Effect of projectile head style on high *g* acceleration waveform of Hopkinson bar calibration system

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Abstract: The freestyle Hopkinson bar is a kind of main high g loading equipment utilized widely in calibration of high g accelerometer and other high shock conditions. The calibration experiment of accelerometer was conducted. With one-dimension stress wave theory, ANSYS/LS-DYNA software and experiment, the effect rules of the projectile's front-head style and the accelerometer's mounted base's length on acceleration waveform were analyzed. The results show that the acceleration duration inspired from Hopkinson bar is almost equal to the rising edge time of perfect half sine stress wave, and it is independent to the mounted base's length. Moreover, the projectile's front-head style is a main affecting factor, and the projectiles with less conical degrees will produce the lower amplitude and longer acceleration duration.

Key words: Hopkinson bar; high *g* acceleration; stress wave; waveform adjustment

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0 Introduction

High g accelerometers have been widely used in acceleration time signal measurements, especially in projectile penetration and explosion dispersion. Because of good reproducibility and convenient operation, a freestyle Hopkinson bar becomes a kind of main high g loading equipment in acceleration calibration[1-3]. In order to gain desired acceleration waveform, relevant means are taken. Forrestal in Sandia Lab in USA adopted a aluminum bar with a length of 0.254 m and Flat ends to coaxially impact a aluminum incident bar with a length of 1.829 m, and plexiglass or copper adjusting pad was placed between two bars. But the acceleration waveform is more similar to rectangle signal, which is very different from the signal commonly used in calibration[4]. The projectile's shape and length were changed to adjust the incident stress wave's rising edge of Hopkinson bar[5-7]. Many factors can affect acceleration waveform, such as projectile head style, impact velocity, adjusting pad's material and thickness, and so on. In this paper, theory analysis, numerical simulation and calibration experiment on freestyle Hopkinson bar have been used to investigate the effects of the projectile's front-head styles and the accelerometer's mounted base's length on accelerometer's inspiring waveform, and conclusion is significant to the waveform regulation in accelerometer calibration test on Hopkinson bar.

1 Experimental principle and test methods

The experiment setup is shown in Fig. 1. In this experiment, a freestyle Hopkinson bar with 1.6 m length and 16 mm diameter made of TC4 titanium alloy is used as a high g shock acceleration generator. A projectile with a certain type conical tip is launched by compressed air to axially impact the adjusting pad made of aluminum alloy. The adjusting pad and ac-

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celerometer mounted base are placed respectively on two ends on Hopkinson bar with grease and a vacuum collar, a evaluated accelerometer is attached to the end of a titanium alloy mounted base with M5 bolt, and the reflecting grating is axially glued on the base's surface, thus the mounted base, accelerometer and grating are kept an ensemble (called flying object) during the impact process.

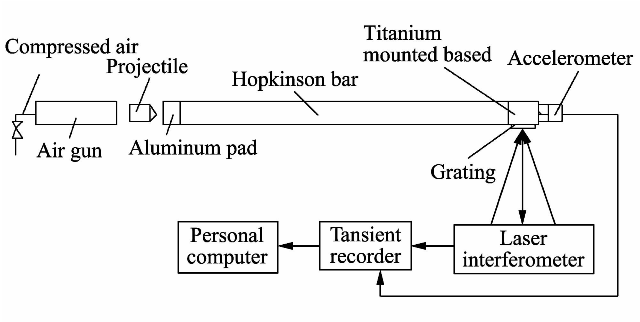

Fig. 1 Sketch of experiment setup

When impacted, an approximate half sine shape elastic stress wave is generated and then it propagates axially in the incident bar. When the compressive stress wave reflects into a tensile one on the free surface of the titanium alloy mounted base and the sum of stress at the interface between bar and base become tensile, the flying object separates axially from the incident bar with certain waveform acceleration, then it is caught by a soft material catcher. By means of grating interference technique, the accelerating course of flying object is directly acquired and recorded from basic quantity and unit (time and length) with high accuracy. According to Doppler effect, the velocity of the base is linearly proportional to Doppler frequency shift, therefore, the base's acceleration can be calculated by means of derivation of the velocity. Moreover, by comparing the base's acceleration and accelerometer's output, calibration can be completed.

2 Theoretical analysis of base's acceleration duration

In order to investigate the relation between acceleration duration and stress wave rising edge, a right propagating perfect half sine compressive stress wave is assumed in Hopkinson bar, as shown in Fig. 2.

