Dynamic compensation and its application of shock wave pressure sensor

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Abstract: In order to correct the test error caused by the dynamic characteristics of pressure sensor and avoid the influence of the error of sensor's dynamic model on compensation results, a dynamic compensation method of the pressure sensor is presented, which is based on quantum-behaved particle swarm optimization (QPSO) algorithm and the mean square error (MSE). By using this method, the inverse model of the sensor is built and optimized and then the coefficients of the optimal compensator are got. This method is verified by the dynamic calibration with shock tube and the dynamic characteristics of the sensor before and after compensation are analyzed in time domain and frequency domain. The results show that the working bandwidth of the sensor is extended effectively. This method can reduce dynamic measuring error and improve test accuracy in actual measurement experiments.

Key words: pressure sensor; dynamic compensation; quantum-behaved particle swarm optimization (QPSO); shock wave test; band expansion

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Shock wave is an important part of the damage effects of projectiles and shock wave pressure test can provide scientific basis for evaluating the power of weapons[1]. The shock wave propagation is a high-speed changing process with wide frequency spectrum, therefore the pressure sensor should have sufficiently high frequency response to reflect the change of the pressure accurately[2]. Due to limitations of fabrication process, the working bandwidth of the existing sensors can not completely cover the effective bandwidth of the shock wave signal, resulting in a distortion between the input and output of the test system[3]. In actual measurement, test signal has a large overshoot, which will bring greate dynamic error if the maximum peak of the test data is regarded as the peak pressure of shock wave directly[4]. To meet the dynamic test requirement and make the test results more accurate, it is necessary to compensate the dynamic characteristics for the sensor so as to improve the response speed and expand the bandwidth[5].

Conventional methods of dynamic compensation include zero-pole redisposing, neural network algorithm, particle swarm optimization (PSO) and so on. Zero-pole redisposing based dynamic compensation is difficult to determine the mathematical model of the sensor, which introduces the error of the sensor's dynamic model[6]. The global searching ability of the neural network algorithm is poor and it is easy to fall into local extremum to get the coefficients of dynamic compensation filter[7]. The PSO algorithm can not search the global optimal solution with probability 100% and the results of the optimization are greatly influenced by the order of the sensor's model[8]. Therefore, to solve the above problems, a dynamic compensation method based on quantum-behaved particle swarm optimization (QPSO) algorithm and the mean square error(MSE) is presented in this pa-

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per. Using the proposed QPSO algorithm, the inverse model of the sensor is built and optimized to get the coefficients of the compensator whose orders are given, and then the optimal order of the compensator is determined by the mean-square error. The whole process can be completed without establishing the dynamic model of the sensor in advance, which can avoid the error of sensor's dynamic modeling further. This method is verified by dynamic calibration and the working bandwidth of the sensor is extended effectively. It meets the dynamic test requirement and makes the test results more accurate in actual measurement experiments.

1 Principle of QPSO algorithm

PSO is a global optimization algorithm based on swarm intelligence, using the particle swarm including M particles to search for the optimum solution in the search space of D-dimensional target[9]. The basic idea of PSO is to initialize a group of random particles and then to find the optimal extremum by updating their position and velocity in each iteration[10]. However, considering PSO algorithm can not search for the global optimal solution with probability 100%[9], the QPSO algorithm proposed from quanta mechanical angle is no longer described by particle velocity and position, and the evolution equation of particle state for each dimension can be got through the wave function, that is[11-12]

$$p_{\mathrm{d}}'(t) = \varphi(t)p_{\mathrm{d}}(t) + (1-\varphi(t))p_{\mathrm{g}}(t), \quad (1)$$

$$X_i(t+1) = p_{\mathrm{d}}'(t) \pm \frac{L(t)}{2}\ln\left[\frac{1}{u(t)}\right], \quad (2)$$

