Research Article

Shock Signal Trend Term Error Correction Method Based on Discrete Wavelet Transform and Low-Frequency Oscillator Combination

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Shock response spectrum (SRS), calculated according to shock loading signal, is the primary metric for assessing the shock resistance ability of shipborne equipment. Nevertheless, the measured shock acceleration signal contains a trend term error that severely distorts the low frequency of the SRS. The accuracy of present correction methods cannot be assured due to a lack of reference. A discrete wavelet transform (DWT) and low-frequency oscillator combination method is proposed for correcting shock signals in this paper. The optimal wavelet parameters can be selected according to a low-frequency spectrum baseline fitted by the measured relative displacement to reject low-frequency trend term errors. Shock machine test results show that the average difference between the low-frequency spectrum baseline and uncorrected SRS is reduced from 89.8% to 3.2%, while the SRS slope rolled off to 5.8 dB/oct after imposing the proposed correction. The corrected SRS can faithfully show the actual shock loading characteristics of shipborne equipment in shock tests.

1. Introduction

Warships, inevitably, are attacked by underwater weapons in the course of battle. Even if a warship is not directly hit, the shock wave generated by the underwater explosion can seriously damage the ship's equipment and degrade its effectiveness [1]. The shock resistance of shipborne equipment directly affects its combat performance [2]. Underwater explosion tests are the most direct and effective approach to determine the shock resistance of shipborne equipment [3], but they are costly, labor intensive, and dependent on a great deal of material resources; they cannot be simply deployed at will [4, 5]. The shock tester is a mechanism that can provide mechanical shock in formation for certain smaller pieces of shipborne equipment. The shock properties are controllable and the shock can be repeated within the appropriate accuracy requirements. Shock test machines thus play an important role in simulating the underwater shock explosion environment [6].

It is first necessary to determine the intensity of the shock loading before the shock resistance can be determined.

According to relevant international standards, shock intensity is usually characterized by a shock response spectrum (SRS) converted from an acceleration signal [7]. However, acceleration signals are susceptible to complex disturbance arising in measurement systems and from environmental factors. Small errors in the experimental data are magnified after integration and then may significantly affect the authenticity of the data. The trend term error is one such type of error [8, 9], which occurs in the low-frequency component of a signal whose period is longer than the record length. Once it emerges, it affects the entire time-domain curve. Irvine [10] summarized six factors that can produce trend errors in shock tests. The existence of a trend term error creates substantial error in the signal itself or may even completely distort the SRS low-frequency band [11]. This seriously affects the shock strength judgment and overall shock test results.

Many scholars have developed data correction methods to separate the low-frequency errors from the measured signal and secure more reliable experimental results. Smyth

and Wu controlled the integral trend term error by high-pass filtering [12]. However, these methods are not suitable for processing nonstationary and nonlinear shock signals. Grillo [13] used the least squares fit to remove the errors from the integrating velocity and then differentiated it to obtain the corrected acceleration. However, this method can hardly correct the acceleration signal containing abrupt spikes. Du et al. introduced a method of combining the acceleration Fourier amplitude spectrum with the design SRS; however, a designed SRS according to relevant standards could not reflect the actual response characteristics of measured shock acceleration [14]. The DWT method was first introduced by Smallwood and Cap to correct zero drift shock test data, but the choice of wavelet parameters is entirely based on personnel experience [15]. Edward conducted a series of shock verification tests [16]; Wang et al. selected wavelet parameters based on the correlation coefficients of positive and negative SRS [17]. However, even if the shock signal does not contain a trend term, the correlation coefficient of positive and negative SRS drops sharply once system damping exceeds 0.02, affecting the choice of wavelet parameters [18]. Li et al. introduced an adaptive EMD method utilizing the cross-correlation coefficient between the positive and negative SRS as a judgment standard; their method has the same disadvantages [19]. The EMD method also has shortcomings such as end effect and modal aliasing.

Due to the strong transient and nonlinear characteristics of shock testing, there is no uniform parameter selection method for accurately correcting shock signals without manual operation. Corrections of increasing severity are typically applied to the shock signals until SRS is physically reasonable. Due to the lack of independent shock response measurements for comparison, the correction effect is mostly judged by personal experience. Hence, although the correction effect seems reasonable, it may not be accurate credible. This affects the overall effect of shock resistance ability assessment for shipborne equipment.