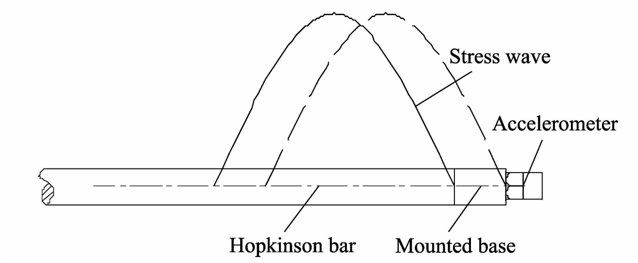

Fig. 2 Stress wave in Hopkinson bar

The equation of incident stress wave σ_i at the interface between Hopkinson bar and mounted base is

$$\sigma_i = \begin{cases} \sin\left(\frac{\pi t}{t_0},\right) & 0 \leqslant t \leqslant t_0 \\ 0, & t > t_0,\ t < 0 \end{cases} \tag{1}$$

where t_0 is half-sine stress wave duration.

The reflective tensile stress wave σ_r form ? (from?) right free end is

$$\sigma_r = \begin{cases} -\sin\frac{\pi\left(t-\frac{2l}{c}\right)}{t_0}, & \frac{2l}{c} \leqslant t \leqslant t_0 + \frac{2l}{c} \\ 0, & t < \frac{2l}{c} \text{ or } t > t_0 + \frac{2l}{c} \end{cases} \tag{2}$$

where l is length of accelerometer's base and c is the velocity of stress wave.

Therefore, the sum of stress at the interface between the base and the bar is

$$\sigma = \sigma_i + \sigma_r = \sin\frac{\pi t}{t} - \sin\frac{\pi\left(t-\frac{2l}{c}\right)}{t_0}. \tag{3}$$

If $\sigma = 0$,

$$\sin\frac{\pi t}{t_o} = \sin\frac{\pi\left(t-\frac{2l}{c}\right)}{t_o}.$$

Thus, $$t = \frac{t_o}{2} + \frac{l}{c}.$$

The base's acceleration duration t_a is described by

$$t_a = t - \frac{l}{c} = \frac{t_o}{2}. \tag{4}$$

In Eq. (4), the base's acceleration duration is equal to rising edge of half sine stress wave, and is independent of the base's length. In order to obtain desired acceleration waveform, the rising edge of stress wave in bar can be modified by certain modes.

3 Numerical simulation of acceleration calibration course

3.1 Finite element model

ANSYS/LS-DYNA software is used to simulate the operation process of acceleration calibration with Hopkinson bar. For the axial symmetry of the whole structure, the plane finite element model of the whole structure is established, including the projectile (see Fig. 3), adjusting pads, Hopkinson bar and the mounted base, with plane 162 axial-symmetrical element. Lagrange algorithm is selected and the nodes on y-axis are constrained into zero displacement.

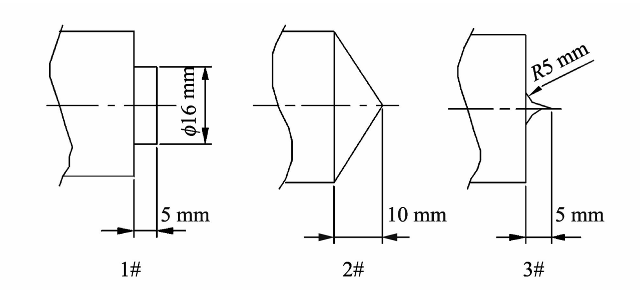

Fig. 3 Shapes of the projectiles

In order to avoid the aberration of element and control the standard of acceleration waveform, the elements are refined in the interface between the projectile and the adjusting pads. The total solution time is estimated with stress wave propagating time from one end to the other of the bar. The wave velocity in TC4 Hopkinson bar is 5 100 m/s and the bar's length is 1.6 m, therefore, the propagating time is almost 314 μs. Moreover, considering the required time that the stress wave reflects back and forth in base and the base flies from the bar's end, the total solution time is assumed to be 700 μs. The impact velocity of the projectile is 15 m/s.

3.2 Material model

The material of the base and bar is TC4 titanium alloy, and the constitutive model of base and bar is isotropic and linear elastic, with elasticity modulus of 113 GPa, density of 4 505 kg/m^3 and Poisson ratio of 0.4. The material constitutive model of projectile (35CrMnSiA) and pad (2A12) is Cowper-Symonds elastic-plastic hardening model, and the parameters are shown in Table 1. It is a kind of strain-rate correlative model, the relation between yielding stress σ_y and strain-rate $\dot{\varepsilon}$ is given as[6-7]

$$\sigma_y = \left[1+\left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{P}}\right](\sigma_y + \beta E_P \varepsilon_{\text{off}}^P),$$
$$E_p = \frac{EE_t}{E-E_t}, \tag{5}$$

where C and P are Cowper-Symonds strain-rate parameters, $\varepsilon_{\text{off}}^P$ is equivalent plastic strain, E_p is plastic hardening modulus, E is elastic modulus and E_t is tangent modulus.

