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Accurate measurement of high-frequency blast waves through dynamic compensation of miniature piezoelectric pressure sensors

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ABSTRACT

To suppress the parasitic effects in explosion test, a blast wave pressure sensor component composed of a pressure sensor, an additional mechanical structure and silicone greases on the sensitive surface is built up for blast wave measurements. If the dynamic characteristics of the sensor component cannot meet the requirements of so-called undistorted measurements, it will result in measurement errors. In this paper, we present a dynamic compensation approach which considers all the components within the frequency range of interest to correct measured blast wave pressure signals. Via the frequency characteristic analysis of the sensor component, we know that the additional mechanical structure and silicone greases introduce a formant within the low frequency range. The amplitude of the formant within the low frequency range is much smaller than that at the resonance frequency, making it difficult to establish the model of the sensor component to reflect this small formant accurately. Therefore, based on dynamic calibration on a shock tube, considering that the effective bandwidth of blast wave pressure signals is generally within 100 kHz, we propose a partial modelling method and establish the partial model of the sensor component. Compared to the full-bandwidth model, the partial model is more accurate within the low frequency range. Then a dynamic compensation approach is presented for accurate measurements. When designing the dynamic compensation filter, all the poles and zeros on the dynamic characteristics of the sensor component are analyzed as influence factors. Using the presented dynamic compensation approach, the working bandwidth of the sensor component is increased from 14.5 kHz to 120 kHz. Compared with the step response signal measured in the dynamic calibration experiment, the step response signal passing through the dynamic compensation filter contains less noises and smaller overshoot. Furthermore, comparing the peak overpressures of the simulated blast wave pressure signal with that of the signals passing through the sensor component and after dynamic compensation, the errors are 16% and 0.094%, respectively. Finally, the measured blast wave pressure signal in an explosion test is corrected using the presented dynamic compensation approach. And compared with the theoretical value of its peak overpressure, the errors before and after dynamic compensation are 13% and 1.4%, respectively.

1. Introduction

Blast wave pressure measurements are important for estimating the damage power of explosives. Due to complex blast environments and steep rising edges and short durations of blast wave pressure signals, it is not easy but of great significance to measure blast wave pressures with high accuracy [1,2]. Nowadays, electrical measurements are mainly applied to explosion tests, and piezoelectric sensors are selected because of their good anti-overload performances and wide working bandwidths [3]. Considering there are dozens of measurement points and cables are hundreds of meters in an explosion test, ICP sensors containing charge amplifiers are chosen [4].

In explosion tests, owing to parasitic effects such as thermal shocks, mechanical shocks and vibrations [5,6], measured signals contain parasitic responses. To suppress parasitic effects, it is necessary to design an additional mechanical structure of the pressure sensor. The blast wave pressure sensor component composed by a pressure sensor, the additional mechanical structure and silicone greases is installed on a test plate for the blast wave pressure measurement. The change of equivalent mass and stiffness of the whole structure makes the sensitivity and dynamic characteristics differ-

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Abbreviations: GLS(SF), generalized least square algorithm with special whitening filter; ICP, integrated circuits piezoelectric.

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ent from before. Therefore, the pressure sensor component should be calibrated and modelled [7]. So that we can know, whether the sensor component meets the requirements of undistorted measurements, that is, whether the working bandwidth of the sensor component is wider than the effective bandwidth of measured signals. If not, the sensor component needs to be compensated.

Dynamic calibration devices include periodic pressure generators, drop-weight devices, quasi-δ function pressure generators, shock tubes [8,9], etc. Which device to choose is primarily determined by calibration pressures and bandwidths. As for the dynamic calibration of blast wave pressure sensors, shock tubes are the most suitable calibration devices. they generate near idea step signals whose bandwidths are wide enough to stimulate the resonances of almost all pressure sensors. Thus, shock tubes are widely used in the dynamic calibration of blast wave pressure sensors [10,11].

According to the dynamic calibration data, the dynamic model of sensor components can be established. Modelling accuracy is the basis of dynamic compensation effects. Currently, modelling methods are divided as traditional modelling methods mainly for linear systems such as the least square algorithm and the maximum-likelihood method, and intelligent algorithms mainly for nonlinear systems like the neural network and the genetic algorithm [12–14]. Among them, considering the sensor component is generally counted on a linear system, the GLS(SF) generated from the least square algorithm is the most widely-practiced modelling method with advantages of easy calculation, fast convergence rate and high accuracy. The estimated parameters are consistent and unbiased because the special whitening filter can convert model noises into white Gaussian noises.

