Design of a Large Measurement Range Piezoelectric Accelerometer

ZHANG Zhong- cai, Yang Li-ming, CHENG Yong-sheng

Abstract—**Piezoelectric accelerometers are used to measure vibration and impact acceleration. In this paper we develop a piezoelectric accelerometer, which can measure the acceleration of a object with high velocity (which is called the measured object) in impact environment. Based on the physical model of accelerometer, the mechanical model is established, and the main factors influencing on the natural frequency are analyzed. With the nonlinear transient dynamics finite element analysis sofeware Msc.dytran, the dynamic stress of the transducer fixed on the measured object has been simulated. The measurement results show that the developed sensor has a measurement range of 100,000g and response frequency of 8 kHz.**

***Index Terms*—piezoelectric accelerometer, response frequency, Msc.dytran**

I. Introduction

A piezoelectric accelerometer is a sensor which can convert mechanical energy to electric charge, and be used to measure shock, vibration and linear acceleration. In engineering the sensor can not only measure the size of the acceleration amplitude, but also reproduce the signal waveform accurately. Due to the acceleration of high-speed impact in a high frequency, the sensor must have a high response frequency. In high-speed impact environment, the force loaded on the sensor is large, a general piezoelectric accelerometers' measurement range and shock resistance can not meet project requirements. In order to develop a piezoelectric accelerometer with large measurement range and high shock resistance, the dynamic stress of the piezoelectric material need to be analyzed. In this paper, with the nonlinear transient dynamics analysis software Msc.dyran[1,2], the piezoelectric sensor is simulated. Key components' (eg, piezoelectric material) dynamic stress can be simulated effectively in the high-speed impact environment, influence of different materials matching on the piezoelectric material's dynamic stress is also simulated. The experimental results show that this method is feasible.

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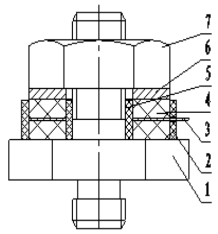
II. Structure and Principle

For measurement in high-speed impact, piezoelectric sensors with central compression are mainly used. This type of piezoelectric sensors is researched in this paper, and its schematic is shown in Figure 1.



7-pre-tightening nut
6-seismic mass
5-insulator 2
4-piezoelectric material
3-conductive plate
2-insulator 1
1-base

Fig1. Schematic of the piezoelectric accelerometer

The sensor moves with the measured object movement. When the inertia force of seismic mass loads on the piezoelectric material, piezoelectric material will produce electric charge proportional to the inertia force.

III. Mechanical Model and Frequency Response

A. Mechanical model

The sensor is a typical single degree of freedom second-order system. In fact, the sensor is a multi-degree-of-freedom system. The frequency response of the sensor is about one-fifth to one-third of the natural frequency. The high frequency response means high natural frequency. To calculate the sensor's natural frequency, it is necessary to establish its mechanical model, the dynamics equations are as follows:

$$[M][\ddot{Y}]+[C][\dot{Y}]+[K][Y]=[P] \quad (1)$$

Where [M] is mass matrix, [Y] is displacement matrix, [C] is damping matrix, [K] is stiffness matrix, [P] is external force matrix. By calculating (taking no account of damping) the following equation

$$|K-\lambda^2 M|=0 \quad (2)$$

The positive real roots of λ can be calculated, the minimum root is called fundamental frequency which is the natural frequency of the sensor.

The assumption is that all the contact surfaces of components are smooth, without considering the effects of contact stiffness. The conductive plates are thin, so they are regarded as rigid bodies. Other parts are as elastic objects. The equivalent mechanical model is shown in Figure 2.

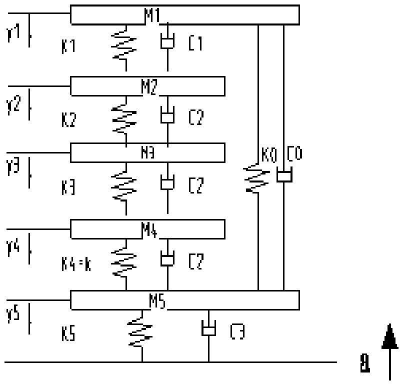


Fig2. Mechanical model of the piezoelectric accelerometer

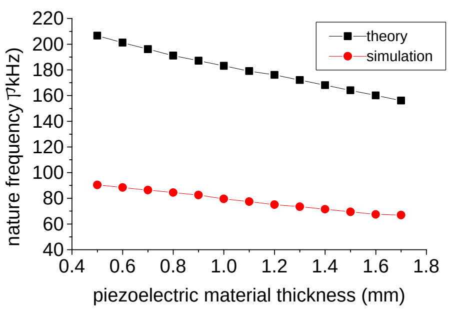
Equations of motion can be written in the form below:

$$\begin{bmatrix} M_1 & & & & \\ & M_2 & & & \\ & & M_3 & & \\ & & & M_4 & \\ & & & & M_5 \end{bmatrix}\begin{bmatrix}\ddot{y}_1\\ \ddot{y}_2\\ \ddot{y}_3\\ \ddot{y}_4\\ \ddot{y}_5\end{bmatrix}+\begin{bmatrix} c_0+c_1 & -c_1 & 0 & 0 & -c_0 \\ -c_1 & c_1+c_2 & -c_2 & 0 & 0 \\ 0 & -c_2 & c_2+c_3 & -c_3 & 0 \\ 0 & 0 & -c_3 & c_3+c_4 & -c_4 \\ -c_0 & 0 & 0 & -c_4 & c_0+c_4+c_5 \end{bmatrix}\begin{bmatrix}\dot{y}_1\\ \dot{y}_2\\ \dot{y}_3\\ \dot{y}_4\\ \dot{y}_5\end{bmatrix}$$

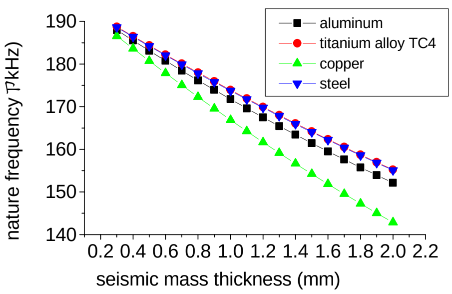
$$+\begin{bmatrix} k_0+k_1 & -k_1 & 0 & 0 & -k_0 \\ -k_1 & k_1+k_2 & -k_2 & 0 & 0 \\ 0 & -k_2 & k_2+k_3 & -k_3 & 0 \\ 0 & 0 & -k_3 & k_3+k_4 & -k_4 \\ -k_0 & 0 & 0 & -k_4 & k_0+k_4+k_5 \end{bmatrix}\begin{bmatrix}y_1\\ y_2\\ y_3\\ y_4\\ y_5\end{bmatrix}=\begin{bmatrix}M_1a\\ M_2a\\ M_3a\\ M_4a\\ M_5a\end{bmatrix} \quad (3)$$

Where M_i is equivalent mass, which is about 1/3 of a component mass [4].

B. *Main factors affecting frequency response*



(a) Effect of the piezoelectric material



(b) Effect of the seismic mass

Fig 3. Nature frequency versus the thickness of piezoelectric material and seismic mass

Without considering the contact stiffness, some conclusions that the structure and material of the base, piezoelectric material, seismic mass etc can affect the nature frequency can be drawn by calculating. For a large measurement range sensor, the piezoelectric materials is often quartz. The thickness of the quartz and seismic mass has a great effect on the natural frequency of sensor. For the sensor structure in this paper, by theoretical calculating and Ansys modal analysis respectively, the relative curve of nature frequency and the thickness of piezoelectric material is obtained and shown in Figure 3 (a). It can be seen that the natural frequency increases when quartz thickness decreases. The relative curve of nature frequency and the thickness of seismic mass are shown in Figure 3 (b), in which the materials of seismic mass are steel, titanium alloy TC4, copper and aluminum respectively. It shows that the natural frequency increases when the thickness of seismic mass decreases. The nature frequency is higher when the material is steel. In order to have a wide flat resonance response, the thickness of piezoelectric material or seismic mass should be thin.

IV. DYNAMICS SIMULATION

A. *Finite element model*

With msc.dytran the impact process can be simulated. The sensor, the measured object (and other components) and the target are symmetric structure, so 1 / 4 model can be used to simulate in order to save computer resources. According to the sensor installed on the measured object, the finite element model is established. The target is a 10mm thick steel(40Cr) plate, an area of 200 × 200mm2. The finite element model [3-5] of impact system is shown in Figure 4. The finite element model of the sensor is shown in Figure 5. All the finite elements are 6 surface element (CHEXA), whose performance is good. The length unit is millimeter. The quality unit is kilogram. The time unit is millisecond.