Table 1 Material model parameters of 35CrMnSiA and 2A12

	Elasticity modulus E(GPa)	Density ρ (kg/m^3)	Poisson ratio μ	Yielding stress σ_y (MPa)	Tangent modulus E_t(MPa)	Strain-rate C	Parameters P	Failure strain ε_f
Pad	70	2 750	0.33	290	1 530	22 515.4	4.843	0.15
Projectile	200	7 800	0.3	1 200	2 000	40	5	0.15

4 Simulation results

The rigid acceleration-time curve of the base is shown in Fig. 4 and stress wave-stress curve is shown in Fig. 5. Comparison of the acceleration duration and the rising edge time of stress wave at middle point is shown in Table 2.

In Fig. 4, the different shapes of projectile's head-ends have tremendous effect on base's acceleration-time curve.

Table 2 Acceleration duration and stress wave rise time

	1#	2#	3#
Stress wave rise time (μs)	35	72	150
Acceleration duration (μs)	37	75	152

The amplitude of acceleration caused by projectile 1# is the largest, while its duration is the shortest. The amplitude of acceleration caused by projectile 3# with the smallest conical degree is the smallest, and its duration is the longest. It can be seen from Table 2 that the base's acceleration duration is nearly equal to stress wave rise time and the simulation results agree with the above theoretical analysis.

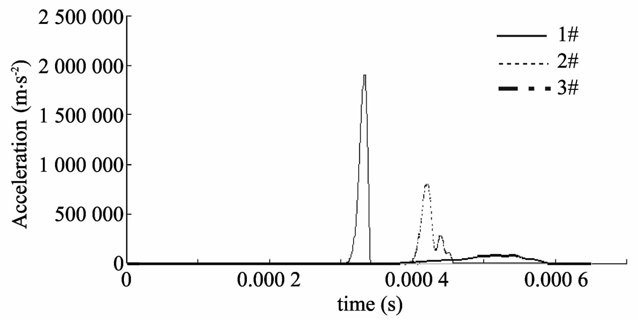

Fig. 4 Rigid acceleration of the base caused by three kinds of projectile's head-ends

In Fig. 5, there are great distinctions between the stress waves at bar's middle point caused by different projectile's head-ends. The stress wave rising edge caused by projectile 1# is very steep, stress amplitude is very high, and the high frequency oscillation arises in trailing edge. With the decrease of conical degree, the stress wave rising edge caused by 3# projectile with small conical degree becomes very gentle, the stress amplitude is very small, and the trailing edge is relatively smooth.

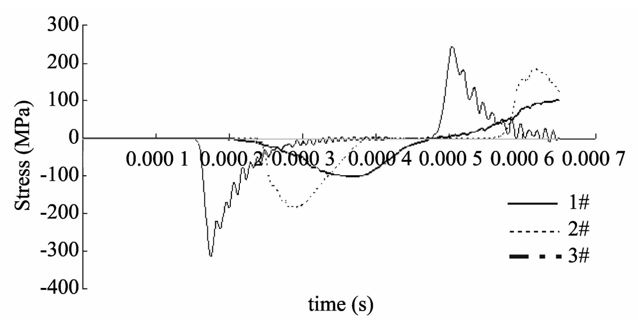

Fig. 5 Stress wave at half point of Hopkinson bar caused by three kinds of projectile's head-ends

5 Calibration test

In calibration experiments, the free-style Hopkinson bar (see Fig. 6) and three types of projectiles (see Fig. 7) are utilized. The piezoelectric accelerometer B&K8309 is chosen to be calibrated, and its installation resonance frequency is 180 kHz in factory specification. Figs. 8-10 give the tested output signals of accelerometer caused by projectiles from 1# to 3#.

