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Review of Evaluation Methods of Underwater Explosion Power of Explosives

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Review of Evaluation Methods of Underwater Explosion Power of Explosives

Mao Zhi-yuan, Duan Chao-wei, Hu Hong-wei, Feng Hai-yun, Song Pu

Xi′ an Modern Chemical Research Institute, Xi′ an 710065, China

944729131@qq.com

Abstract. Reasonable evaluation of underwater explosion power of explosives is very important for underwater warhead design and other tasks. This paper summarizes the typical experiments of underwater explosion power evaluation, discusses the power characterization methods involved in the tests, and focuses on the explosion bulge test of plate structure and its corresponding dimensionless deflection characterization means. Based on the existing research results, it is proposed to establish a standardized effect target evaluation method, strengthen the research on the relationship between work parameters, explosive detonation parameters and load parameters, and apply the dimensionless deflection method in explosion expansion test to the characterization of underwater explosion power.

Keywords. underwater explosion; explosion power; evaluation method; explosion bulge test

1. Introduction

Warhead is the main source of damage energy of underwater weapons, and the charge energy directly affects the damage efficiency of warhead. Scientific evaluation of charge explosion power is of great significance to warhead design and ship damage evaluation.

The load types and load characteristics of underwater explosion are complex. In addition to the shock wave and bubble pulsation load of free field explosion, it also has a variety of coupling effects such as local cavitation and water jet in near-field explosion. The traditional evaluation methods cannot well reflect the power of underwater explosion. Therefore, it is necessary to develop a power evaluation method suitable for underwater environment.

Underwater explosion parameter measurement test can evaluate the energy output and distribution characteristics of explosives. It has the advantages of large test Charge quantity (tens of grams to tens of kilograms) and high accuracy. However, it needs to be carried out in the explosion pool, so the test cost is high and the operation is complex. In addition, it only represents the energy characteristics of explosive, and cannot reflect the coupling between explosion energy and target. In order to characterize the driving work [1] and plastic deformation work[2] of the underwater explosion of explosives on the target, people have developed the power experiment and evaluation method based on effect target, such as underwater explosion ballistic pendulum test[1], plate structure explosion bulge test[3] (EBT), etc. to evaluate the explosion power with parameters such as deformation energy, kinetic energy and deformation deflection[4-6], This kind of method can more comprehensively reflect the coupling effect of plate structure and explosion energy. However, due to the complex factors affecting the work of explosion, a standardized test and evaluation method has not been established. This paper believes that the dimensionless deflection of plate structure can not only realize standardization and universality, but also provide an important theoretical basis for explosive formula design, type selection and power evaluation.

This paper lists the test methods and 3. Characterization method of underwater explosion power at home and abroad, analyses the advantages, disadvantages and application scope of different methods, and puts forward some suggestions on the research and development direction.

2. Underwater explosion power experiment

Underwater explosion power test can be divided into two categories based on whether it is based on effect target, they are underwater explosion parameter measurement test based on free field and underwater explosion power test based on effect target.

2.1. Measurement experiment of underwater explosion parameters based on free field

The measurement test of underwater explosion parameters based on free field is an important method to determine the explosion power of explosives, its main principle is to hang the explosives at a certain height under the water, start the explosives under the experimental conditions of ensuring the ideal water area, measure the variation curve of explosion shock pressure with time through the underwater pressure sensor, and integrate to obtain the corresponding energy output parameters[7], such as shock wave energy and bubble energy, then, the explosion power is evaluated by comparing the energy and energy distribution ratio of different component explosives[8-12]. In essence, the underwater explosion method of free field is an energy measurement method, which discusses the explosive power based on the output energy and distribution structure of explosion. It has the advantages of large test charge, stable and controllable test conditions and good repeatability of results， is a practical measurement technology of explosive power. However, this method has high requirements for the experimental environment, high difficulty and cost of test implementation, and there is no corresponding relationship with the dynamic response of the target, which cannot directly reflect the damage power of explosive explosion [2].

2.2. Underwater explosion power experiment based on effect target

There are two main types of underwater weapon warheads, namely blasting warheads and shaped charge armor breaking warheads [13]. Blasting warheads uses the charge explosion to cause plastic damage to the target shell, which requires the charge to have stronger plastic deformation work ability. Shaped charge warheads enhance the local destruction by forming a metal jet with strong penetration ability, which requires the explosive to have stronger metal acceleration ability [14]. Therefore, the charge with different work characteristics is required for different combat scenes [15]. For the rigid body driving acceleration ability and plastic deformation work ability of underwater explosion of explosives, corresponding experimental methods are designed respectively. These experimental methods combine the explosion power with different application scenarios, and indirectly reflect the explosive power through the measured work parameters.