where $p_{\mathrm{d}}(t)$ is the historical optimal value of the i-th particle position, $p_{\mathrm{g}}(t)$ is the global optimal value of all particle current positions, $p_{\mathrm{d}}'(t)$ is reappraisal optimal center attract position. $X_i = (x_{i1}, X_{i2}, \cdots, X_{iD})$ is the present position of the ith particle, φ and u are all the random numbers which are uniformly distributed on the $[0,1]$. $L(t)$ can be evaluated by the introduction of an average optimal position and it can be expressed as

$$\bar{L}(t) = (\bar{L}P_{i1}(t), \bar{L}P_{i2}(t), \cdots, \bar{L}P_{iD}(t)) = \frac{1}{M}\sum\left\{\frac{1}{M}\sum_{i=1}^{M} p_{i1}(t), \frac{1}{M}\sum_{i=1}^{M} p_{i2}(t), \cdots, \frac{1}{M}\sum_{i=1}^{M} p_{iD}(t)\right\}, \quad (3)$$

$$L(t) = 2\alpha \mid \bar{L}(t) - X_i(t) \mid, \quad (4)$$

where α is the only parameter called compression-expansion factor which requires to be certain in the QPSO algorithm.

2 Design of dynamic compensation filter based on QPSO algorithm

At present, the method of dynamic compensation of pressure sensor is to connect a compensator in series after the output of the sensor[6], as shown in Fig. 1.

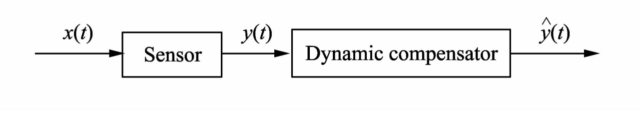

Fig. 1 Dynamic compensation principle of sensor

The original signal $x(t)$ got by the sensor is converted to the output signal $y(t)$ which has a large dynamic test error because of delayed response of the sensor. To improve the test accuracy, the sensor output $y(t)$ passes through a compensator, so that the sensor output $y(t)$ is replaced by the compensator output $\hat{y}(t)$ so as to correct the dynamic error in this way.

To avoid building the dynamic model of the sensor, this paper directly designs a dynamic compensator with the experimental data, converting the dynamic compensator design into identification of compensator parameters. The specific principles are as follows.

In actual applications, the dynamic compensator of sensor can be described by variable differential equation as

$$\hat{y}(t)(a_0 + a_1 z^{-1} + \cdots + a_n z^{-n}) = y(t)(b_0 + b_1 z^{-1} + \cdots + b_m z^{-m}), \quad (5)$$

where z^{-1} is delay operator; m and n are the orders of compensator; and $e(t)$ denotes output noise.

Eq. (5) can be expressed in a vector form as

$$\hat{y}(t) = \boldsymbol{\omega}^{\mathrm{T}} \boldsymbol{X}_t + \boldsymbol{b}, \tag{6}$$

where $\boldsymbol{b}$ is a constant,

$$\boldsymbol{\omega} = (-\mathrm{a}_1, \cdots, -\mathrm{a}_n, \mathrm{b}_0, \mathrm{b}_1, \cdots, \mathrm{b}_m)^T,$$

$$\boldsymbol{X}_t = [z^{-1}\hat{y}(t), \cdots, z^{-n}\hat{y}(t), y(t), z^{-1}y(t), \cdots, z^{-m}y(t)]^{\mathrm{T}}.$$

The design principle of the dynamic compensation filter based on QPSO algorithm is as follows: firstly, the actual measured excitation signal $x(t)$ and response signal sequence $y(t)$ are got by shock tube dynamic calibration experiment. Then, the signal $y'(t)$ is designed to meet the requirement of dynamic performance according to $x(t)$. Finally, by using the QPSO algorithm, dynamic compensation filter coefficients are got with $y(t)$ and $y'(t)$. The specific method of dynamic compensation of sensor based on QPSO algorithm is shown in Fig. 2.

