

Full Length Research Paper

Design and experimentation of sensitive element of piezoelectric crystal sensor array for grain cleaning loss

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This study described the optimal design for the sensitive element of the piezoelectric crystal sensor array for grain cleaning loss. To improve the signal-to-noise and resolution of grain cleaning loss, the dynamic model for grain collision sensor array was established by using elastic thin plate theory and also the best structural parameters of sensitive element were determined to make out the grain and the stems momentum. The structural parameters of the thin plate were length of 300 mm, width of 200 mm, thickness of 1.5 mm, plate structural style and four corners fixed. Then, the experiment that grain impacted the sensitive elements with the thickness of 0.5, 1.5 and 2.5 mm was established on the test bench to verify the overall performance of the sensitive element. The results showed that the stiffness of the sensitive element designed was moderate, grain collision signal amplitude was about 1.2 V and decay time was within 1s, which was easily separated from other signals generated from the glumes and the straws. The sensitive element not only had high resolution between grain and stems, but also measured the highest frequency of grain impact, which significantly improved the overall performance of grain cleaning loss sensor.

Key words: Grain cleaning loss, sensor array, sensitive element, elastic thin plate theory, structural parameters.

INTRODUCTION

During harvesting, the grain amounts are less than those of the stems and the grass when they get across the sorting screen. The grain loss signals are so weak as to be submerged in the noises from the combine and the sieve when it is detected by the sensors, which, with the disturbance of the mixture of stems and grass, results to difficulty in testing the grain loss amounts (Wu, 1986). On the other hand, the grain and the stems are discharged from the sorting screen and fall into the sensitive elements installed in the rear of the sieve. It is a space-time continuum process. Shaver et al. (1976) designed the grain loss monitor by using transducer and tachometer that could measure grain loss per-unit area. The obtained grain loss signal is uncertain with this method owing to only using a single measurement loss sensor. Strelieff et al. (1977) advanced the sound of the

grain striking the sensor which was amplified by a microphone and was fed to a computing device. It is obvious that the result was influenced by the external interference, such as the sound of combine vibration. Eldredge and Kim (1985) fixed a piezoelectric crystal to the vibrational cleaning sieve. Loss grain impacted the piezoelectric crystal and caused electric signal. The signal was amplified and transmitted to the counting device. This detection has some disadvantages, such as small detection range, strong signal interference and fragile piezoelectric ceramics. In order to improve the grain loss sensor installation method, Osselaere (1985) put the sensor into a sealed enclosure. This device protected the grain loss sensor static performance from the external interference, but the dynamic performance of the sensor has not been improved and the influence of the combine vibration; the ground bump can not be restrained during harvesting. Diekhans and Behnke (1990) suggested that, an electroacoustic transducer was fixed on the back of the metal plate to detect the

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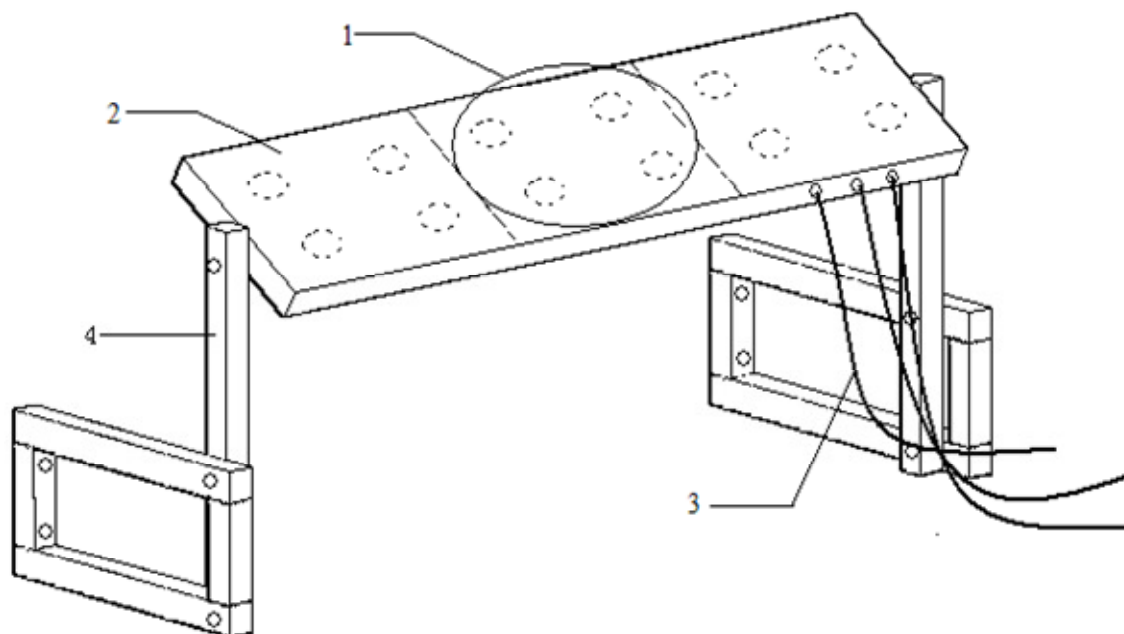