Zhang [1] designed a ballistic pendulum for measuring the driving ability of underwater contact explosion based on the principle of ballistic pendulum method of air explosion. The impulse obtained by the explosion driving pendulum is used to characterize the power of underwater contact explosion. The experimental device is shown in Figure 1, mainly including swing arm, support and pendulum. The experimental device mainly makes a special design for the pendulum part, by designing a two-stage split anvil, the strength and replacement efficiency of the pendulum part impacted by explosion are ensured. The schematic diagram of the anvil is shown in Figure 2, during the design of the device, the reliability analysis is also carried out for the influence caused by the end face deformation of the anvil, which proves the rationality of the measurement results.

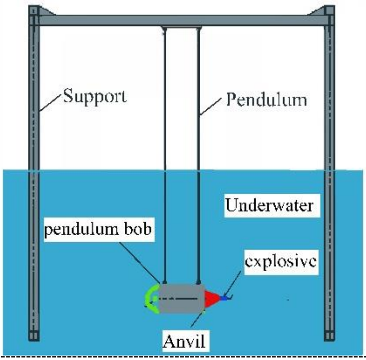
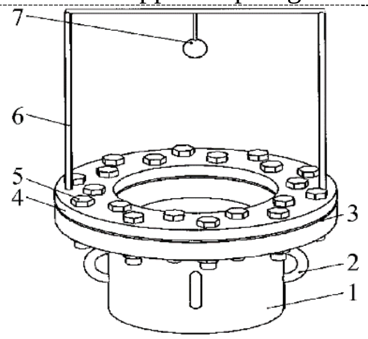


Figure 1. Testing apparatus for underwater ballistic pendulum.

Figure 2. Anvil part of pendulum.

The scaled model damage experiment of cabin is a common method in the evaluation of explosion power, but due to the complex damage effect, it is impossible to evaluate the explosion power quantitatively. Therefore, for non-contact near-field explosion, Zhang [16] proposed to strengthen the structural strength of the cabin scale model to make it approximate to a rigid body under the action of explosion, and characterize the driving ability of explosion load with its overall motion response, such as displacement and motion acceleration. Using this method, they discussed the energy absorption ratio under different explosion distance and compared it with the incident wave energy of free field. Compared with the ballistic pendulum method, this method is closer to the actual ship target.

The shell structures of ships and submarines are mostly air backed metal plates, stiffened plates, multilayer plates, composite plates, etc. there are rich studies on the underwater explosion response of these structures. Due to the typicality of plate structures, they have long been used in the evaluation of explosive power. As early as the 1920s and 1930s, Bruce ton and Woods Hole laboratories have used the plastic deformation of copper diaphragm to discuss the strength of explosion effect [7].



1. Base of device; 2. Lifting ring; 3. Sealing ring; 4. Pressing iron; 5. Hold down bolt; 6. Fixing rod; 7. Explosives

Figure 3. Underwater explosion bulge test device

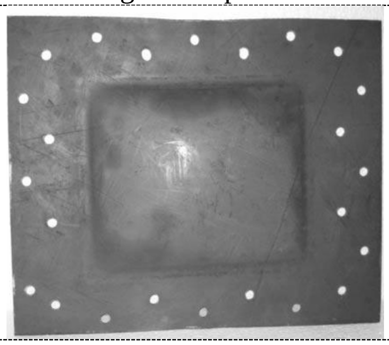


Figure 4. Physical drawing of plate deformation.

Since the structures of striking targets in underwater warfare are mostly metal plates and their reinforced structures, the evaluation of the explosion power of plate structures plays an important role in underwater explosion. Some countries have formed specified military specifications for the underwater explosion bulge test (EBT) of plate structures [3]. The typical explosion bulge test device is shown in Figure 3[17], including base, clamping plate, explosive fixing rod and experimental plate. The explosion bulge test has two main uses. One is to evaluate the impact response of new materials and structures and test their explosion resistance; The second is to evaluate the explosive power. Using the explosion bulge test, Kumar [18] discussed the influence of aluminium powder content on the power of RDX based mixed explosive in combination with the expansion deflection of the test plate. The experimental device used includes the air back metal plate fixed by the base and the explosive suspended in front of the metal plate, the deformation form of the plate after explosion under typical working conditions is shown in Figure 4. Table 1 shows the expansion deflection of metal plate after explosion of explosives with different aluminium content under the condition of consistent charge quantity, metal plate material and explosion conditions.

Table 1. Extent of bulge in test plates in EBTs.

