impact 12 213-8
[11] Tao He 2007 Study on the penetrating behavior of kinetic energy projectile in targets of different materials Hefei: University of Science and Technology of China