Research on Calibration Method of Underwater Shock Wave Pressure Measurement Sensor Systemt

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Abstract. Underwater explosions are distinguished from explosions in the air, and their environment is complex, making sensor systems more difficult to calibrate. In this paper, the calibration method of underwater shock wave pressure sensor system is studied. The dynamic pressure calibration method based on water shock tube is proposed to calibrate the system. The propagation characteristics of the pulse pressure signal in the water shock tube are studied. The water shock tube device suitable for the calibration of the underwater shock wave pressure sensor system is designed. In the end, the advantages of the water shock tube in measuring the underwater shock wave pressure are summarized.

1. Introduction
The underwater shock wave pressure has been a key parameter of the underwater explosion test. By measuring the pressure of the shock wave, the magnitude of the blast load suffered by the ship can be determined to evaluate the power of various explosives. This is of great significance to antiknock research of ships and weapon design. Different methods and probes are used for the measurement of underwater shock waves. According to the principles of measurement, the common measurement systems of pressure of underwater shock waves can be divided into optical measurement systems and electrical measurement systems at present. Among these methods one can mention optical fast streak or frame photography of shock wave propagation laser interferometry of target velocity measurements [1], various probes based on the piezoelectric effect, carbon-based probes [2] and the time-of-flight (TOF) method [3]. Sayapin A et al. [4] compared and summarized various methods of measuring underwater shock pressures, and pointed out that optical systems can give information about the shock wave velocity which can be used for the evaluation of shock wave pressure, but this information is insufficient for shock wave energy estimation. Relatively, electrical measurement method reflects the whole process of pressure change with time which contains a large amount of information and real-time data. In the fields of design, development, and theoretical ballistics analysis of weapon systems, the electrical measurement method is an effective and scientific method for pressure measurement which recognized all over the world. The pressure signal generated during the underwater explosion of explosives has the characteristics of high-speed transformation and complex frequency components [5-8]. Therefore, to accurately measure the pressure, the sensors in the electrical measurement system must have advantages of wide frequency bandwidth, high frequency response, strong mechanical strength, accurate and stable sensitivity, suitable range, small noise, good tightness, strong corrosion resistance and other features. John E.Slater tested and compared various free-field pressure sensors for underwater explosion and found that the test results of piezoelectric sensors have good repeatability and comparability, in contrast, the carbon resistance sensor is 10% to 15% lower than the other sensors
and the resonance phenomenon occurs. This illustrates the limitations of the carbon resistance sensors in testing underwater shock wave pressure. Piezoelectric pressure sensors have much better dynamic characteristics than others, their natural frequency can reach several hundred kilohertz, and their effective bandwidth can meet the requirements of pressure measurement of underwater shock waves. Therefore, piezoelectric sensors are widely used to measure the pressure of underwater shock waves.

In order to accurately measure the change of the signal under test, the measurement system of underwater shock wave pressure needs to be calibrated. However, the insulation resistance of the piezoelectric system is not infinite, resulting in poor low frequency characteristics of the sensors and the leakage of charge inevitably. When static calibration is used to calibrate the system, the accuracy of the obtained sensor sensitivity is not high enough. In addition, during static calibration, because the standard pressure gauge needs a certain time to reach a certain stable pressure, the loading time is too long, which seriously affects the service life of the expensive piezoelectric pressure sensor. Therefore, it is not appropriate to statically calibrate the piezoelectric pressure measurement system, and dynamic calibration should be used. Some scholars use TNT to dynamically calibrate the pressure measurement system of underwater shock waves. The basic principle is based on the calculation formula of underwater shock wave pressure of TNT explosive by Cole [9] (Swiddak and Mellor conducted a large number of experiments on underwater explosions, summarizing the law of the propagation of shock waves after explosion of different explosives in water at different depths and at different temperatures, and made some amendments to Cole's conclusions), to calculate the peak pressure of underwater shock waves according to the explosive charge, compare the value with the actual measured output signal, and calibrate the sensor sensitivity. However, the environment of underwater explosion is complicated, and the density and composition of the standard TNT will affect the release of energy, those cause the stability and reproducibility of shock waves generated by explosives cannot be guaranteed, and the theoretical calculation conditions are quite different from actual conditions. So the calculated pressure is not equal to the actual pressure. In addition, the standardization of equipment for this method and the traceability of measurement results have not been completely solved. In summary, this method has obvious defects.

In this paper, the calibration method of the measurement system of underwater shock wave pressure is discussed. The dynamic pressure calibration method based on the water shock tube is put forward. The calibration system which is aimed at calibrating the measurement system is designed. The method to calculate the characteristic parameters of the calibrated system is studied. At last, the advantages of water shock tubes in measuring the pressure of underwater shock waves are summarized.

