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测试压阻式三轴高 g 加速度计的霍普金森杆法

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摘要: 研究了一种压阻式三轴高 g 加速度计的霍普金森杆法测试实验及其数据处理方法。被测加速度计安装于标定杆的端部, 从高压气枪中射出的子弹高速撞击标定杆, 所产生的冲击以应力波的形式在标定杆中传播, 并可以通过安装在杆中部的应变计记录。通过比较应变计的输出和加速度计输出的积分, 可以计算得出被测加速度计的灵敏度。利用这种标定方法, 测试了一种压阻式单片集成三轴高 g 加速度计的 Z 轴单元和 X 轴单元的灵敏度, 测试结果分别为 $(2.18 \mu\text{V}/g)/5 \text{ V}$ 和 $(2.15 \mu\text{V}/g)/5 \text{ V}$ 。这一测试结果与利用自由落杆测试系统得出的测试结果基本吻合, 表明本文所采用的测试系统及实验数据处理方法是可信的。

关键词: 高 g 加速度计; 压阻加速度计; 霍普金森杆

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Characterization of triaxial piezoresistive high- g accelerometer by Hopkinson bar method

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Abstract: The characterization of a triaxial piezoresistive high- g accelerometer by a Hopkinson bar and a data processing method are discussed. After fixing the accelerometer on the end of a calibration bar, the projectile launched from a barrel strikes the calibration bar at a high speed. The impact propagates in the calibration bar in the form of stress wave, which is recorded by a strain gauge fixed in the middle of the calibration bar. The sensitivity of the accelerometer can be obtained by comparing the output of the strain gauge and the integral of the accelerometer output. Using this method, the sensitivities of the Z -axis element and X -axis element of a monolithic triaxial piezoresistive high- g accelerometer is characterized by $(2.18 \mu\text{V}/g)/5 \text{ V}$ and $(2.15 \mu\text{V}/g)/5 \text{ V}$, respectively. The test results are coincident with the previous results by dropping-bar test system, which shows that the characterization

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system and the data processing method used in this paper are reliable.

Key words: high- g accelerometer; piezoresistive accelerometer ; Hopkinson bar

1 Introduction

For assessment and analysis of structural destroy, rupture and collision process, high- g accelerometers are in demand^[1-2]. The measure range can be as high as tens of thousands of gravities. Triaxial accelerometers are frequently needed for simultaneously detecting the three-dimensional vectors of acceleration. A monolithically integrated triaxial piezoresistive accelerometer for 50 000 – 100 000 g measure range has been developed^[3].

As the measure range of high- g accelerometer is much higher than that of low- g accelerometer, the characterization method of high- g accelerometer is very different. To characterize a high- g accelerometer, high shock needs to be generated. With instruments of the laboratory in Shanghai Institute of Microsystem and Information Technology, the developed high- g accelerometer has been characterized by dropping-bar testing system and Dongling shocking machine^[3-4]. But the highest shock generated by the dropping-bar testing system and Dongling shocking machine is only 50 000 g . To characterize the accelerometer in a wider range up to 100 000 g or even higher, the Hopkinson bar method should be adopted.

2 Hopkinson bar characterization system

The Hopkinson bar method has been studied by many researchers^[5-7]. The schematic and the package of the high- g accelerometer to be characterized are shown in Fig. 1 and Fig. 2. The characterization system is schematically shown in Fig. 3. The projectile is launched from the

barrel by the air compressor and strikes the calibration bar. Then a stress wave will be generated and propagates in the calibration bar. By changing the pressure of the air compressor, the velocity of the projectile can be adjusted. The pulse shaper fixed in the head of the calibration bar is used to adjust the shape of the shock pulse. The propagation of the stress wave can be recorded by the strain gauge in the middle of the calibration bar. The test accelerometer is fixed in the end of the calibration bar. The output of the strain gauge and the accelerometer are both acquired by the oscilloscope and processed by the computer.

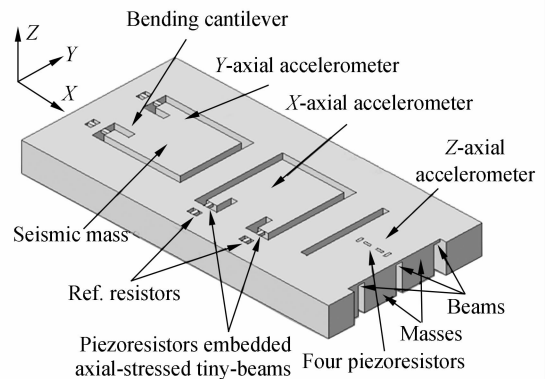


Fig. 1 Schematic of triaxial piezoresistive high- g accelerometer

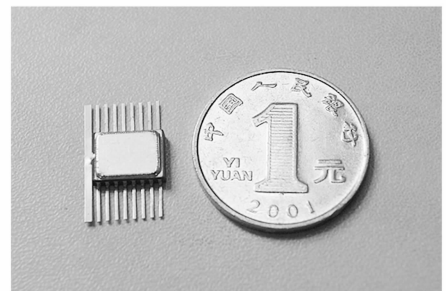


Fig. 2 Packaged accelerometer

The material of the bar is aluminium. The length of the bar is 1.8 m and the diameter is 2 cm. The diameter of the bar is much smaller

than the length. Therefore, the attenuation and the dispersion of the stress wave can be neglected. The relationship between the velocity of the end of the calibration bar and the strain recorded by the gauge is:

$$v = 2c\epsilon, \quad (1)$$

where: c is the propagation velocity of the stress wave, $c = \sqrt{E/\rho}$, E is the Young's module of the bar material and ρ is the density.