A shock signal correction method based on DWT and low-frequency oscillator data combination is proposed in this paper. The SRS calculation method and DWT theory are presented below. A method for quantitatively selecting wavelet parameters based on the best Pearson correlation coefficient between the corrected SRS and a low-frequency spectrum baseline is then given. Section 3 reports a series of shock machine tests conducted to obtain the low-frequency spectrum baseline; the corrected shock signal is shown to contain no low-frequency trend term error. The SRS corrected via the proposed method accurately and precisely reflects actual shock loading characteristics.

2. Combination Correction Method Principle

2.1. Calculation of Shock Response Spectrum. The SRS describes the maximum response of SDOF systems (e.g., a mass on a spring) related to a generalized excitation (Figure 1). Therefore, the SRS effectively reflects the damage potential of the shock environment to equipment with different natural frequencies. The SRS can be divided into three categories based on the response parameters: the relative displacement

response spectrum ($Z_{\max} - \omega$), pseudovelocity response spectrum ($PV_{\max} - \omega$), and absolute acceleration response spectrum ($A_{\max} - \omega$).

For any frequency SDOFs, the kinematic equation of mass block can be expressed as follows:

$$-c(x' - y') - k(x - y) = mx'', \quad (1)$$

where x is the absolute displacement of the mass block, y is the absolute displacement of the foundation, and m , c , and k represent the mass, damping coefficient, and stiffness of the system, respectively.

Defining z as the relative displacement of the mass block to the foundation, it allows the above equation to be rewritten as follows:

$$z'' + 2\zeta\omega_n z' + \omega_n^2 z = -y'', \quad (2)$$

where $\zeta = c/2m\omega_n$ is the damping ratio of the SDOFs and $\omega_n = \sqrt{k/m}$ is their natural frequency.

Assuming that the initial velocity and initial displacement are both zero, the response of aperiodic random excitation can be solved using the Duhamel integral according to the transient characteristics of shock excitation [20]:

$$z = -\frac{1}{\omega_d} \int_0^t y''(\tau) e^{-\zeta\omega_n(t-\tau)} \sin \omega_d(t-\tau) d\tau, \quad (3)$$

where $\omega_d = \eta\omega_n$ is the damped natural frequency, $\eta = \sqrt{1 - \zeta^2}$, and τ is an integral variable.

According to the definition of the SRS, the relative displacement response spectrum ($Z_{\max} - \omega$) is composed of the maximum relative displacement of each frequency of SDOFs. Therefore, it can be calculated by equation (3), and then, the test shock environment is obtained.

In addition, since the pseudovelocity is equal to the system natural frequency multiplied by the relative displacement response, the pseudovelocity response spectrum ($PV_{\max} - \omega$) can be obtained as follows:

$$PV_{\max} = \omega Z_{\max} = \left[-\int_0^t y''(\tau) e^{-\zeta\omega_n(t-\tau)} \sin \omega_d(t-\tau) d\tau \right]_{\max}. \quad (4)$$

The acceleration is equal to the natural frequency of the system multiplied by the pseudovelocity, so the acceleration response spectrum ($A_{\max} - \omega$) can be expressed by

$$\begin{aligned} A_{\max} &= \omega PV_{\max} \\ &= \omega^2 Z_{\max} \\ &= \left[-\omega_d \int_0^t y''(\tau) e^{-\zeta\omega_n(t-\tau)} \sin \omega_d(t-\tau) d\tau \right]_{\max}. \end{aligned} \quad (5)$$

Equations (3)–(5) indicate that the accuracy of the shock acceleration load y'' directly affects the accuracy of the SRS. It also seriously interferes with the shock resistance design of shipborne equipment. Therefore, it is necessary to remove the trend term error contained within the shock acceleration data.

FIGURE 1: SRS principle.