2. Building calibration system

The overall scheme of the dynamic calibration of the measurement system is shown in Figure 1. This scheme uses a water shock tube with preloading capability. Detonation control system detonates TNT and then quasi-delta pulse pressure signal is generated in water shock tube. Because the signal cannot be accurately known based on the physical relationship, a method named "comparison calibration" is used. The so-called "comparison calibration" method refers to the comparison of the measured values between a standard sensor measurement system with a known high accuracy and a same type system which should be calibrated under the specified conditions, so as to evaluate the measurement error of the calibrated system. This is a bottom-up traceability method method. The specific operation is to place the standard sensor and the calibrated sensor in the same environment, apply the excitation source simultaneously and store the data through the multi-channel data acquisition system. The underwater shock tube uses the pulse pressure signal as a pressure excitation to act on the pressure monitoring sensor system and the calibrated sensor system respectively to realize the dynamic calibration of the calibrated measurement system of the shock wave pressure. In order to ensure that the shock wave pressure characteristics on the standard pressure sensor and the calibrated sensor are consistent, the standard sensor and the calibrated sensor should be symmetrically installed on the end surfaces of the water shock tube.
The calibration system consists of a mechanical device named water shock tube, a detonation control system, a preloading system, a monitoring sensor system, a calibrated sensor system, and a signal acquisition and processing system. The mechanical device in the water shock tube is an axisymmetric tube with high pressure resistant. Different number of tubes are combined by a special flange sealing structure to adjust the tube length to meet different calibration pressure requirements. The explosive is located at the geometric center of the tube and the explosive equivalent is adjusted according to the required quasi-δ pressure pulse amplitude. The detonation control system mainly provides ignition power supply and pre-trigger signal of data acquisition system. It can be used for the detonation control of explosives, and its trigger signal adopts pre-delay trigger mode. The preloading system can apply a certain static pressure to the water shock tube before the experiment, raise the overall pressure inside the shock tube, and avoid the occurrence of the negative pressure of sensors. The signal acquisition and processing system collects and processes the pressure peaks measured by the standard pressure monitoring system and the voltage signals output by the calibrated sensor system.

The value transfer is the basis of the calibration of the shock wave pressure measurement system. In order to ensure the accuracy of the value transfer, the measurement result should be "traceable". To ensure the accurate and traceability of the shock wave pressure measurement, when the shock wave pressure measurement system is dynamically calibrated, it is necessary to discuss the value transfer method of the dynamic calibration. The "comparative" calibration method adopted by the water shock tube has a short transmission path and high precision. The system is subjected to step-by-step value transmission according to the national measurement level chain to ensure accurate and uniform measurement of the measured object. The specific value transmission path is shown in Figure 2. Since the accuracy of the system being calibrated will be based on the accuracy of the standard pressure monitoring system, the accuracy of the standard pressure monitoring system is much higher. Because the high frequency component of the effective band of the underwater shock wave pressure is complex, to effectively monitor the working bandwidth of the shock wave pressure sensor, the standard sensors in the standard pressure monitoring system must have a high working bandwidth, which can well complete monitoring tasks in the DC~200 kHz frequency band. In addition, the range of the standard pressure monitoring system cannot be less than the range of the calibrated sensor system. Therefore, the high-impedance, high-frequency Kistler 603B1A piezoelectric pressure sensor is used as the standard pressure sensor to form a monitoring system with the Kistler 5018 charge amplifier and PXI-5105 data acquisition module. Other equipment except the sensors is more consistent with the standard pressure monitoring system.
The basic idea of using the quasi-δ pressure pulse to obtain the dynamic transmission characteristics of the shock wave pressure measurement system is the normalized spectrum of impulse signal is within the effective signal band and the difference between the spectrum of the quasi-δ function does not exceed the default error. Then the spectrum of the signal can be regarded as the spectrum of the δ function, that is, the amplitude is always 1 in the effective frequency band. According to the Fourier transform property of the δ function, the Fourier transform processing of the sensor output can be considered as the frequency response of the system. However, the actual input is quite different from perfect δ function, transfer function (frequency response function) are required to obtain the sensitivity and dynamic transfer characteristics of the measurement system. To calculate transfer function, the signal measured by the standard pressure monitoring system is used as the actual excitation signal, and the signal measured by the calibrated pressure measuring system is used as the actual system response signal.