Figure 1. Piezoelectric crystal sensor array. 1, piezoelectric crystal detection array; 2, detection array sensitive element; 3, shielded transmission cables; 4, fixed bracket.

grain loss that impacted the plate but the plate structure was not calculated and designed in detail. When the grains impacted the plate, the signal attenuates slowly and radiates noise, which makes the sensitivity distribution on the plate surface uneven. In order to improve sensor performance, Strubbe (1991) designed a transducer associated with the sensor plate according to grain loss signal frequency character. The transducer had a resonant frequency in the range of 8 to 25 KHz. Furthermore, they developed a high-pass filter to differentiate the grain signal from stems signal. Owing to a single transducer and a single sensor plate, the grain loss signal was small and was liable to disturbance. Bernhardt and Hubner (2005) proposed an indirect means to measure grain loss. The method reduces the drawbacks of direct measurement and improves measurement accuracy. Li (2006) provided some improvements for decreasing vibration to improve the grain loss sensor sensitivity and the dynamic characteristic. As a consequence of using a single piezoelectric crystal as a force-sensitive element, its accuracy is still relatively low and the proposed measures are not applied to the field test. Li and Jie. (2007) proposed a grain loss detection method based on virtual test system, but the method is still under research.

From the existing reports about the grain loss detection of agricultural harvester, grain loss detection sets focus on pasting the piezoelectric unit on a flat panel. This structure does not bring into play the piezoelectric ceramic mechanical and electrical conversion capabilities and the output signal is characterized by the weakness and

the poor linearity. Since it is sensitive to the noises, its reliability is poor.

Based on the question for detection of grains cleaning loss, a piezoelectric crystal sensor array was designed and the information was obtained based on the method from the multi-regional and many-sided access (Ni and Mao. 2008a, 2008b) In this study, how to design the structure parameters about sensitive element of grains cleaning loss sensors was introduced to improve the resolution between the grain and the stems, enhance grain collision signal and improve signal-to-noise. At the same time, the overall performance of sensitive element was verified by the experiment on the test bench.

MATERIALS AND METHODS

Piezoelectric crystal sensor array

Piezoelectric crystal sensor array include piezoelectric detection array, sensitive element, shielded transmission cables and fixed bracket, as showed in Figure 1. The detection array was composed of several piezoelectric crystals with a certain arrangement, the structure of which not only enhances the grain collision signal, but also gives a uniform sensitivity in the all-width range for the sensitive element. Piezoelectric detection array was fixed to the sensitive element on the back and sealed in a fixed bracket. When the grain and the stems are discharged from the sorting screen and randomly impact the sensitive elements installed in the rear of the sieve, detection array can obtain the information from the multi-regional and many-sided access, which can reduce the information uncertainty and enhance the system reliability by the extra data and the complementary data from the sensor array. Meanwhile, the single sensor performance was extended. An elastic film layer was

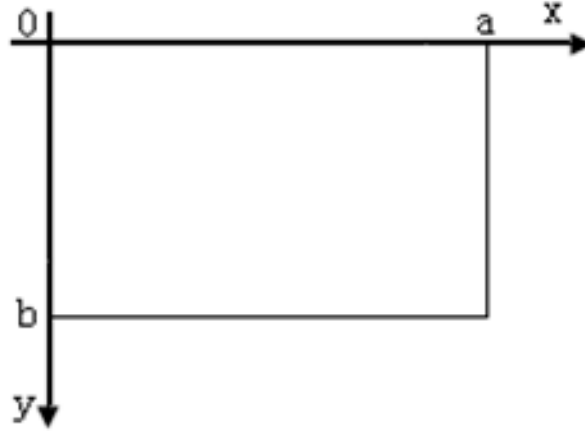


Figure 2. Two-dimensional coordinate system of the sensitive element.

pasted on the front facet of the sensitive element to reduce the bending waves generated from the grain impacting the sensitive element (Figure 1)