2.2. Discrete Wavelet Decomposition. In practical applications, the continuous wavelet transform has a massive computational burden and must be discretized prior to use. The discrete wavelet function can be expressed as follows [21]:

$$\begin{aligned}\psi_{m,n}(t) &= a_0^{-(m/2)} \psi\left(\frac{t - nb_0 a_0^m}{a_0^m}\right) \\ &= a_0^{-(m/2)} \psi(a_0^{-m} t - nb_0),\end{aligned}\quad (6)$$

where ψ satisfies the perfect reconstruction condition. The discretization equations of dilation parameter a and translation parameter b are

$$a = a_0^m, \quad (7)$$

$$b = na_0^m b_0, \quad (8)$$

where m and n range over $\mathbf{Z}$ while $a_0 > 1$ and $b_0 > 0$ are fixed. The discretized wavelet coefficients can be expressed as

$$\begin{aligned}d_{m,n} &= \langle y''(t), \psi_{m,n}(t) \rangle \\ &= \int_{-\infty}^{+\infty} y''(t) \psi_{m,n}^*(t) dt.\end{aligned}\quad (9)$$

After calculating the wavelet coefficients, the original shock signal $y''(t)$ can be decomposed into a linear combination of wavelet and scaling functions with different dilation and translation parameters:

$$y''(t) = \sum_{m=1}^N \sum_n d_{m,n} \psi_{m,n}(t) + \sum_n c_{N,n} \varphi_{N,n}(t), \quad (10)$$

where $\varphi_{m,n}$ is the scaling function and $c_{m,n}$ is the scaling coefficient. These calculation methods are similar to equation (6) and (9), respectively. $\sum_{m=1}^N \sum_n d_{m,n} \psi_{m,n}(t)$ is the high-frequency component in the corresponding decomposition. $\sum_n c_{N,n} \varphi_{N,n}(t)$ is the low-frequency trend term component of the last decomposition.

Furthermore,

$$D_m = \sum_n d_{m,n} \psi_{m,n}(t), \quad (11)$$

$$A_m = \sum_n c_{m,n} \varphi_{m,n}(t). \quad (12)$$

Eliminating the influence of the translation parameter allows equation (10) to be simplified:

$$\left. \begin{aligned}y''(t) &= \sum_{m=1}^N D_m + A_N \\ y''_d &= \sum_{m=1}^N D_m, y''_a = A_N\end{aligned} \right\}, \quad (13)$$

where A_N is the low-frequency approximate component of the N th decomposition, so y''_a is the trend term to be eliminated. D_m is the high-frequency detail component of the m of the decomposition. Therefore, y''_a is the sum of the detailed components of each order, i.e., the corrected signal.

After DWT decomposition, the original shock signal must satisfy the following conditions:

- (1) The corrected signal y''_a contains the main features of the original signal y''
- (2) The removed low-frequency signal y''_a contains the trend term error which leads to zero integration drift

2.3. Selection of DWT Parameters. According to equations (6)–(13), the correction effect by DWT mainly depends on the decomposition level N and the wavelet function ψ . As a biorthogonal wavelet function, the dB wavelet contains no truncation error. The selection of the wavelet function can be transformed into the determination of the vanishing moments of the dB wavelet.

A set of low-frequency spring oscillators were designed here in order to obtain the proper wavelet parameters (decomposition layers and vanishing moments). The oscillators can accurately measure the relative displacement response of SDOFs with three different frequencies. According to the literature [21], the low-frequency band (4–20 Hz) of the SRS is characterized by equal displacement. The Pearson correlation coefficient ρ_{P,P^*} of the corrected low-frequency SRS $PV(f_L)$ and the oscillator low-frequency spectrum baseline $PV^*(f_L)$ can be expressed as follows:

$$\rho_{PV(f_L), PV^*(f_L)} = \frac{\text{cov}(PV(f_L), PV^*(f_L))}{\sigma_{PV(f_L)} \sigma_{PV^*(f_L)}}. \quad (14)$$

To ensure that trend components y''_a in the reconstructed signal are completely removed, the threshold value of correlation coefficient was set to 0.98. The optimal wavelet parameters were then selected by comparing the correlation coefficients at different decomposition layers and vanishing moments.

In equation (14), $PV(f_L)$ can be obtained through equation (13) by the corrected acceleration y_a'' . $PV^*(f_L)$ can be obtained by fitting the displacement data measured from the spring oscillator. The structure of the spring oscillator and the low-frequency spectrum baseline acquisition method are discussed below.