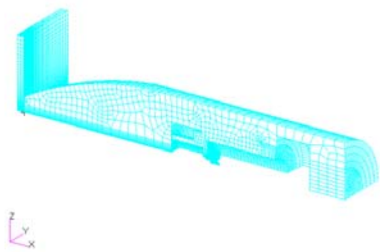


Fig4. The FEM model of the impacting system

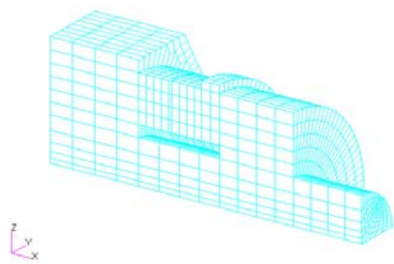


Fig5. The FEM model of the sensor

Boundary conditions are as follows: all nodes of the plate margin have restriction with 6 degree freedom. The measured object impact the target in the x direction. As a result of using 1 / 4 model, all nodes in perpendicular to the y-axis (or z axis) profiles should have a displacement constraint in y (or z) direction. The impact process is armor-piercing (or penetration). The contact between the measured object and the target is defined as the adaptive master-slave contact [2,3]. The measured object is defined as the master surface. The target is defined as the slave surface.

Initial conditions: the speed of the measured object in the X direction is -1000m/s.

B. Material mode

For simplicity, an ideal elastic-plastic model is used. "Elastic-plastic+damage" material model is used. Yield model is the von Mises yield model. Failure model is the largest plastic strain. The material of the measured object is high strength steel. The basic material properties used is shown in table 1.

Table1. Material parameters

Material	Young's modulus (GPa)	Poisson ratio	Density (kg/m^3)	Yield strength (MPa)	Maximum plastic strain
40Cr	200	0.3	7.8×10^3	800	2.0
quartz	86.74	0.23	2.65×10^3	98	0.5
copper	120	0.34	8.9×10^3	200	2.0
high strength steel	200	0.3	7.8×10^3	1100	2.0
aluminum	70	0.3	7.8×10^3	260	2.0
Titanium alloy TC4	113	0.32	4.7×10^3	950	2.0

C. Simulation

The material of the measured object is titanium alloy TC4. The material of the base is steel. The thickness of quartz is 1mm. The simulation begins when the distance between the measured object and the target is 1mm.

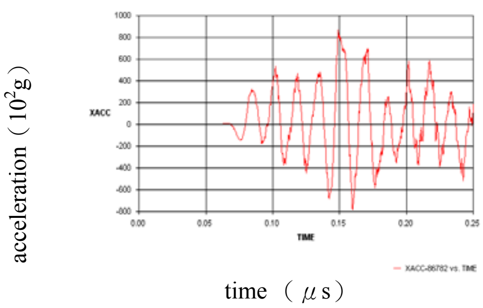


Fig6. Variation of acceleration with time

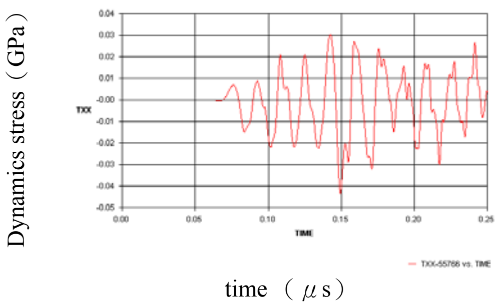


Fig7. Variation of dynamics stress with time

The acceleration-time curve of quartz in 0.25ms is shown in Figure6. The maximum acceleration amplitude is approximately 90,000g. The dynamics stress-time curve in the x direction of quartz is shown in Figure 7 (tensile stress is positive, compressive stress is negative). The trend of two curves is basically the same. The maximum dynamics stress is about 42.5MPa.

For the structure studied in this paper, by simulation the relationship of the maximum dynamics stress and the quartz thickness is shown in Figure 8. For this structure, the dynamics stress of quartz is minimum when the thickness is 1mm.

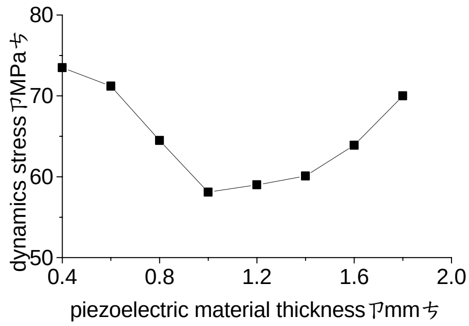


Fig8. The relationship between dynamics stress and transducer thickness

D. Effects of materials matching on dynamics stress

Whether material's acoustic impedance ($\rho_0 C_0$) is matched has a great impact on the dynamics stress of the quartz. When material changes, the reflection and transmission intensity of stress wave will change, also the time and location of stress wave superposition will change. The quartz is 1mm thick, under the same impact conditions, some materials in Table 1 are selected to analyze the effect of the measured object and the base material on the dynamics stress of the quartz. The results is shown in table 2.