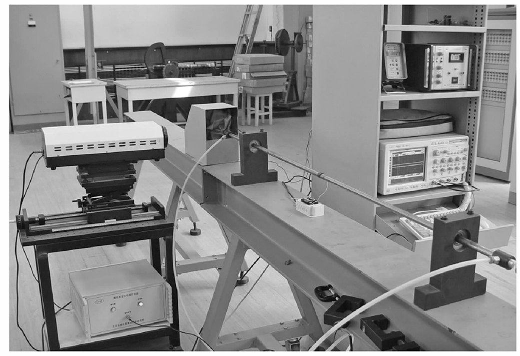

Fig. 6 Free-style Hopkinson bar

Fig. 7 Projectile with different heads

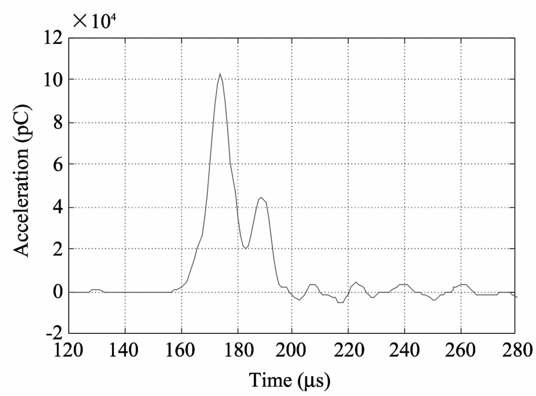

Fig. 8 Tested acceleration-time curve by projectile 1#

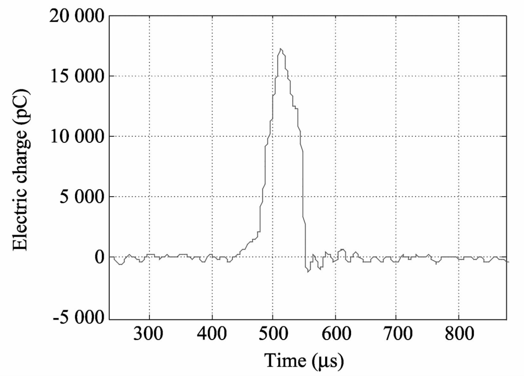

Fig. 9 Tested acceleration-time curve by projectile 2#

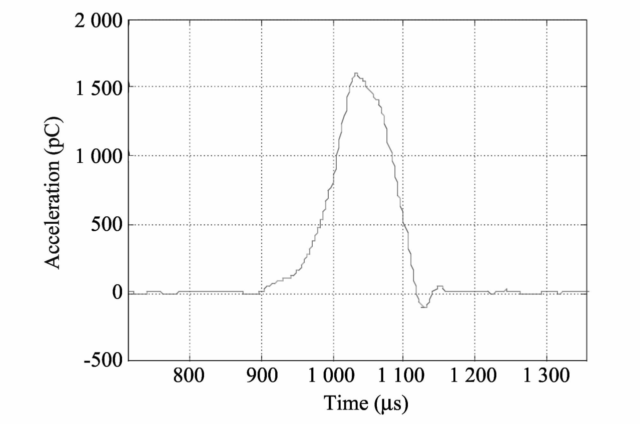

Fig. 10 Tested acceleration-time curve by projectile 3＃

Because the head end of 1＃ projectile is plane, it can load rapidly when impacting Hopkinson bar, and its acceleration duration is only 38.6 μs. In contrast, the acceleration duration of 2＃ projectile with 45 degree taper is 95 μs, and 3＃ projectile with smaller taper has 190 μs acceleration duration. The impacted adjusting pads are shown in Fig. 11. The impacted deformation arises at local central position and the dent becomes deeper with the taper of projectile head decreasing. As the projectiles with small conical degree head ends have small impact area, thus the local stress at impact point is very high, and the plastic deformation and the plastic stress wave with slower propagating velocity are produced. Because the impact energy is dissipated, the loading rate becomes slower, the loading duration becomes longer, and the stress wave rising edge in bar is gentle. When the local high amplitude plastic stress wave with slower velocity propagates forward, the stress amplitude will reduce with the increase of the impact area.

Fig. 11 Impacted adjusting pads

6 Conclusion

When the high g accelerometer is calibrated with free-type Hopkinson bar, the required different wave-style acceleration signals can be gained by exactly design of projectile's head-ends.

1) With one-dimension stress wave theory, the mounted base's acceleration duration inspired from free-type Hopkinson bar is almost equal to the rise-edge time of perfect half sine stress wave. In order to gain the desired inspiring acceleration signal, the method of controlling stress waveform must be considered.

2) The head-ends' shapes of the projectiles have great effect on acceleration-time curves. The projectile with small conical can produce smaller acceleration amplitude and wider duration. In order to get the acceleration with larger amplitude, the projectile with flat head-end has to be taken.

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弹头形状对 Hopkinson 杆校准系统高 g 值加速度波形的影响

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摘 要： 自由式 Hopkinson 杆是一种主要的高 g 值加载设备，已经被广泛应用于高 g 值加速度计校准和其它高冲击环境中。介绍了自由式 Hopkinson 杆校准的加速度计试验，应用一维应力波理论和 ANSYS/LS-DYNA 软件以及试验手段，分析了子弹头部形状，加速度计安装座长度等因素对加速度波形的影响。结果表明：自由式 Hopkinson 杆产生的加速度持续时间等于理想半正弦应力波前沿，并与安装座长度无关；子弹头部形状对加速度波形影响较大，头部锥度小的子弹产生的加速度幅值较低、持续时间较宽。

关键词： Hopkinson 杆；高 g 值加速度；应力波；波形调节

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