3. Shock Test Machine Experiment

3.1. Shock Test Machine Method. A shock test was carried out with a 500 kg vertical shock test machine developed by the Chinese Naval Research Academy. As shown in Figure 2, the test machine is mainly composed of a basic system, hydraulic system, mechanical system, and measurement and control system. At the beginning of the test, the velocity generator drives the shock hammer to collide with the waveform generator at the bottom of the shock table, thus producing a positive sinusoidal shock wave. After the collision, the hydraulic damping cylinder buffers and limits the shock table to produce a negative sinusoidal shock wave. The test can generate a double sine wave shock signal that satisfies the BV043/85 military standard. The shock load effectively simulates the positive and negative double-wave shock environment during an underwater noncontact explosion [22].

The layout of shock test site is shown in Figure 3. Newly developed small shipborne equipment was dispersedly fixed on the shock table in this setup; the shipborne equipment is blurred in the photo given here for confidentiality. The equipment's shock strength was measured with accelerometer sensor (B&K, Model 8309, Denmark) fixed on the shock table, as shown in Figure 4; their acceleration signals were then converted to SRS information. In order to correct the SRS with trend errors, a low-frequency oscillator group which can measure displacement response accurately was installed next to the accelerometers. The test was divided into three conditions that were carried out successively. The shock loading information is given in Table 1.

3.2. Low-Frequency Oscillator Structure. Figure 5 shows the low-frequency oscillator structure, which consists of three suboscillators with three different natural frequencies. It is generally accepted that the low-frequency range of SRS is between 4 to 20 Hz [23], so the frequencies of the suboscillators were adjusted here to 6, 10, and 20 Hz. Besides, the three independent suboscillators were fixed to the bottom base to ensure the consistency of their shock response. The bottom base was also rigidly fixed onto the shock table.

Each suboscillator consists of a mass, two springs, a main guide shaft, an auxiliary guide shaft, a sliding bearing, and a guide plate. The two cylinder springs were precompressed and fixed on either end of the mass. The main guide shaft has a smooth surface, and the mass slides on its surface through a sliding bearing for reducing the friction coefficient between the mass and the main guide shaft, thereby minimizing system damping. After testing, the damping ratio of the low-frequency oscillator was found to be only 0.016 at most,

which can be ignored. A guide plate and a cooperated auxiliary guide shaft were also designed to prevent the mass from rotating due to the spring force.

Noncontact magnetostrictive displacement sensors (Balluff, Model BTL6, Germany) were used to measure the displacement response of each suboscillator; this effectively minimized system damping as well. The sensor has a linear error of $\pm 0.04\%$ Fs and a measurement range of $-100 \sim +100$ mm, which meets the relevant shock test. The main block of each displacement sensor was placed behind its matching oscillator and parallel to the main guide shaft. The active magnetic block was installed on the guide plate. When shock occurred in tests, the magnetic sensing block reciprocated in the direction with the mass, thereby revealing the displacement response of each suboscillator. As per the Liaoning Institute of Metrology, the maximum error of the relative displacement of the vibrator at full scale is 1.38 mm, which has less than a 1.7% influence on the SRS. Because each suboscillator system can be considered a SDOFs, the displacement of each suboscillator can be considered as the relative shock displacement response at that corresponding natural frequency.

3.3. Low-Frequency Spectrum Baseline Fitting. The maximum pseudovelocity $PV_{\max}$ can be calculated as follows:

$$PV_{\max} = 2\pi f_L \cdot Z_{\max}, \quad (15)$$

where the displacement response Z was measured by the low-frequency oscillator group.

Table 2 lists the maximum displacement and pseudovelocity results at three frequencies and under various test conditions.

As shown in Table 2, each test condition exhibits approximately equal maximum displacement in the low-frequency band, which is consistent with [23]. The maximum deviations under the three test conditions are only 3.36, 3.35, and 3.89 mm.

The data was fitted to a low-frequency spectrum baseline via the linear regression model based on the maximum pseudovelocity data given in Table 2. The pseudovelocity functional form (low-frequency spectrum baseline) under each condition was expressed by equations (16)–(18). The goodness of fit R^2 values for each function is 0.9975, 0.9997, and 0.9955:

$$\begin{aligned} S_1^*(f_L) &= PV_1 \\ &= 0.1152f_L + 0.1744, \end{aligned} \quad (16)$$

$$\begin{aligned} S_2^*(f_L) &= PV_2 \\ &= 0.1233f_L + 0.4108, \end{aligned} \quad (17)$$

$$\begin{aligned} S_3^*(f_L) &= PV_3 \\ &= 0.1438f_L + 0.2905. \end{aligned} \quad (18)$$

The maximum value of pseudovelocity and the fitted low-frequency spectrum baseline $PV^*(f_L)$ under each condition are presented in Figure 6 on a quadruple logarithm coordinates.