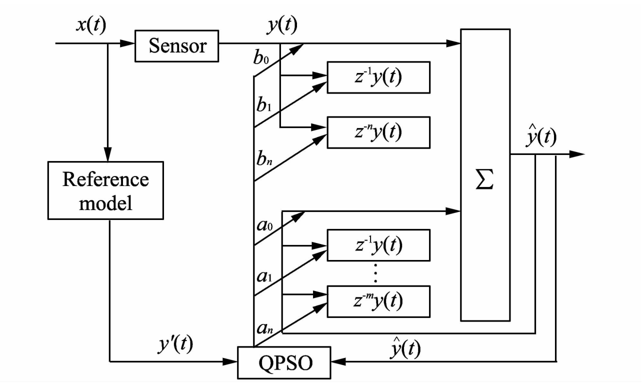

Fig. 2 Principle of dynamic compensation of sensor based on QPSO algorithm

3 Selection of optimal order of dynamic compensation filter

As the order of dynamic compensation filter is higher, it will increase the calculation work and make the hardware implementation more difficult, as a result, the effect of corresponding compensation is limited[7]. Therefore, to determine the structure of the compensation filter accurately, it is necessary to verify how to select the optimal order of the compensator. In the actual identification of system, the sampling groups of the input and output are significantly more than the number of the parameters of identification. In this case, with the increase of the model order, the error value will decrease obviously. However, when the order number of the model is larger than the order of the real system, the prominent decline of the error will stop, so that the optimal order of the model can be determined in this way[12]. In this paper, by means of the shock tube dynamic calibration experiment, the mean square error between the compensated data and the actual step signal can be got by

$$\sigma = \min \frac{1}{N} \sqrt{\sum_{i=1}^{N} (\hat{y}(t) - y'(t))^2},$$

where N is the number of data, y' is the actual step signal; and $\hat{y}(t)$ is the compensated data. Therefore, the optimal order of compensation filter can be determined based on the relationship between the mean square error and the different order of compensation filter.

4 Dynamic calibration experiment

In the dynamic calibration experiment, the shock tube can generate a standard step pressure to act on the measured pressure sensor, and thus the actual working capacity of the sensor is analyzed by the output response of the sensor. The actual response curve of the pressure sensor in the dynamic calibration experiment is drawn in Fig. 3.

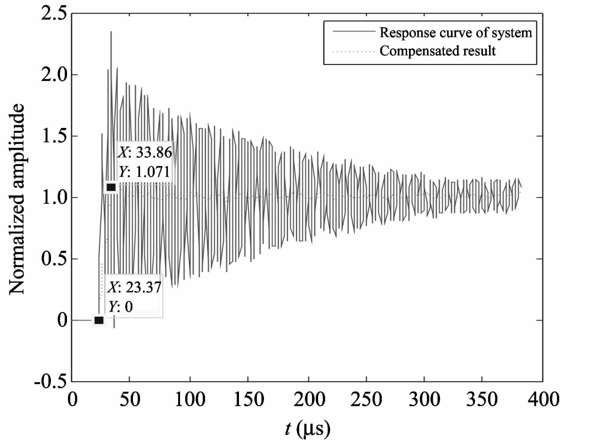

Fig. 3 Compensation results of sensor

Using the QPSO algorithm, the inverse model of the sensor is built and optimized to get the coefficients of the compensator. The output of the sensor can be equivalent to the input of the compensation system and the input signal can be equivalent to the output of the compensation system. In this paper, curve 1 is the input of the compensation system and the output of the reference model is the ideal step signal.

By means of the optimization of the QPSO algorithm, the coefficients of the compensator whose orders are given in advance will be got as long as the mean square error reaches the minimum. The relationship between the mean square error and the different orders of compensation filter is shown in Fig. 4.