Table2. Simulation results

The measured object-base	Steel -steel	Steel -TC4	Steel -copper	Steel -aluminum
Dynamics stress (MPa)	-31.0	-23.5	-38.0	-17.0
The measured object-base	Copper -steel	Copper - TC4	Copper - TC4	Copper -aluminum
Dynamics stress (MPa)	-24.0	-24.0	-25.0	-22.5
The measured object-base	TC4 -steel	TC4 -TC4	TC4 -copper	TC4 -aluminum
Dynamics stress (MPa)	-42.0	-41.0	-46.0	-32.0
The measured object-base	Aluminum -steel	Aluminum - TC4	Aluminum -copper	Aluminum -aluminum
Dynamics stress (MPa)	-56.0	-45.0	-58.0	-42.5

V. Experimental Results

The experiments were completed on the dropping hammering shock machine. The sensor's signal was transmitted to oscilloscope through the charge amplifier. Quartz thickness was 0.4,0.6,0.8,1.0,1.2,1.4,1.6,1.8 mm respectively, the tooth number is 23.

Table3. The experimental results

The measured object-base	Steel -steel	Steel -TC4	Steel -copper	Steel -aluminum
Acceleration (10,000g)	7.57	6.77	8.32	6.08
The measured object-base	Copper -steel	Copper - TC4	Copper - TC4	Copper -aluminum
Acceleration (10,000g)	6.83	6.83	6.93	6.67
The measured object-base	TC4 -steel	TC4 -TC4	TC4 -copper	TC4 -aluminum
Acceleration (10,000g)	8.50	8.41	8.82	7.68
The measured object-base	Aluminum -steel	Aluminum - TC4	Aluminum -copper	Aluminum -aluminum
Acceleration (10,000g)	8.97	8.76	9.12	8.80

When the quartz is 1mm thick, the sensor output voltage is minimum, which means the stress of quartz is small corresponding to the simulation results. Commutators (the measured objects) with different materials were mounted on the hammer, the sensor was mounted on the commutator. The quartz thickness is 1mm, the material of the commutators and the bases are steel, titanium alloy TC4, copper and aluminum respectively. Results are shown in Table 3. The experimental results and simulation results are close, which indicates the method employed in this paper is correct.

According to engineering applications, stainless steel base is better, the sensor prototype is in Figure 9. The sensor (quartz thickness is 1mm) was calibrated on Hopkinson bar. The test curve is shown in Figure 10. It can be seen that the measurement range is up to 100,000 g and the impact limit is 120,000 g. The frequency response is 8 kHz, which is tested on B&K Corporation Vibration Transducer Calibration System Type 9610.

Fig 9.The sensor prototype

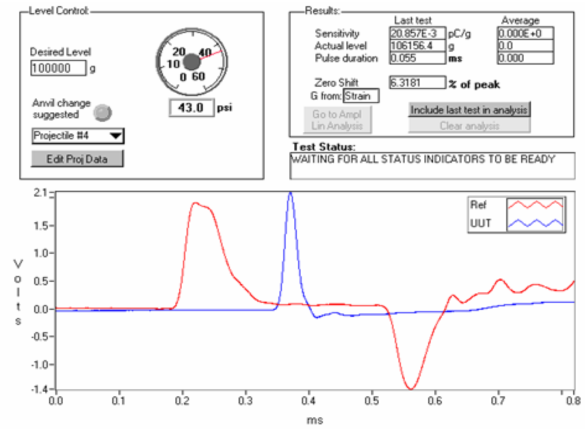


Fig 10.The test curve of calibration

VI. Conclusions

Through simulation and experiments, some conclusions as the following:

1) The thickness of the piezoelectric material and seismic mass has a great effect on the natural frequency of sensor.
2) For this structure in this paper, the best thickness of quartz is 1.0mm.
3) In our research when the measured material is steel or copper, the stress of quartz is smaller. When the base material is aluminum , and the stress of quartz is smallest. These material matching will help improve the measurement range and impact limit of the sensor. From the application point of view, the measured objects and the base material should be chosen properly to improve the performances of the sensor.

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