The strain of the calibration bar can be deduced from the output of the gauge:

$$\epsilon = \frac{2\mu_\epsilon}{k_1 k_2 U_\epsilon}, \quad (2)$$

where: u_ϵ is the output of the strain gauge, k_1 is the sensitivity of the strain gauge bridge, k_2 is the coefficient of the amplifier and U_ϵ is the driving voltage of the strain gauge bridge.

The acceleration of the end of the calibration bar can be deduced from the output of the accelerometer:

$$a = \frac{u_a}{k_a s}, \quad (3)$$

Where: u_a is the output of the accelerometer, k_a is the amplify coefficient of the interface circuit and is the sensitivity of the accelerometer to be characterized.

The velocity should be the same as the integral of the acceleration. Then, the sensitivity of the accelerometer can be deduced from the above three equations:

$$s = \frac{k_1 k_2 U_\epsilon \int u_a dt}{4ck_a u_\epsilon}, \quad (4)$$

It should be noted that it will cost a short time for the stress wave to propagate from the strain gauge to the accelerometer. This time is neglected in the description form of the above equations and it will not affect the deduction of the equations.

Fig. 4 shows the simplified schematic of the original characterization system that we used before. It is a little different from the one shown in Fig. 3. There are two bars in the original system; the incident bar (the calibration bar in

Fig. 3) and the transmission bar. The accelerometer is fixed between the two bars. The stress wave generated by the strike of the projectile will propagate in the incident bar and be transmitted to the transmission bar through the accelerometer. In theory, the characterization results will be more accurate if the strain recorded by the gauge fixed in the transmission bar is adopted to calculate the sensitivity of the accelerometer. As shown in Fig. 2, the accelerometer is ceramic packaged. Ceramic is a kind of fragile material, then high shock will break the package easily. In the future, the high-g accelerometer could be packaged with stainless steel material. Then the system in Fig. 4 could be used to characterize the high-g accelerometer.

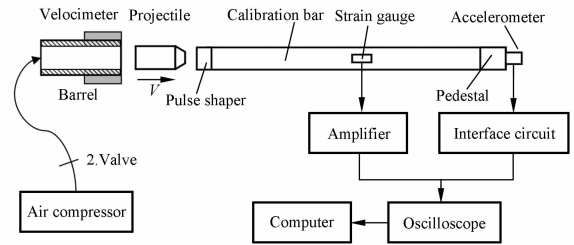


Fig. 3 Schematic of Hopkinson bar characterization system

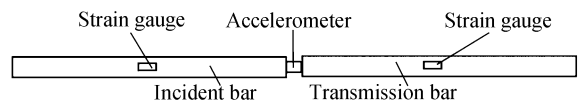


Fig. 4 Simplified schematic of original characterization system

3 Characterization results

The sensitive direction of the Z-axis element is perpendicular to the accelerometer plane. When characterizing the sensitivity of Z-axis element, the fixing configuration is simple. There is no need of the pedestal shown in Fig. 4. The accelerometer can be directly fixed in the end of the calibration bar with Z-axis along the length direction of the bar, which is shown in Fig. 5.

The sensitive directions of X- and Y-axes are

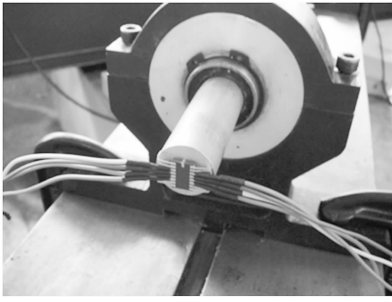


Fig. 5 Fixing configuration for characterizing Z element

perpendicular to each other. They are both parallel to the accelerometer plane. When characterizing the sensitivities of X - and Y -axes elements, the fixing configurations are almost the same. Take the characterization of the X -axis element as an example. A pedestal is fixed in the end of the calibration bar. There is a plane and a concave machined on the pedestal in order that the accelerometer can be fixed in the concave with the sensitive direction along X -axis, which is shown in Fig. 6. The accelerometer should be fixed as near as possible to the end of the pedestal to make the characterization results more accurate.