Nomenclature	Composition	Depth of Bulge /（mm）
PBX-35	RDX/AL/HTPB(50/35/15)	30.2
PBX-30	RDX/AL/HTPB(55/30/15)	31.7
PBX-25	RDX/AL/HTPB(60/25/15)	35.1
PBX-20	RDX/AL/HTPB(65/20/15)	31.8
PBX-15	RDX/AL/HTPB(70/15/15)	30.7
PBX-0	RDX/HTPB(85/15)	28.2
HBX-3	RDX/TNT/AL/ Micro crystalline wax (31.3/29/34.8/4.9)	34.4

By comparing the deflection of the target plate, Kumar [19] believed that pbx-25 had better explosion power. In addition, Kumar also studied the response difference between water back plate, gas back plate and semi water filled plate with the help of explosion bulge test. In China, Zhang[2] analysed the dynamic response characteristics of the target plate through the explosion bulge test of the sliding boundary effect target, established the experimental device and experimental method for the power evaluation of explosive near-field non-contact explosion, analysed the energy absorption and utilization under the action of near-field explosion, and discussed the difference from the power evaluation results of conventional charge in combination with deformation energy and incident shock wave energy. Zhang and Li [17,20] analysed the explosion resistance and impact resistance under multiple underwater explosions loads with the help of explosion expansion test, and analysed the plastic deformation law of steel plate and welded plate.

On the basis of experiments, with the development of numerical simulation technology, the explosion expansion simulation calculation based on LS-DYNA and AUTODYN has also been realized [21-22]. Suresh combined with the test data, established and verified the underwater EBT simulation model based on LS-DYNA, used the model to study the influence of the water filling proportion of the air back compartment on the plate deformation results [23], analysed the deformation deflection and deformation deflection curve law of low-carbon rectangular steel plate under different plate thickness, and discussed the impact factor [24]. In China, Zhang [25], Li [20] and others also discussed the deformation law of plate structure under multiple explosions loading by establishing simulation model, and simulation models accurately restored the secondary loading effect of cavitation closure measured in the test. At present, simulation technology has become an effective auxiliary means of explosion bulge test.

The existing effector-based test methods compare the underwater explosion power of explosives from the aspects of driving acceleration ability and plastic work ability. As a highly standardized test method, the explosion bulge test of metal plate has been widely used.

3. Characterization method of underwater explosion power based on effect target

The previous section summarizes the relevant experiments of underwater explosion power evaluation, but for the same experiment, there are often different characterization methods. For example, in the explosion bulge test of plate structure, deformation deflection, deformation energy or dimensionless impulse can be selected to characterize the damage power. The selection of characterization methods directly affects the reliability and accuracy of power comparison. Therefore, this section discusses the characterization methods involved in the experiment separately.

In the research on the characterization method of the damage power of underwater explosion to effectors, the work parameters such as hole radius, plastic deformation energy and acceleration field are involved [26]. Relevant research [4] combined with the test, the characterization model of damage length based on steel plate thickness and charge equivalent is obtained, so as to characterize the explosion power by using the total damage length of the target ship shell. Similarly, the failure radius of the effector shell can also be used. Combined with the test data, the empirical formula based on the corresponding coefficient of ship shell and explosion equivalent can be obtained to characterize the explosion power [5]. Gao [6] used the multi-point acceleration of the hull as the evaluation standard to construct the functional relationship between the acceleration field and the charge equivalent, and finally compared the explosion power by comparing the equivalent in the case of similar acceleration. Although the above characterization methods use different work parameters of effectors to reflect the explosion power, they do not consider the characteristic quantity of the effector itself, so they can only compare the power on the premise that the effector remains unchanged, which is lack of universality.

As a typical structure, the metal plate with boundary fixed support has mature explosion bulge test technology and perfect experimental method. The study of its deformation law under explosion load is of great significance for the evaluation of underwater explosion power of explosives. Relevant scholars use dimensional analysis methods to comprehensively analyse the relevant parameters affecting the deformation deflection of plate structure. Based on these analysis results, we can comprehensively consider the characteristic parameters of explosion load and metal plate, establish the empirical relationship with dimensionless deformation deflection, and then compare the explosion power under different working conditions, so as to expand the universality of characterization methods.

In 1972, Johnson [27] simplified the material into rigid-perfectly plastic and dimensionless the motion control equation. After derivation and analysis, a dimensionless number called Johnson number was obtained:

$$\alpha_J = \frac{\rho V^2}{\sigma_0} \tag{1}$$

In the above formula, V is the impact velocity, ρ is the density of the impacted material, and σ_0 is the yield strength of the material. Combined with the order of magnitude of Johnson number, the response types (such as quasi-static elasticity, partial plasticity, complete plasticity, etc.) and damage modes (such as local fracture, plastic large deformation, etc.) of the effect target under the action of near-field non-contact explosion can be distinguished.