FIGURE 2: Shock test machine.

FIGURE 3: Shock test site layout (dispersed shipborne equipment).

4. Shock Signal Correction Results and Discussion

The effect of our proposed correction method was verified through analyzing the shock test results. Figure 7 shows the time-history record of original acceleration signal and its two integrations under test condition I. Gaberson pointed out that the integral velocity should be zero and the integral displacement should be stable when the shock ends [24]. However, the acceleration curve did not reveal whether the shock signal contained the trend term error in the test, but the integral velocity at the end was -2.87 m/s and the integral displacement tended toward negative infinity. Both suggest a serious zero drift phenomenon.

Figure 8 shows the comparison between the original SRS and the fitted low-frequency spectrum baseline. Based on the low-frequency oscillator measurements, the displacement response of low-frequency band (4–20 Hz) was practically 21.3 mm. However, the displacement response computed by the acceleration data reached 63.2 mm. The maximum relative difference in this case is as high as 196.5%.

The proposed method was next applied to correct the original shock signal. The optimal wavelet parameters were determined by comparing the Pearson correlation coefficients of $PV(f_L)$ and $PV^*(f_L)$. A larger vanishing moment order not only indicates stronger localization ability in the frequency domain but also weakens the support of the signal in the time domain. In addition, valuable medium- and

FIGURE 4: Acceleration installation.

TABLE 1: Shock test machine conditions.

Test condition	Positive wave		Negative wave	
	Amplitude (g)	Pulse width (ms)	Amplitude (g)	Pulse width (ms)
I	53.73	9.38	-23.20	16.42
II	62.29	9.38	-30.64	14.06
III	73.89	9.38	-35.76	13.28

FIGURE 5: Low-frequency oscillator structure.

high-frequency components in the signal are affected if the decomposition level is too small. If the level is too large, the low-frequency trend term error cannot be effectively removed. Vanishing moments dB 4–9 and decomposition levels 2–7 were selected to calculate the shock acceleration data shown in Figure 7(a). Table 3 shows the Pearson correlation coefficients ρ_{P,P^*} of the different vanishing moments and decomposition levels.

As shown in Table 3, as the decomposition level increases, the correlation coefficient between the corrected SRS and the low-frequency spectrum baseline first increases and then decreases. The correlation coefficients reach their respective maxima (all above 0.998) at the decomposition level of 7. Among all the vanishing moments, dB 7 has the strongest ability to remove signal trend terms; the correlation coefficient is 0.9995 under a decomposition level 7.

Figure 9 shows the low-frequency approximate component A_m and high-frequency detail component D_m obtained by applying the decomposition level 7 and the vanishing moment dB 7 to the original shock acceleration data.

The corrected acceleration signal and corresponding integration results after discrete wavelet decomposition and reconstruction are shown in Figure 10. The acceleration signals appear to be nearly consistent, yet the integral velocity converges to zero and the integral displacement is stable. In effect, the low-frequency trend term error within the shock signal has been eliminated.

The comparison results of SRS before and after the proposed correction is shown in Figure 11. The medium-high frequency signal components are almost unaffected, while the low-frequency trend terms are effectively eliminated. The maximum difference between the SRS and the low-frequency spectrum baseline is reduced roughly from 196.5% to 13.5% and the average difference roughly from 87.4% to 2.7%. The slope of the corrected SRS is 5.8 dB/oct, which is within the reasonable range [25]. The correction accuracy meets the requirements for shipborne equipment shock resistance tests.

The results also show that, under test condition II, the maximum difference between the SRS and low-frequency spectrum baseline is reduced from 173.5% to 12.7%. The average difference is reduced to only 2.1%. Under test condition III, the maximum difference is reduced from 184.7% to 13.8%, while the average difference is reduced to only 3.2%. The selection of wavelet parameters in these cases was the same as under test condition I. Furthermore, the medium-high frequency band of SRS which is unaffected by the trend term error has little change. Thus, the corrected

TABLE 2: Maximum displacement and pseudovelocity from low-frequency oscillator group.

