A Novel PVDF Based High G\textsubscript{n} Shock Accelerometer

Wu zutang\textsuperscript{1,2}, Shao Xianzhong\textsuperscript{2}, Jiang Zhuangde\textsuperscript{1}, Li Peng\textsuperscript{2}, Ge Lin\textsuperscript{2}, Jiang Xingdong\textsuperscript{2}

\textsuperscript{1}Institute of Precise Engineering, Xi’an Jiaotong University, Xi’an, CHINA
\textsuperscript{2}Northwest Institute of Nuclear Technology, POBox 69-8, Xi’an, CHINA, 710024

E-mail: wuzutang@163.com

Abstract. High-Gn accelerometers are always used in explosion and shock measurement. The principle and solution of high-Gn piezoelectric accelerometers are introduced in detail. Focusing on piezoelectric material, structure model and assembling techniques, we investigated high G\textsubscript{n} accelerometers with compression mode, with an energy converter made of novel piezoelectric material PVDF. The dynamic range and operating frequency range are within 50000-Gn and 15 kHz respectively. The shock tests indicated that the characteristics of waveforms acquired from test were similar to those of ready commodities. It can be used for specific test conditions during explosion and shock process.

1. Introduction

High-Gn accelerometers are widely used in explosion and shock test. However, the acceleration environment experienced by the sensors and electronics in an earth penetrating weapon is extreme, with average accelerations in the 20000-Gn range and peak transient accelerations up to several hundred thousand G\textsubscript{n’s}. The commercially available accelerometers used in shock testing of earth penetrating weapons components are both expensive and prone to failure. In our research work, the acceleration is always from 10000-Gn to 100000-Gn, and valid signal’s frequency is about 5 kHz. So we need to develop a new high-Gn accelerometer which would be capable of surviving and measuring high-Gn shock with dynamic range above 10000-Gn and operating frequency within 15 kHz.

A piezoelectric accelerometer is widely used in explosion and shock measurement. The principle and solution of high-Gn piezoelectric accelerometer are introduced in detail in this paper. Focusing on piezoelectric material, structure model and assembling techniques, we have studied an inertial mass’ accelerometer using the PVDF in thickness. Figure 1 shows us the structure modes we’ve adopted.

Figure 1. the Compression Mode of High G\textsubscript{n} Accelerometer
2. Basic Principle and Solutions of High-Gn Accelerometer Based on PVDF

2.1. Piezoelectricity and Piezoelectric Matrix
Piezoelectric accelerometers rely on the piezoelectric effects of quartz or ceramic crystals to generate an electrical output that is proportional to applied acceleration. The piezoelectric effect produces an opposed accumulation of charged particles on the crystal. This charge is proportional to applied force or stress. A force applied to a quartz crystal lattice structure alters alignment of positive and negative ions, which results in an accumulation of these charged ions on opposed surfaces. These charged ions accumulate on an electrode that is ultimately conditioned by transistor microelectronics.

Let $T$ stands for stress and $S$ for strain respectively, the piezoelectric matrix can be expressed as:

$$
\begin{align*}
S &= s^T + dE \\
D &= dT + e' E
\end{align*}
$$

Where, $s^E$ is normal elastic compliance ($m^2/N$), $e'$ for normal dielectric constant ($F/m$), $d$ for normal piezoelectric constant ($C/N$), $D$ for normal electric displacement ($C/m^2$), $E$ for normal electric field ($V/m$).

2.2. Principle of Piezoelectric Accelerometer
In an accelerometer, the stress on the crystals occurs as a result of the seismic mass imposing a force on the crystal. Over its specified frequency range, this structure approximately obeys Newton's law of motion. Therefore, the total amount of accumulated charge is proportional to the applied force, and the applied force is proportional to acceleration.

The piezoelectric element, modeled by a spring with a stiffness constant $k$ and viscous damping $c$, is disposed between a seismic mass $m$ and the body of sensor, as shown in figure 2.

![Figure 2. Principle of Accelerometer with Seismic Mass](image)

The absolute position of the body is $x(t)$ and its acceleration, which we want to measure, is $a(t) = d^2 x / dt^2$. Further, the absolute position of the mass $m$ is $x_m(t)$ and the relative position between the mass and the body is $x_m(t) - x(t)$. We assume that the model is linear, so the following study will be executed in dynamic rate, without taking into account static rate: pre-stress due to the weight of the mass to the anchor elements.

Newton's law applied to the mass $m$ for little variations and projected to the motion axis gives the following equation:

$$
m \frac{d^2 x_m}{dt^2} = -c \frac{d(x_m - x)}{dt} - k(x_m - x) \quad (2)
$$

The relation shows that $a(t)$ is only a function of $x_m(t) - x(t)$. Yet, the modeling of the piezoelectric element by a spring implies that $x_m(t) - x(t)$ is tied to the applied force $F$ by:

$$
F = k_y(x_m - x) \quad (3)
$$

When a force is applied, the piezoelectric effect allows us to obtain an electric quantity, which gives us an estimate of $a(t)$.

2.3. Solutions of High-Gn Piezoelectric Accelerometer
The basic request of acceleration signal test is that the sensor’s intervention should not change the characteristic of vibration mode of the structure to be measured. So the mass of a high-Gn
accelerometer to be used should be as small as possible with wide dynamic range and high operating frequency.