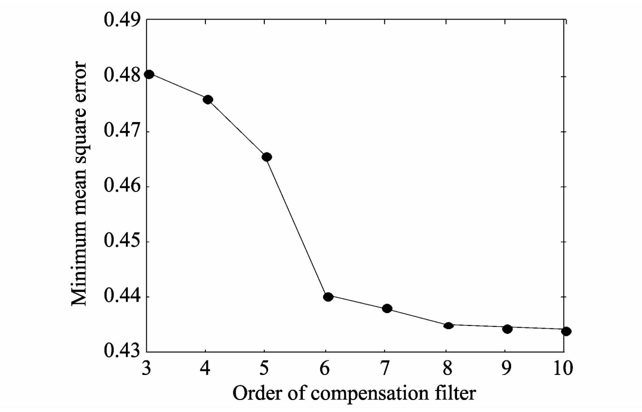

Fig. 4 Relationship between mean square error and order

It can be known that the error curve of the compensated data decreases gradually with the increase of the filter's order, but the decrease amplitude obviously becomes small from the sixth order. According to the proposed principle, the optimal order of the compensation filter is 6 and the coefficients of the dynamic compensation filter a and b are shown in Table 1.

Table 1 Coefficients of optimal dynamic compensation filters *a* and *b*

Parameter a	Parameter b
$a_0 = 1.5156$	$b_0 = 0.9519$
$a_1 = -0.2066$	$b_1 = -0.1478$
$a_2 = 0.2489$	$b_2 == 0.9988$
$a_3 = 1.2367$	$b_3 = 0.2167$
$a_4 = -0.1061$	$b_4 = 0.5392$
$a_5 = 0.0725$	$b_5 = 0.1835$
$a_6 = 0.0074$	$b_6 = 0.0416$

And then the transfer function of this dynamic compensation filter can be got by

$$H(z) = \frac{0.9519 - 0.1478z^{-1} + 0.9988z^{-2} + 0.2167z^{-3} + 0.5392z^{-4} + 0.1835z^{-5} + 0.0416z^{-6}}{1.5156 - 0.2066z^{-1} + 0.2489z^{-2} + 1.2367z^{-3} - 0.1061z^{-4} + 0.0725z^{-5} + 0.0074z^{-6}}.$$

Fig. 3 shows the compensation result, the response time is 10 μs and the overshoot volume is 10% after the compensation, which achieve the technical index requirements.

To verify the effects of the compensation further, the amplitude-frequency characteristics of the system before and after the compensation are analyzed. The sensor' model can be set up with the same method. The amplitude response, the amplitude-frequency characteristic of the dynamic compensation filter and the amplitude-frequency curve after dynamic compensation are shown in Fig. 5. It can be seen that the sensor has a flat working band below 75 kHz, but a big amplitude error appears around the resonant frequency of 250 kHz. By using dynamic compensation filter, the "straight section" can be extended to 350 kHz. It can be concluded that the method of the dynamic compensation has expanded the effective working band of the sensor largely.

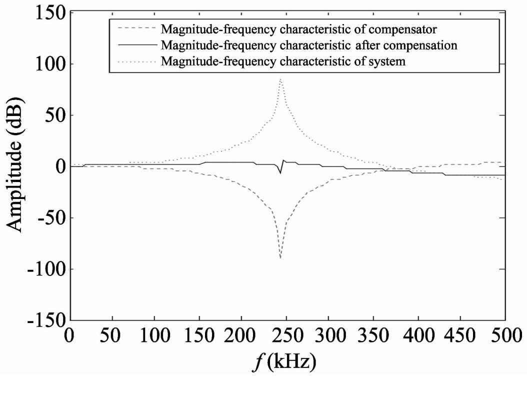

Fig. 5 Comparison of amplitude-frequency characteristics before and after compensation

5 Application in actual test

After the test system is established, the dynamic calibration of each shock wave's pressure sensor is carried out and the corresponding compensation filter is designed. The arrangement of measuring points in the static burst power test for a certain warhead is shown in Fig. 6.