Test condition	Frequency (Hz)	Maximum displacement (mm)	Maximum pseudovelocity (m/s)
I	6	23.08	0.87
	10	21.15	1.32
	20	19.72	2.48
II	6	24.13	0.91
	10	25.50	1.60
	20	22.15	2.78
III	6	30.11	1.13
	10	27.41	1.72
	20	26.22	3.29

FIGURE 6: Pseudovelocity value and low-frequency spectrum baseline under three test conditions.

FIGURE 7: Continued.

FIGURE 7: Original acceleration data and its integrations (test condition I).

FIGURE 8: Original SRS and fitted low-frequency spectrum baseline.

TABLE 3: Pearson correlation coefficients under different wavelet parameters.

Decomposition level	Vanishing moment					
	dB 4	dB 5	dB 6	dB 7	dB 8	dB 9
2	0.7449	0.7540	0.7661	0.8422	0.813	0.7823
3	0.9175	0.9189	0.9208	0.9333	0.9273	0.9235
4	0.9335	0.9339	0.9344	0.9370	0.9359	0.9352
5	0.9398	0.9421	0.9448	0.9543	0.9507	0.9475
6	0.9841	0.9847	0.9851	0.9857	0.9852	0.9849
7	0.9983	0.9985	0.9990	0.9995	0.9989	0.9985
8	0.9813	0.9817	0.9819	0.9828	0.9824	0.9823
9	0.8495	0.8548	0.8501	0.8523	0.8515	0.8507

FIGURE 9: Wavelet components of original shock signal.

FIGURE 10: Corrected acceleration data and its integrations (test condition I).

FIGURE 11: SRS before versus after correction.

SRS faithfully reflects actual shock loading characteristics. The proposed combination correction method markedly improves the precision of shock resistance tests.

5. Conclusions

A novel technique comprised of DWT and low-frequency oscillator data was developed in this study for shock test signal correction. The method was validated in a shock machine test. The main conclusions of this work can be summarized as follows:

- (1) It is difficult to accurately determine shock acceleration signals in shock resistance tests on shipborne equipment. The trend term error that is mixed within the signals severely distorts the low-frequency response and then seriously affects the shock resistance assessment. The actual shock signal must be accurately restored.
- (2) The low-frequency oscillator group introduced in this study can precisely measure the displacement response at three frequencies (6, 10, and 20 Hz). The displacement responses measured under various test conditions were consistent; the goodness of fit for each displacement line equation was higher than 0.9955.
- (3) The optimal vanishing moment to support the proposed correction method is dB 7, and the optimal decomposition level is 7. The correlation coefficient of the corrected SRS and the low-frequency spectrum baseline in the low-frequency band can reach 0.9995. The wavelet parameters selected in this study are suitable in processing the actual shock test.
- (4) Compared with the low-frequency spectrum baseline, the maximum and average differences of the

corrected SRS were reduced to 13.8% and 3.2%, respectively. The SRS of the medium-high frequency band without trend term errors was nearly unchanged. The results of shock tests conducted in this study indicate that the proposed method effectively removes the trend term error from shock acceleration signals. Its effect fully satisfies the requirement for shipborne equipment shock resistance test.

Data Availability

The data used to support the findings of the study are restricted because they involve military secrets.

Conflicts of Interest

The authors declare that they have no conflicts of interest with respect to the research, authorship, and/or publication of this article.