Cable whip can introduce noise, especially in high impedance signal paths. This phenomenon is known as the tribo-electric effect. Also, cable strain near either electric connector can lead to intermittent or broken connections and loss of data. So the cable should be securely fastened to the mounting structure with a clamp, tape or other adhesive to minimize cable whip and connector strain.

The solder connector adapter provides an affordable and simplistic method for making cables in the field. Only solder and a soldering iron are required.

3. Experimental Results and Discussion

3.1. Experimental Conditions

3.1.1. The Drop Hammer Shock Machine
The principle of drop hammer shock machine is to convert the dropping potential to kinetic energy and then convert the kinetic energy to a load force. The frame of machine is shown in figure 3. We can get variable peak acceleration according to different weight and height of dropping hammer. Table 1 is the Peak acceleration of drop hammer shock machine.

![Figure 3. Frame of the Drop Hammer Shock Machine](image)

![Figure 4. Frame of the Measurement System](image)

| Tooth number | 2  | 3  | 5  | 10 | 15 | 23 |
|--------------|----|----|----|----|----|----|
| m_p=1kg; m_c=0.685kg; m_total=1.685kg | 5327 | 6875 | 9510 | 11720 | 20675 | 40000 |
| m_p=0.61kg; m_c=0.744kg; m_total=1.384kg | 6755 | 9320 | 11440 | 16480 | 24390 | 50400 |
| m_p=0.4kg; m_c=0.754kg; m_total=1.154kg | 6590 | 8420 | 12260 | 18580 | 28790 | 64540 |

3.1.2. Measurement system
The configuration of measurement system is shown in figure 4. The charge amplifier model is YE5862 with the limitation of input charge is 1000000 pC, 100 kHz band width and ±10 Vp/10mA output capabilities. The oscilloscope model is TDS460A. The maximum sampling frequency is 10 MS/s with 120K record length.

3.2. Experimental Results
In order to examine the characteristics of the high Gn accelerometers we have studied based on PVDF. A number of dynamic performance tests were completed on the dropping hammer shock machine shown in figure 3. Table 2 shows us the difference properties among 8 accelerometers base on PVDF.

![Table 1. Peak Acceleration of Drop Hammer Shock Machine (Unit: Gn)](image)

| No    | Sensitivity pC/Gn | Horizontal sensitivity < % | Dynamic range < Gn | Freq. Range < kHz |
|-------|-------------------|----------------------------|--------------------|------------------|
| PVDF-1| 0.421             | 5.1                        | 50000              | 30               |
| PVDF-2| 0.317             | 4.9                        | 60000              | 25               |
| PVDF-3| 0.091             | 5.2                        | 60000              | 26               |
| PVDF-4| 0.345             | 5.3                        | 60000              | 27               |
| PVDF-5| 0.170             | 5.5                        | 60000              | 23               |
3.3. Application

A number of dynamic performance tests were completed on the dropping hammer shock machine shown in figure 3 and then we compared the waveforms acquired by these sensors with the waveforms acquired by the commercially available accelerometer 988-316. Figure 5 shows the typical waveforms acquired by 988-316, PVDF-1 accelerometer and PVDF-8 accelerometer made by us with different peak shock acceleration. The top one curve is acquired by 988-316, the middle one by PVDF-1 accelerometer and the bottom one by PVDF-8 accelerometer. From the waveforms we can draw the following conclusions: Most accelerometers that we’ve fabricated by ourselves can work normally within 50000-Gn peak shock acceleration.

![Waveforms](image)

(a) peak acceleration 5300-Gn  (b) peak acceleration 9500-Gn  (c) peak acceleration 11700-Gn

(d) peak acceleration 20600-Gn  (e) peak acceleration 28800-Gn  (f) peak acceleration 60000-Gn

Figure 5. the Typical Waveforms Acquired by 988-316, PVDF-1 Sensor and PVDF-1 One

4. Conclusions

The principle and solution of high-Gn piezoelectric accelerometer was introduced in detail. Focusing on piezoelectric material, structure model and assembling techniques, we have studied an inertial mass’ accelerometer using the PVDF in thickness. The dynamic range and operating frequency are within 50000-Gn and 15 kHz respectively. The shock tests indicated that the characteristics of waveforms acquired from test were similar to those of ready commodities. It can be used for specific test conditions.

References

[1] Still Robert D. Testing techniques involved with the development of high shock acceleration sensors [R]. Endevco tech paper TP284

[2] Brady R. Davies, Stephen Montague, Vesta I. Bateman, Frederick A. Brown, Rajen Chanahani, Todd Christenson, James R. Murray, Danny Rey, David Ryerson. High-g accelerometer for earth penetrator weapons applications LDRD final report [R]. SANDIA REPORT 1998-050

[3] Zhang Fuxue. Piezoelectric force and acceleration sensor [M]. Chengdu: Sichuan science and technology publishing house, 1985

[4] Huang Junqin, Gu Jianxiong. Dynamic Calibration Method and System of Ultra High g Accelerometer and Piezoelectric Force Transducer [J]. Acta Metrologica Sinica, 2001, 22 (4) : 300～304

[5] Luo Xianhe, Huang Junqin. Study on dynamic performance repeatability of sensor [J]. Journal of Transducer Technology, 1997, 2: 38～42

[6] Yuan Xiguang. Handbook of transducer [M]. Beijing: Defense industry press, 1986

[7] C.M. Harris, C.E. Cred. Handbook of shock and vibration [M]. Beijing: Science press, 1990