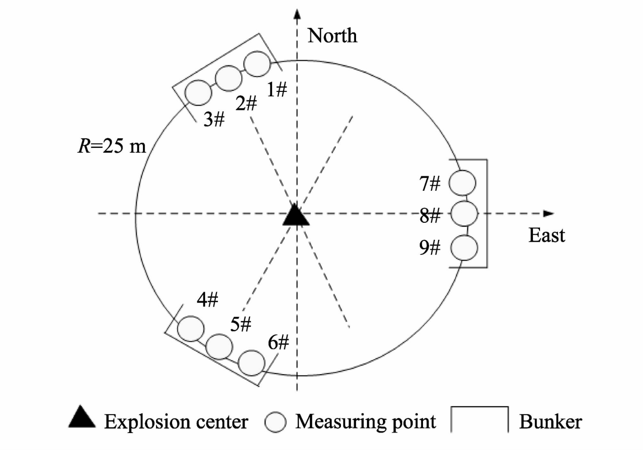

Fig. 6 Site layout of measuring points

The actual shock wave curve measured by the measuring point 7# and its corresponding curve after dynamic compensation is shown in Fig. 7.

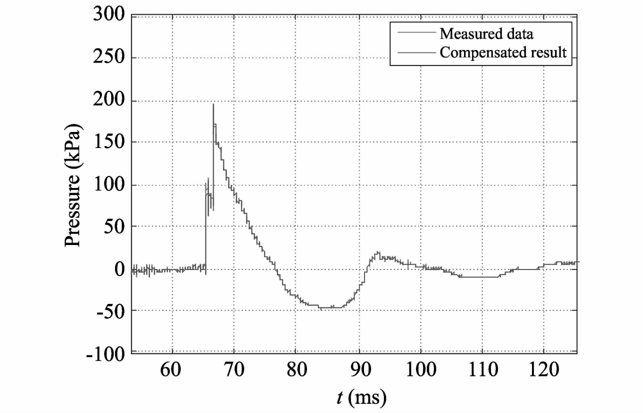

Fig. 7 Actual shock wave curve and modified curve

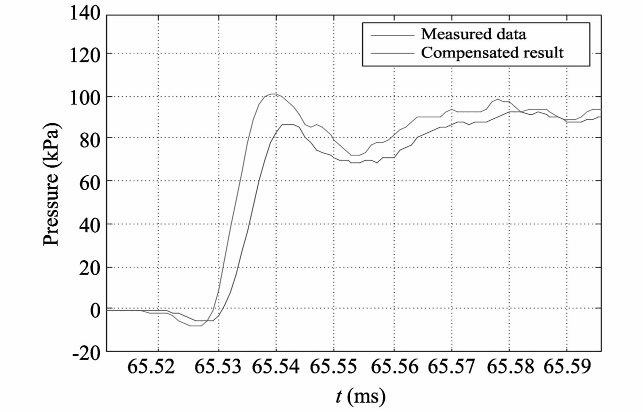

Fig. 8 Magnification of rising edge

The rising edges of the curves are partially enlarged as shown in Fig. 8.

It can be seen that the measured overpressure peak of shock wave is 101.13 kPa and the modified value after dynamic compensation is 89.78 kPa. Peak pressure is decreased by 11.22% and the peak time is delayed for 3.0 μs by correction. The measured overpressure and the result after compensation of each measuring point are shown in Table 2.

