Acquisition and Analysis Technology of Pyroshock Response on Spacecraft

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Abstract. Wide frequency range and high acceleration amplitude are two typical characteristics of transient vibration in the environment of pyroshock on spacecraft. The Piezoelectric accelerometer is widely accepted as the best available transducer for the absolute measurement of vibration. “Ringing” and “Zero Drift” are very easily to occur if the accelerometer is being used to measure transient vibrations outside its useful frequency range. This paper introduced the working principle of piezoelectric accelerometer, the scheme of reducing “Ringing” phenomenon was given, the mechanism of “Zero Drift” phenomenon was analysed. The methods to restrain the “Zero Drift” were discussed from the aspects of the selection of test equipment, the installation of piezoelectric accelerometer and the setting of data acquisition parameters. Finally, the wavelet analysis method was used to decompose and reconstruct the distortion data caused by “Zero Drift”, and the effective pyroshock response signal was extracted.

1. Introduction
A large number of pyrotechnic devices are used on the spacecraft in order to meet some specific needs, such as separation of satellites and launch vehicles, deployment of solar arrays, etc. The actions of these pyrotechnic devices will cause high-frequency shock response on the spacecraft structure, and will have a destructive effect on brittle materials and electronic products, which must be evaluated effectively. The recurrence of the pyroshock response can provide an important basis for the designer, and the test requirements are getting higher and higher.

The test of structural response under pyroshock environment belongs to the category of transient response test. When selecting the sensor, its linearity must be considered, otherwise the reproduced shock response will be distorted. The piezoelectric accelerometer has excellent linearity over a very wide dynamic range and usable over very wide frequency range. Compact structure, small size, no moving parts, durable, and wide frequency range are the advantages of it, also the acceleration signal can be electronically integrated to provide velocity and displacement data. Based on above advantages, the piezoelectric accelerometer is widely accepted as the best available transducer for the absolute measurement of vibration.

2. Working principle of piezoelectric accelerometer
The structure of the piezoelectric accelerometer is shown in Figure 1. When the sensor moves with the measured object, the sensitive element is deformed by the inertial force of the mass. According to the
piezoelectric effect, the sensitive element generates a charge proportional to the force\(^1\).

![Figure 1. Structure and classification of piezoelectric accelerometers](image)

1- Shell, 2- Spring, 3-Seismic mass, 4-Output, 5- Piezoelectric element, 6- Accelerometer base; a-Compression design, b-Single-ended compression design, c-Base isolated compression design, d-Annular shear design, e-Center mounted annular shear design, f-Isolated shear design.

Piezoelectric accelerometers can be regarded as voltage sources or charge sources. The piezoelectric element can be equivalent to a capacitor \(C_a\). Its internal leakage resistance is \(R_a\). The equivalent circuit is the parallel connection of the capacitance and the leakage resistance, as shown in Figure 2

![Figure 2. Equivalent circuit of piezoelectric accelerometer](image)

Due to the high impedance of the piezoelectric crystal, the piezoelectric accelerometer should be connected to a preamplifier with a very high input impedance and a low output impedance. Taking the equivalent capacitance and equivalent resistance of the cable and preamplifier as the load of the accelerometer, in Figure 2, the capacitance of equivalent circuit becomes \(C_r\) and the resistance becomes \(R\). Among them, \(C_r = C_a + C_v + C_p\); \(C_a\) is the electrode capacitance of the piezoelectric accelerometer; \(C_v\) is the capacitance of the connecting cable, \(C_p\) is the input capacitance of the charge amplifier, \(\frac{1}{R} = \frac{1}{R_a} + \frac{1}{R_c} + \frac{1}{R_p}\); \(R_a\) is the leakage resistance of the insulation layer of the accelerometer, \(R_c\) is the resistance of the cable and the connecting plug; \(R_p\) is the input resistance of the preamplifier.

3. Transient capture

Shock is a sudden release of energy. The duration is extremely short and the vibration acceleration can reach a very high level. Therefore, this signal contains a wide frequency component. The linearity of the measurement system is limited by both high frequency and low frequency. When the high
frequency limit is not enough, "Ringing" will occur. When the low frequency limit is not enough, the measurement result will have Zero Drift, as shown in Figure 3.

3.1 "Ringing" phenomenon
The Ringing phenomenon is due to the high frequency components in the shock signal being close to or equal to the resonance frequency of the accelerometer, which arouses the resonance of the accelerometer itself. Using a mechanical filter to install the accelerometer, or using a preamplifier with a low-pass filter, can reduce the Ringing phenomenon to some extent. If the preamplifier method is used, the low-pass filter of the preamplifier must be required to have a high frequency attenuation slope of 12dB/oct, and its -3dB upper limiting frequency $f_u$ is half of the accelerometer resonance frequency $f_m$, that is $f_u = 0.5 f_m$. Then the amplitude error of the transient signal with an impact time of $T = 1/ f_u$ is less than 10%, as shown in Figure 4.