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References

- [1] K. J. Middleton and A. J. Carr, "The identification of combat survivability tasks associated with naval vessel damage in maritime environments," *Applied Ergonomics*, vol. 59, pp. 27–33, 2017.
- [2] Z. H. Zhang, Y. Chen, X. C. Huang, and H. X. Hua, "Underwater explosion approximate method research on ship with polymer coating," *Proceedings of the Institution of Mechanical Engineers—Part M: Journal of Engineering for the Maritime Environment*, vol. 231, no. 2, pp. 384–394, 2017.
- [3] J. K. Kambrath, C. Yoon, J. Mathew et al., "Mitigation of resonance vibration effects in marine propulsion," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 8, pp. 6159–6169, 2018.
- [4] A. M. Zhang, W. X. Zhou, S. P. Wang et al., "Dynamic response of the non-contact underwater explosions on naval equipment," *Marine Structures*, vol. 24, no. 4, pp. 396–411, 2011.
- [5] L. Yang, Y. Wang, Q. M. Zhang et al., "Numerical study on damage response of ship composite armor structures to contact underwater explosion," *Advanced Materials Research*, vol. 79, 2009.
- [6] Z. Duan, C. Tang, Y. Li, J. Han, and G. Wu, "Pulse shaping techniques for a high-g shock tester based on collision principle," *Review of Scientific Instruments*, vol. 87, no. 9, Article ID 095104, 2016.
- [7] R. L. Wells, "Using shock response spectra to design motion control profiles for flexible structures," *Journal of Vibration and Control*, vol. 7, no. 6, pp. 905–921, 2001.
- [8] R. J. Scavuzzo, G. D. Hill, and P. Saxe, "The 'spectrum dip': dynamic interaction of system components," *Journal of Pressure Vessel Technology*, vol. 137, no. 4, Article ID 044701, 2015.
- [9] V. Bateman and R. Merritt, "Validation of pyroshock data," *Journal of the IEST*, vol. 55, no. 1, pp. 40–56, 2012.

- [10] T. Irvine, "An introduction to the shock response spectrum," 2010, http://www.vibrationdata.com/tutorials2/srs_intr.Pdf.
- [11] D. O. Smallwood, "Shock response spectrum at low frequencies," *The Shock and Vibration Bulletin*, vol. 1, pp. 279–288, 1986.
- [12] A. Smyth and M. Wu, "Multi-rate Kalman filtering for the data fusion of displacement and acceleration response measurements in dynamic system monitoring," *Mechanical Systems and Signal Processing*, vol. 21, no. 2, pp. 706–723, 2007.
- [13] V. J. Grillo, "De-trending techniques: methods for cleaning questionable shock data," in *Proceedings of the 81st Shock and Vibration Conference*, Orlando, FL, USA, October 2010.
- [14] Z. P. Du, Y. Wang, Y. Yang et al., "Curve fit method for naval underwater explosion shock signal and its application," *Zhen Dong Yu Chong Ji*, vol. 29, no. 3, pp. 182–184, 2010.
- [15] D. Smallwood and J. Cap, "Salvaging pyrotechnic data with minor overloads and offsets," *Journal of the IEST*, vol. 42, no. 3, pp. 27–35, 1999.
- [16] T. S. Edwards, "An improved wavelet correction for zero shifted accelerometer data," *Shock and Vibration*, vol. 10, Article ID 972829, 9 pages, 2003.
- [17] J. Wang, X. Meng, C. Qin, and J. Yi, "Vibration frequencies extraction of the forth road bridge using high sampling GPS data," *Shock and Vibration*, vol. 2016, pp. 18–18, Article ID 9807861, 2016.
- [18] H. A. Gaberson, "Pseudo velocity shock data analysis calculations using octave," *Special Topics in Structural Dynamics*, vol. 6, pp. 499–514, 2013.
- [19] G. H. Li, H. X. Pan, and H. F. Ren, "Baseline correction of impact signals using the cross-correlation coefficient of shock response spectrum," *Journal of Vibration and Shock*, vol. 35, no. 16, pp. 219–225, 2016.
- [20] C. Lalanne, *Mechanical Shock: Mechanical Vibration and Shock Analysis*, John Willey and Sons Ltd, Hoboken, NJ, USA, 2009.
- [21] I. Daubechies, *Ten Lectures on Wavelets*, Society for Industrial and Applied Mathematics, Philadelphia, PA, USA, 1992.
- [22] G. X. Wang, H. X. Hua, and Y. Wang, "Mechanism analysis and simulation for a novel anti-shock testing system for heavy-weight ship board equipment," *Mechanics in Engineering*, vol. 31, no. 4, pp. 54–58, 2009.
- [23] L. Zhang, Z. P. Du, J. B. Wu et al., "Low-frequency shock response data analysis of underwater explosion test of 200-ton class floating shock platform," *Chinese Journal of Ship Research*, vol. 13, no. 3, pp. 60–65, 2018.
- [24] H. A. Gaberson, *Pseudo Velocity Shock Spectrum Rules for Analysis of Mechanical Shock*, IMAC XXV, Orlando, FL, USA, 2007.
- [25] C. Wright, "Effective data validation methodology for pyrotechnic shock testing," *Journal of the IEST*, vol. 53, no. 1, pp. 9–30, 2010.