Table 2 Measured data and results after compensation

Measuring distance (m)	Measuring point	Measured overpressure (kPa)	Modified value (kPa)	Dynamic error (%)
25	1#	96.25	89.96	6.53
	2#	103.2	95.38	7.58
	3#	101.62	95.94	5.59
	4#	98.92	90.15	8.86
	5#	97.52	91.37	6.31
	6#	98.56	89.35	9.34
	7#	101.13	89.78	11.22
	8#	99.65	91.74	7.94
	9#	98.43	92.08	6.45

6 Conclusion

The method of dynamic compensation of pressure sensor based on QPSO algorithm and mean square error is proposed in this paper. The parameters of the optimal dynamic compensation filter are got with the input and output of press sensor through the optimization and calculation in the dynamic calibration experiment instead of setting up dynamic model of sensors, which avoids the influence of modeling errors on dynamic compensation. In time domain and frequency domain, the performance of the sensor before and after the compensation is analyzed. The results show that the effective working band of the sensor has been widened. It reduces the error of dynamic test and improves the accuracy of the test by applying in the actual measurement. In addition, according to the parameters of dynamic compensation filter, the corresponding filter can be constructed by software programming in the appropriate microprocessor and then the filter is solidified into the acquisition system to realize the real-time processing of the data. The proposed method can also be used to solve the dynamic test problem of other sensors or test systems.

References

[1] ZHANG Zhi-jie, WANG Dai-hua, WANG Wen-lian, et al. Shock wave pressure measurement system function with wireless data transmission and control. Metrology & Measurement Technology, 2010, 30(1): 22-25.

[2] YOU Wen-bin, MA Tie-hua, DING Yong-hong, et al. Dynamic modeling and application of shock wave testing system. Chinese Journal of High Pressure Physics, 2014, (4): 429-434.

[3] YE Xiang-bin, ZHANG Wen-na. Analysis and improvement for dynamic performance of pressure sensor. Journal of Transducer Technology, 2002, 21(2): 11-14.

[4] HUANG Zheng-ping. Explosion and shock electrical measurement technology. Beijing: Defense Industry Press, 2006: 26-49.

[5] LIU Qing, CAO Guo-hua. Study on dynamic compensation method for micro-silicon accelerometer based on swarm optimization algorithm. Chinese Journal of Scientific Instrument, 2006, 27(12): 1707-1710.

[6] XUAN Chun-qing, XUAN Zhi-wei, CHEN Bao-li. Dynamic compensation method based on least squares algorithm and particle swarm optimization for pressure sensor. Chinese Journal of Sensors and Actuators, 2014, (10): 1363-1367.

[7] WU Jian, ZHANG Zhi-jie, WANG Wen-lian. FPGA Implementation of high speed parallel correction for sensor's dynamic error. Journal of Transduction Technology, 2012, 25(1): 67-71.

[8] GUO Hui-ling, LI Wei. Dynamic compensation of sensors based on QPSO algorithm and its FPGA implementation. Computer Measurement & Control, 2014, 22(1): 178-180.

[9] QIN Feng, XIA Xuan, XU Xiao-quan. Rule reduction in fuzzy reasoning. Advances in Mathematics, 2011, (4): 457-470.

[10] Arfia F B, Messaoud M B, Abid M. Nolinear adaptive filters based on particle swarm optimizer. Leonardo Journal of Sciences, 2009, 5: 244-251.

[11] CHEN Jie, PAN Feng, CAI Tao. Acceleration factor harmonious particle swarm optimizer. International Journal of Automation and Computing, 2006, 3(1): 41-46.

[12] MU Ge, LI Qiao-li, MENG Qing-jun, et al. System modeling. Beijing: Defense Industry Press, 2013: 166-174.

冲击波压力传感器动态特性补偿及其应用

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摘　要： 为修正压力传感器动态特性引起的测试误差，避免传感器动态建模误差影响补偿结果，提出了一种基于量子粒子群优化(QPSO)算法和均方误差的传感器动态补偿方法。通过对传感器进行逆建模，寻优得到了最优阶次的补偿器系数，利用激波管动态校准实验对该方法进行了验证，分析了补偿前后传感器的时域与频域特性。结果表明，该方法有效扩展了传感器的工作频带；在实弹测试中，减小了动态测量误差，提高了测试精度。

关键词： 压力传感器；动态补偿；QPSO算法；冲击波测试；频带拓宽

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