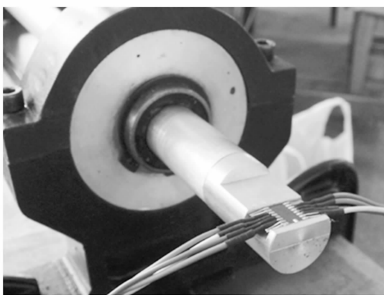


Fig. 6 Fixing configuration for characterizing X element

Fig. 7 shows a typical shock pulse when characterizing Z -axis element. The velocity of the projectile measured by the velocimeter is 8.3 m/s. The purple line is the output of the strain gauge and the black line is the output of the accelerometer.

In the four equations in section 2, $k_1 = 1.95$, k_2

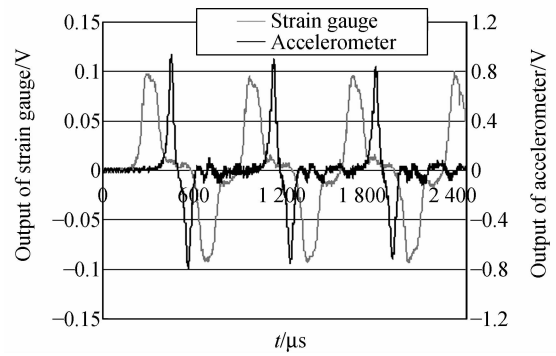


Fig. 7 Outputs of strain gauge and accelerometer

$= 9.64$, $U_\epsilon = 11.96$ V, $k_a = 23$. Then the velocity of the end of the bar can be deduced from the output of strain gauge. The integral of the accelerometer can also be calculated. In Fig. 8, the purple line shows the velocity of the end of the bar and the black line shows the integral of the accelerometer output.

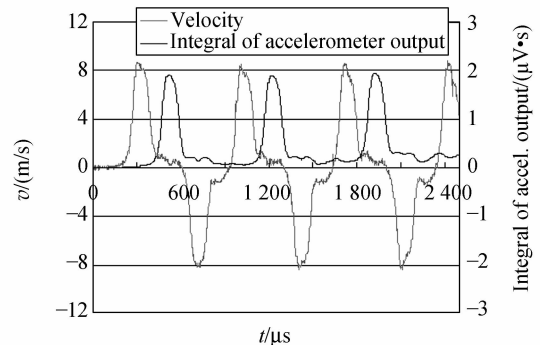


Fig. 8 Calculated velocity and the integral of accel. output

The Young's module of aluminium is 70 GPa. The density is 2 700 kg/m³. Then the velocity of the stress wave in the calibration bar can be calculated from the equation $c = \sqrt{E/\rho}$, i. e. , 5 092 m/s. The length parameters of the Hopkinson bar characterization system are shown in Fig. 9. The distance between the strain gauge and the accelerometer is about 1 m. The theoretical time period for the stress wave to propagate from the strain gauge to the accelerometer can be calculated as $t = L_1/c = 196$ μ s. This time period has good accordance with the one obtained in Fig. 8.

From Fig. 8, it can also be concluded that the attenuation and the dispersion of the stress wave can be neglected, which accords with the theory of stress wave very well.

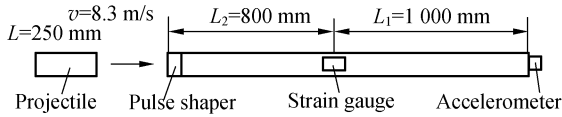


Fig. 9 Length parameters of Hopkinson bar characterization system

By comparing the two curves in Fig. 8, the sensitivity of Z -axis element of the triaxial high-g accelerometer has been characterized as $2.18 (\mu\text{V}/g)/5 \text{ V}$. The sensitivities of the X and Y axial elements can also be characterized by the same method except that a pedestal is needed between the end of the calibration bar and the accelerometer. The sensitivity of the X axial element is characterized as $2.15 (\mu\text{V}/g)/5 \text{ V}$. The two results are both in general accordance with

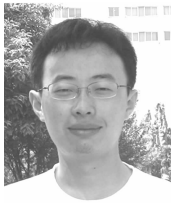
the results in the reference literature^[1]. The sensitivity of Y axial element will be characterized in the following experiment.

4 Conclusion

The Hopkinson bar characterization system and the data processing method are discussed in this paper. A high-performance monolithic triaxial piezoresistive high-g accelerometer was characterized. The sensitivities of the Z -axis and the X -axis elements were characterized as $2.18 \mu\text{V}/g/5 \text{ V}$ and $2.15 \mu\text{V}/g/5 \text{ V}$ respectively, which are both in general accordance with the previous results that were characterized by dropping-bar test system. In the following experiments, the sensitivity of Y axial element, the cross-axis sensitivity and the linearity of the triaxial high-g accelerometer will be characterized. Mount has great effects on the characterization of high-g accelerometers. This effect will also be studied in detail in the future work.

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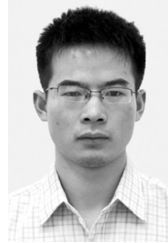
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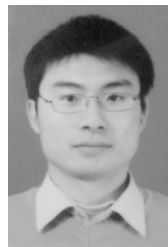
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