Postprint of Research on Physical Filtering Methods for Overload Testing in Projectile Penetration Experiments

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Abstract

Abstract: Aiming at the problem that rigid body overload testing in projectile penetration experiments is susceptible to high-frequency physical interference, this study first decouples the measured overload signals to separate the low-frequency rigid body overload component from the high-frequency vibration interference component. Secondly, based on a single-degree-of-freedom dynamic model, a theoretical analysis of the spring-damping vibration isolation system is conducted, and the mathematical relationship between the input frequency and the system' s natural frequency under different vibration isolation efficiencies is derived. The stiffness parameters of the low-damping vibration isolation system can be specifically designed according to the target vibration isolation efficiency and input excitation frequency. Finally, verified by penetration test overload measurement data, this physical filtering method can effectively suppress the interference of vibration loads on the rigid body overload signal, successfully extracting the true rigid body overload signal with an amplitude in the range of (30,000–40,000) g, thereby improving the fidelity of overload measurement. The research results can provide high-precision testing theory and technical support for the design and optimization of strong dynamic load testing systems for penetration warheads.

Full Text

Research on Physical Filtering Methods for Projectile Penetration Overload Testing

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Abstract: Aiming at the problem that rigid-body overload measurements in projectile penetration tests are susceptible to high-frequency physical interference, this study first performs decoupling of the measured overload signals. The low-frequency rigid-body overload component is separated from the high-frequency vibration interference component. Subsequently, based on a single-degree-of-freedom (SDOF) dynamic model, a theoretical analysis of a spring-damping vibration isolation system is conducted. The mathematical relationship between the input frequency and the system’ s natural frequency under different vibration isolation efficiencies is derived. This allows for the targeted design of stiffness parameters for low-damping vibration isolation systems based on the target isolation efficiency and input excitation frequency. Finally, verification through penetration test overload data demonstrates that this physical filtering method effectively suppresses the interference of vibration loads on the rigid-body overload signal. The method successfully extracted authentic rigid-body overload signals with amplitudes ranging from $30,000g$ to $40,000g$, significantly improving the fidelity of overload measurements. The research results provide high-precision testing theory and technical support for the design and optimization of strong dynamic load measurement systems for penetrating warheads.

Keywords: Penetration test; Overload testing; Physical filtering; Vibration isolation

1 Introduction

The measurement of high-g acceleration during projectile penetration into hard targets is critical for evaluating weapon performance and structural reliability. However, the harsh impact environment generates complex stress waves and high-frequency structural resonances that often exceed the dynamic range of electronic data acquisition systems or obscure the underlying rigid-body motion. While digital filtering is commonly applied post-test, it cannot recover information lost due to sensor saturation or “zero-shift” phenomena caused by high-frequency components. Therefore, physical filtering—the use of mechanical damping and impedance matching—is essential to ensure the quality of the raw data.

Traditional signal processing relies heavily on digital filtering. While effective, digital filtering cannot prevent “input-side” issues such as sensor saturation or “clipping” caused by high-frequency components. Physical filtering, which involves placing buffering materials between the sensor and the projectile body, acts as a mechanical low-pass filter. This approach attenuates high-frequency energy before it reaches the sensing element, thereby protecting the sensor and ensuring the integrity of the captured low-frequency data.

2 Theoretical Analysis of Physical Filtering

2.1 Dynamic Modeling

To understand the mechanism of physical filtering, the sensor installation can be simplified into a mass-spring-damper system. Let the projectile body be the base excitation, the buffer material be the spring and damper, and the sensor be the mass element. The governing equation of motion for this system is:

$$m\ddot{x}_o + c(\dot{x}_o - \dot{x}_i) + k(x_o - x_i) = 0$$

where m is the mass of the sensor and its mounting, c is the damping coefficient of the filtering material, and k is the stiffness. Let $x_g(t)$ represent the true displacement signal of the projectile body, while $x_t(t)$ represents the displacement signal recorded by the sensor. The displacement of the projectile motion, $x_g(t)$, can be simplified into two components: the overall rigid-body displacement of the projectile, $x_{g0}(t)$, and the displacement resulting from high-frequency vibrations, $x_{ga}\sin(\omega t)$.