On the basis of Johnson number, relevant scholars corrected it from different ways by introducing external variables. The principle of correction is to highlight the linear correlation between dimensionless quantity and dimensionless deflection of plate structure. In the air explosion, the relevant results are relatively rich, but the research results of dimensionless deflection in water are still relatively few. Table 2 lists the dimensional analysis results that have been applied in underwater explosion and the corresponding empirical formula of dimensionless deflection of target plate.

Table 2. Dimensionless factor and empirical formula.

Dimensionless factor	Empirical formula
$\phi_c = \dfrac{I}{\pi R t^2 (\rho\sigma_0)^{1/2}}$ a[28]	$\left(\dfrac{\delta}{t}\right)_c = 0.541\phi_c - 0.433$ [29]
$\phi_q = \dfrac{I}{2t^2 (BL\rho\sigma_0)^{1/2}}$ b[28]	$\left(\dfrac{\delta}{t}\right)_q = 0.533\phi_q + 0.741$ [29]
$\phi_z = \dfrac{\beta E_t}{\pi R^2 t \sigma_0 \eta^{0.0973}}$ c[2]	$\left(\dfrac{\delta}{t}\right)_c = 169.4\sqrt{\phi_z} - 2.1.$ [2]

[a] c refers to the circular plate, I refers to the impulse of the target plate, t refers to the plate thickness, R refers to the radius of the circular plate

[b] q refers to the rectangular plate, B and L respectively refer to the length and width of the rectangular plate

[c] $\beta = E_{tot} / E_t$, E_{tot} and E_t respectively refer to the deformation energy of the target plate and the total theoretical incident shock wave energy, η refers to the ratio of the clamping area of the plate to the actual impacted area

In the first two rows of Table 2, the dimensionless impulse was obtained by Nurick [28] in the analysis of air explosion, Rajendran [30] tried to apply it to underwater explosion and obtained the empirical formula of dimensionless impulse and deformation deflection combined with the experimental data. The dimensionless number introduces the area parameters $S_c = \pi R^2$ (circular plate) and $S_q = BL$ (rectangular plate) of the plate based on the Johnson number, is widely used in air explosion, but it has the disadvantage that the total impulse of the plate is difficult to measure.

Rajendran's empirical formula uses a single source of experimental data and has not been verified in more experimental conditions. The empirical formula in the third row of Table 2 is obtained by Zhang [2]. In this method, the plate impulse is replaced by the theoretical incident shock wave energy E_t, and the plate clamping area factor η is introduced to explore the deformation law of the sliding boundary plate. However, the empirical formula for the ratio of the target plate deformation energy to the premier's theoretical incident shock wave energy has not been verified under different working conditions, and the universality of the result and method needs to be verified. On the whole, the dimensionless deflection analysis method of EBT is based on Johnson number, which takes into account the diameter thickness ratio and loading rate, and establishes the relationship between deflection and impulse, equivalent and total energy, is widely used in the deflection prediction of air explosion, and has good universality for the experimental results under different working conditions [30], but there are relatively few experimental studies on underwater explosion, most of the existing empirical formulas lack universality and are limited in scope of application.

In general, relevant studies characterize the power of underwater explosion from the perspectives of energy, motion parameters and deformation, but the existing methods are lack of systematization and universality. The dimensionless deflection analysis method of EBT provides a feasible idea for the characterization and prediction of explosive underwater explosion power, by collecting more experimental data and modifying its form in combination with practice, its applicability and accuracy in underwater explosion can be further expanded.

4. Epilogue

The load of underwater explosion is diverse and complex, and there will be different load forms under different explosion distance and different structural characteristics. The test method based on the measurement of underwater explosion parameters can only discuss the output energy, while the effector-based method can reflect the coupling effect between the output energy and the structure. The research on the effector-based method should be strengthened in combination with the specific combat scenario of underwater weapons, so as to better evaluate the power of underwater explosion.

1) At present, most of the effect target evaluation methods are aimed at single working condition and lack of standardization and universality. It is suggested to design more standardized experiments and establish a standard system that can scientifically and reasonably evaluate the power of underwater explosion.

2) The existing effector-based methods do not clarify the relationship between work parameters, explosive detonation parameters and explosion load parameters. It is necessary to further explore the correlation between explosive performance parameters and explosion power, so as to better guide the formulation design of explosives.

3) The analysis and characterization methods of dimensionless deflection of plate structure explosion bulge test are relatively rich, which is worthy of verification, popularization and application in underwater environment, so as to better evaluate the underwater explosion power of explosives.

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