Dynamic compensation can be implemented by hardware and software methods. The hardware method is limited by materials and technologies. By contrast, the software method develops better because of its flexibility and reliability [15]. It can be divided into the dynamic error correction and the dynamic characteristic compensation. The dynamic error correction is aimed at time domains, and realized by corresponding calculations of output signals, including the frequency-domain correction method which gets the corrected signal through dividing the output signal by the transfer function and then implementing Fourier inversion, the superposition integral method which gets the corrected signal via multiplying a series of step signals which the output signal is broken into by the stationary sensitivity of the system, the numerical differential method which gets the corrected signal by substituting the output signal and its differential coefficients into the differential function of the system, the deconvolution method which gets the corrected signal directly by the deconvolution of the impulse responses of the system and the output signal [16–18], etc. Considering the frequency-domain correction and the deconvolution are prone to lead to spectral aliasing, spectral leakage and picket fence effects, meanwhile the numerical differential and the superposition integral may cause error accumulations, thus they are gradually replaced by the dynamic characteristic compensation aimed at frequency domains, which designs a dynamic compensation filter connecting to the system to get the compensated system that can meet the requirements of distorted measurements and gets the corrected signal after the output signal passing through the compensation filter, including the inverse filtering [19], the zero-pole cancellation [20,21], the artificial neural network [22], the support vector machine [23], etc. Among them, the zero-pole cancellation method is widely used in the dynamic compensation of linear systems because of its simple calculation and good compensation effects.

Based on the dynamic calibration experiment on a shock tube, the GLS(SF) and the zero-pole cancellation are widely combined for the dynamic compensation of a sensor component [24–26]. As the additional mechanical structure and silicone greases result in a non-negligible formant within the low frequency range, the dynamic model is fitted better within the high frequency range. But the energy of blast wave pressure signals is mainly concentrated within the low frequency range. So, we proposed a partial modelling method and established the partial model of the sensor component to improve the modelling accuracy within the low frequency range. In the zero-pole cancellation method, generally, designing a compensation filter is as follows: the poles of the sensor component that cannot meet the requirements are selected to be the zeros of the dynamic compensation filter; the poles of the dynamic compensation filter are calculated according to the requirements; the additional poles and zeros of the compensation filter may also be considered to improve the dynamic characteristics [26]. However, aimed at the sensor component built in this paper, it is hard to get good compensation effects following the above steps. Therefore, we proposed a dynamic compensation approach combining the partial modelling and the zero-pole cancellation for accurate measurements of the blast wave pressure sensor component.

This paper is organized as follows. Section 2 introduced the structure of the blast wave pressure sensor component and the dynamic calibration experiment of the sensor component on a shock tube. Then we presented the partial modelling method, compared the full-bandwidth model with the partial model in Section 3. In Section 4, we analyzed the subsystems of the pressure sensor component, and designed the dynamic compensation filter by the zero-pole cancellation method. Section 5 validated the dynamic compensation effects, and finally a blast wave pressure signal in an explosion test was effectively corrected.

2. Dynamic calibration of blast wave pressure sensor component

2.1. Blast wave pressure sensor component

In explosion tests, parasitic effects exist when thermal shocks cause a thermal drift on the piezoelectric crystal of the sensor component, the impact stress produced by the blast wave impacting the test plate changes, the seismic wave produced by the blast wave impacting ground vibrates the sensor, leading to additional outputs of the blast wave pressure sensor.

To suppress parasitic effects, a sensor component composed of a sensor, an additional mechanical structure and silicone greases on the sensitive surface is built up. First, the additional mechanical structure is mounted on the blast wave pressure sensor to reduce the influences of the mechanical shock and vibration, shown in Fig. 1(a). This structure contains one vibration dampening ring of XY direction whose internal diameter is 6.3 mm and external diameter 8.3 mm,and two vibration dampening rings of Z direction whose thickness is 3.0 mm, fixed with a locking ring and a fixing bolt. The three dampening rings are all made of rubber whose density is 0.92 g/m^3, strength of extension 20 MPa and Poisson's ratio 0.35, assembled using interference fit. The locking ring, the fixing bolt and the component shell are all made of structural steel. The dimensions of the locking ring and the fixing bolt are nonstandard and designed for being tightened by hands easily. Then, the sensitive surface is covered with 0.3 mm thickness of silicone greases for thermal insulation [27]. Due to the additional structure and the silicone greases, the sensitivity and dynamic characteristics of the sensor component vary, so a dynamic calibration experiment is required. In explosion test, the sensor component is installed on the test plate as shown in Fig. 1(b) to ensure that the surface of the sensor with silicone greases and the upper surface of the test plate are flush with the ground. The base of the test plate is buried into the soil to make the plate and the ground a whole, so that the