2.2 Transmissibility and Frequency Ratio

The performance of a vibration isolation system is primarily characterized by its transmissibility T_r, which defines the ratio of the force or motion transmitted to the foundation relative to the input excitation. For a linear single-degree-of-freedom (SDOF) system, the force transmissibility for a damped system is expressed as:

$$T_r = \sqrt{\frac{1 + (2\zeta\lambda)^2}{(1-\lambda^2)^2 + (2\zeta\lambda)^2}}$$

where ζ is the damping ratio and $\lambda = \omega/\omega_n$ is the frequency ratio. Vibration isolation is achieved when $T_r < 1$, which occurs when $\lambda > \sqrt{2}$. The isolation efficiency η is defined as:

$$\eta = (1 - T_r) \times 100\%$$

For a system with negligible damping ($\zeta \approx 0$), the relationship simplifies to $T_r = |1/(1-\lambda^2)|$. For effective isolation ($\lambda > \sqrt{2}$), this becomes $T_r = 1/(\lambda^2 - 1)$. Solving for λ, we obtain:

$$\lambda = \sqrt{\frac{1}{T_r} + 1}$$

Figure 1

Figure 1: Figure 1

This derivation demonstrates that as the required isolation efficiency increases, the gap between the input excitation frequency and the system’ s natural frequency must widen significantly.

3 Vibration Isolation Stiffness Design

The design of vibration isolation stiffness is critical for tuning the natural frequency to avoid resonance. The natural frequency f_n is defined by the relationship between stiffness k and mass m:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

In this study, the vibration isolation material consists of a series-connected stack of polytetrafluoroethylene (PTFE) and rubber gaskets. The overall stiffness k is calculated as:

$$\frac{1}{k} = \frac{1}{k_R} + \frac{1}{k_P}$$

where k_R and k_P are the stiffnesses of the PTFE and rubber, respectively. The stiffness for each material is determined by $k = E \cdot A/h$, where E is the elastic modulus, A is the contact area, and h is the thickness. Based on spectral analysis of initial test data, the primary noise was concentrated between $1,000$ and $20,000$ Hz. Using $1,000$ Hz as the target input frequency and a target efficiency of $\eta = 0.9$, the required design stiffness was calculated to be 271.56 kN/m.

4 Experimental Verification

The effectiveness of the physical filtering method was verified through live-fire penetration tests against high-performance reinforced concrete (compressive strength $\geq$ 120 MPa).

The experimental results demonstrate that the proposed physical filtering method effectively suppresses high-frequency stress waves and structural vibration interference. Before filtering, the rigid-body overload signal was completely obscured by noise. With the vibration isolation and filtering device installed, the projectile’ s deceleration platform became clearly observable, allowing for the extraction of authentic rigid-body overload waveforms with amplitudes of $30,000g$ to $40,000g$. Fourier transform analysis confirmed that the device effectively stripped high-frequency noise in the $1,000$ to $20,000$ Hz band while preserving the low-frequency characteristic signals.

Figure 4

Figure 2: Figure 4

Figure 5

Figure 3: Figure 5

5 Conclusion

1) Based on the SDOF dynamic model, the governing equations for the acceleration sensor were derived, allowing for the decoupling of rigid-body overload from structural vibration interference.
2) A quantitative mathematical relationship between isolation efficiency, excitation frequency, and natural frequency was established, providing a precise method for stiffness parameter design in low-damping systems.
3) Live-fire tests validated that the physical filtering method significantly improves measurement fidelity and the signal-to-noise ratio, providing reliable data for the structural design and fuse optimization of penetrating warheads.

Figures