In the process of calibration, due to the influence of external factors such as vibration and temperature, high frequency clutter will inevitably be mixed in the data. The error between the Chebyshev filter and the ideal filter's frequency response is the smallest, which can better complete the filtering work. After removing the trend term and low-pass filtering for and respectively, the spectrum is refined by Chirp-z transform (CZT). CZT is a z-transformation refinement method that calculates a finite time width along a spiral orbit in the z-plane. It increases the original frequency resolution to the required resolution. The closer the spectral line is to the actual peak, the smaller the amplitude and phase error, and it is suitable for the frequency segment where no serious interference occurs.

The sensitivity of the standard pressure sensor is known. After CZT, the frequency response function of the measurement system of underwater shock wave pressure can be calculate as function (1) to (3).

$$X_s(j\omega) = \text{FFT}[x_s(t)]$$  \hspace{1cm} (1)

$$Y_s(j\omega) = \text{FFT}[y_s(t)]$$  \hspace{1cm} (2)

$$H(j\omega) = \frac{Y_s(j\omega)}{X_s(j\omega)}k_s$$  \hspace{1cm} (3)

where: $x_s(t)$ - $x_s(t)$ after CZT;

$y_s(t)$ - $y_s(t)$ after CZT;

$k_s$ - the sensitivity of the standard pressure sensor, unit: mv/psi.

4. Advantages

Compared with other similar calibration systems, water shock tubes have the following three advantages:

4.1 Water depth simulated by preloading
The water shock tube generates a certain preload on the internal medium through the preloading system. This preload value can be equivalent to different water depth pressures during actual underwater environment testing. The preload value is controlled by the preload valve, under the condition of preloading, the result of sensor calibration is more accurate, and the coupling degree with the actual working condition is higher, which has more practical engineering significance.

4.2 Simulating characteristics of water transfer
In order to obtain the inherent characteristics of the measurement system, some of gauges (carbon-based probes) are calibrated under static pressure conditions. Other gauges (piezoelectric) are calibrated in the air shock tube [10], but acoustic impedance of the air being different from the acoustic impedance of the water, this method ignores the actual working conditions of underwater shock wave pressure measurement, that is, the influence of shock wave pressure transmission path on the measurement results. Studies have shown that the same amount of explosives explode underwater, the pressure is much higher than the air, and the attenuation is slower. The underwater explosion environment is complex and has many influencing factors. The water shock tube is used as a dynamic calibration device. The tube is filled with water medium as a pressure transmission medium, which can effectively simulate the influence of underwater environment on pressure transmission, and the calibration result is more accurate.

4.3 Solve the problem of damage to the sensor caused by negative pressure
Gerry Rude et al. used the AWE TR2-5000G sensor to perform an explosion test in a small 2 m deep explosive container. Although the complete history curve was obtained, the negative pressure after the water surface cutoff reached nearly 1 MPa. Gerry Rude believed that the abnormal phenomenon was caused by the sensors, but there was no specific analysis. The sensor for underwater shock wave pressure measurement can be simplified into a single degree of freedom spring-damper system. When the quasi-δ pressure signal is applied to the sensor system, the signal measured by the sensor will oscillate around zero pressure, generating a negative pressure signal which will cause permanent damage to the sensor in severe cases. The water shock tube device fully raises the pressure at the zero input by applying the preload, and does not generate excessive negative pressure during the calibration, effectively prolonging the service life of the sensor, saving the test cost, and there is no adverse effect on the calibration results.

5. Conclusions
The underwater shock wave pressure is the main technical index for evaluating various underwater weapon systems. Currently, piezoelectric pressure sensors are often used to measure them. The piezoelectric pressure sensor has good dynamic characteristics, but its low frequency characteristics are poor, and it is difficult to accurately obtain its sensitivity characteristics by means of static calibration. At present, the standard explosive method is used to dynamically calibrate the underwater shock wave pressure measurement system. The standard explosive method is based on the quality of the explosive and the empirical formula of the underwater shock wave pressure and is used for the dynamic calibration of the measurement system. Due to the complexity of the underwater explosion and the uncertainty of the standard explosive, the theoretical calculation results are quite different from the actual result, and the calibration accuracy is difficult to guarantee. In addition, the standard explosive method cannot reflect the inherent characteristics of the measurement system.

In this paper, the current underwater shock wave pressure measurement method and the calibration method are discussed. Aiming at the problems existing in the calibration method of underwater shock wave pressure sensing system, the method of dynamic calibration based on water shock tube is adopted. The necessity of constructing the preloading system is discussed. The overall scheme of the pre-pressure water shock tube calibration system is designed. The method of value transfer and the dynamic characteristics of the underwater shock wave pressure measurement system are studied. The advantages of water shock tube in the calibration of underwater shock wave pressure system are
introduced. In summary, the dynamic calibration method based on the water shock tube device can ensure the calibration accuracy and reflect the dynamic characteristics of the sensor system, which is superior to the general calibration method.

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