3.2 Zero Drift
The Zero Drift of the shock sensor refers to a potential difference between the sensor output zero point before and after the sensor is subjected to a large shock signal. This potential difference will gradually decrease over time and return to the original zero position. The mechanism is that the piezoelectric elements are not considered to be perfectly elastic materials, then when the force on the element is suddenly decreased, the structure may not all return to the state they were in before the shear force was applied. Therefore, when the force is removed the elements still produce a charge which slowly decays with time as the preamplifier output returns to zero at a rate determined by its Lower Limiting Frequency.
3.2.1 The mechanism of Zero Drift. The pyroshock can be expressed by a sawtooth shock wave whose formula is [2]:

\[
a(t) = \begin{cases} \frac{A}{\tau}t & 0 \leq t \leq \tau \\ 0 & \text{else} \end{cases}
\]

(1)

The impact waveform and output of piezoelectric accelerometer are shown in Figure 5:

![Figure 5. Sawtooth shock wave and output waveform of piezoelectric accelerometer](image)

The loop equation obtained from the circuit in Equation 2 is [3]:

\[
I = C_T \frac{de_f}{dt} + \frac{e_f}{R} = \frac{Q_E}{t} = \frac{S_q \ast a}{t}
\]

(2)

Bring in the initial conditions: \(t=0\), \(e_f = 0\)

\[
e_f = \frac{S_q AR}{\tau}(1 - e^{\frac{-t}{RC}}) \quad 0 \leq t \leq \tau
\]

(3)

When \(t = \tau\), the theoretical voltage of the sawtooth wave is:

\[
E = \frac{S_q A}{C_T}
\]

(4)

The maximum voltage deviation is:

\[
\Delta E = \frac{S_q A}{C_T} (1 - \frac{RC}{\tau} (1 - e^{\frac{-\tau}{RC}}))
\]

(5)

Let \(y = \frac{\Delta E}{E}\), \(x = \frac{RC}{\tau}\), then \(\lim_{x \to \infty} y = 0\)

![Figure 6. Deviation trend of output voltage](image)
Figure 6 shows the relationship between x and y. It can be seen that the greater the $RC_T$, the smaller the voltage deviation. When $RC_T \geq 10\tau$, the Zero Drift deviation is controlled within 5%. Theoretically, there are two solutions to enhance $RC_T$:

1. Increase the length and capacitance $C_e$ of the test cable, but this will reduce the voltage sensitivity and lose a certain dynamic range.
2. Adopt a preamplifier with high input resistance.

3.2.2 Sensor installation and parameter setting. In order to reduce the possibility of Zero Drift during the test and improve the accuracy of the SRS analysis, on the basis of improving the performance of the equipment, the sensor installation and parameter setting shall try to meet the following requirements:

1. The farther the sensor installation location is from the explosion source, the better the measurement is, and try to avoid near-field installation (see Table 1 for the division of pyroshock environment);
2. It is best to fix the sensor by glue and screw connection at the same time. If conditions permit, a mechanical filter can be used to overcome Zero Drift\[4\][5];
3. The recommended sampling rate is 10 times the highest analysis frequency;
4. Anti-aliasing filtering must be performed before A/D conversion, and the cut-off frequency should be set to 1.5 times of the highest signal frequency;

| Area       | Distance to explosion source /cm | Environmental characteristics | Shock acceleration amplitude /g | Frequency Range /KHz |
|------------|---------------------------------|-------------------------------|---------------------------------|-------------------|
| Line source | Near-field: <15                 | Stress wave propagation       | >5000                           | >100              |
|            | Mid-field: 15-60                | Stress wave and structural response | 1000-5000                     | >10               |
|            | Far-field: >60                 | Structural response           | <1000                          | <10               |

4. Analysis and processing of Zero Drift data
It can be seen from Section 3.2.1 that the Zero Drift phenomenon is caused by the working mechanism of piezoelectric accelerometer, and it is difficult to avoid it completely during shock test. For the distortion data measured by the piezoelectric accelerometer, it is particularly important to remove the Zero Drift component in the signal by signal analysis and processing.

Fourier transform is the most commonly used signal analysis and processing method. However, the Fourier transform is a global transform and cannot reflect the time domain characteristics of the signal. The wavelet transform based on the Fourier transform has the characteristics of multi-resolution analysis. It has the ability to characterize the local characteristics of the signal in both time and frequency domain, and is a local analysis method in time and frequency domain with changeable time window and frequency window. Wavelet transform has high frequency resolution and low time resolution in the low frequency part, and high time resolution and low frequency resolution in the high frequency part. Therefore, the time domain and frequency domain characteristics of the signal can be observed at the same time\[7]. The pyroshock signal is a typical transient signal, which is more suitable for applying wavelet analysis. Applying wavelet analysis to the measured data can remove the distortion caused by amplifier saturation and extract the real pyroshock signal.
Select a certain pyroshock test, and the test data of the measurement point near the explosion source was shown in Figure 7. Because the measurement point was very close to the explosion source, Zero Drift phenomenon occurred in the measurement signal. Multi-scale wavelet decomposition was performed on the signal, and the approximate part and detail part coefficients at the scale 5 level were extracted and reconstructed, as shown in Figure 8.

It could be seen that a5 was the low-frequency component caused by the saturation of the charge. When reconstructed the signal after filtering out a5, the comparison between the processed signal and the original signal was obtained, as shown in Figure 9.


Figure 9. Time domain data comparison before and after signal processing

SRS analysis was performed on the original signal and the processed signal, as shown in Figure 10.

Figure 10. Comparison of SRS before and after signal processing

It could be seen that the wavelet analysis of the signal only filtered out the low frequency part of the signal, and had little effect on the high frequency part of the signal.

5. Conclusions
a) The "Ringing artifacts" and "Zero Drift" phenomena of the piezoelectric accelerometer were caused by exceeding the frequency range of the sensor;
b) The upper frequency limit of the test system could be increased by using mechanical filters or low-pass filters, and the occurrence of Ringing could be reduced;
c) The lower frequency limit of the test system could be improved by increasing the $RC$ value of the equipment, and the probability of Zero Drift could be reduced;
d) Distortion test data that produced Zero Drift phenomenon could be decomposed and reconstructed by using wavelet analysis to filter out the low-frequency components of Zero Drift, which could restore the test signal effectively.
6. References

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