Design for sensitive element

Because the detection array sensitive element is impacted directly by the grains from the sorting screen, the materials and structural design of the sensitive element had an important effect on the signal acquisition and recognition. In the study, the thin multi-plate was distributed in full-wide range to detect, theoretically, the full width of the distributed thin plates and the higher resolution of grain but in fact, the more the thin plates, the more the sensor array needed, as a result, the hardware designed will be very complicated and field work will be difficult to achieve. The combine harvester used in this article was the 4LZ-2.0-type full feeding style, whose sorting screen export width was 1 m. By the grain harvesting experiments, the output was 1.2 kg/s. According to the technical requirements, the grain cleaning loss was less than 1%. The grain cleaning loss calculated was 12 g/s at most. Because the newly harvested grain had more water, the number of the grain cleaning loss was calculated at 400 per second on the assumption that the thousand-grain weight was 30 g. In order to improve sensitive element resolution to the grain collision signal and ensure the discharged grains from the sorting screen falling mostly into the detection range, three thin plates were designed and distributed at the left, middle and right of the sorting screen export in full-wide range. As far as a piece of thin plate was concerned, the grain falling frequency was less than 130 Hz, which effectively improved the detection sensitivity. According to the sorting screen export width, the structural parameters of the sensitive element were as follows: structural style, plate size dimension, length (300mm) and width (200) mm, materials, austenitic stainless steel 304, four corners fixed, aperture Φ (4 mm) and side-distance of 3 mm, while the parameters of the austenitic stainless steel 304 were as follows: elastic modulus, $E = 193 \text{ KN/mm}^2$, surface density, $\rho = 7.75 \text{ g/cm}^3$ and poison ratio of $\nu = 0.28$.

Thickness of the sensitive element was the most important structural parameter and it concerns the grain signal recognition. If the sensitive element is too thick, the stiffness will be very strong and the response of sensitive element to the grain collision will be extremely weak. If the sensitive element is too thin, the vibration signal generated from the grain impacting the sensitive element lasts long and radiates noise due to vibration, which results in

uneven distribution of sensitivity across the entire plate surface. Therefore, thickness of the sensitive element needs to be studied in order to determine the best structural parameters that can distinguish grain collision.

Dynamic analysis of the sensitive element based on elastic thin plate theory

When the sensitive element is impacted by the grain and straw, the thin plate will damply vibrate in its symmetry plane. Based on vibration theory of plates and shells, the theory can be used as long as the thickness of plate is much smaller than the plane size. At present, it is generally considered that the ratio of plate thickness to plane span are less than 1:6; the plate can be seen as thin plate in projects (Cao, 1989). When the sensitive element is impacted by the grain and straw, lateral vibration function of the thin plate is seen as:

$$\rho h \frac{\partial^2 Z}{\partial t^2} + D \frac{\partial^2}{\partial x^2} \left(\frac{\partial^2 Z}{\partial x^2} + \frac{\partial^2 Z}{\partial y^2} \right) + D \frac{\partial^2}{\partial y^2} \left(\frac{\partial^2 Z}{\partial x^2} + \frac{\partial^2 Z}{\partial y^2} \right) = 0 \quad (1)$$

Where $Z(x, y, z, t)$ represents lateral displacement of the sensitive element, ρ is the surface density, h denotes thickness,

$$D \text{ denotes flexural rigidity and it is } D = \frac{Eh^3}{12(1-\nu^2)}$$

Coordinate system of the sensitive element is established in the Cartesian coordinates, as showed in Figure 2.

As for the sensitive element with four corners fixed, the boundary conditions were:

$$\text{Where } x = 0, x = a \quad \frac{\partial Z}{\partial x} = 0 \quad (2)$$

$$\text{Where } y = 0, y = b \quad \frac{\partial^2 Z}{\partial x^2} + \frac{\partial^2 Z}{\partial y^2} = 0 \quad (3)$$

The mode shape solution that is suitable for equations 2 and 3 can be represented with double trigonometric functions.

$$Z_{ij}(x, y) = A \sin \frac{i\pi}{a} x \sin \frac{j\pi}{b} y$$

$$(i, j = 1, 2, 3 \dots) \tag{4}$$

Where A is constant, the equation 1 is simplified to;

$$\nabla^2 (\nabla^2 Z) + \frac{\rho h}{D} \frac{\partial^2 Z}{\partial t^2} = 0 \tag{5}$$

Where, ∇^2 is named two-dimensional Laplacian operator, that is

$$\nabla^2 = \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right)$$

Substituting equation 4 into 5, the equation was obtained as:

$$A \left[\pi^4 \left(\frac{i^2}{a^2} + \frac{j^2}{b^2} \right)^2 - \frac{\rho h}{D} \omega_{i,j}^2 \right] \sin \frac{i\pi}{a} x \sin \frac{j\pi}{b} y = 0 \tag{6}$$

Where, $\omega_{i,j}$ represents resonant frequency of the sensitive element. From Equation 6, equation 7 was obtained as;

$$\left[\pi^4 \left(\frac{i^2}{a^2} + \frac{j^2}{b^2} \right)^2 - \frac{\rho h}{D} \omega_{i,j}^2 \right] = 0 \tag{7}$$

To solve equation 7, the equation below was obtained;

$$\omega_{i,j} = \pi^2 \left(\frac{i^2}{a^2} + \frac{j^2}{b^2} \right) \sqrt{\frac{D}{\rho h}} \quad (i, j = 1, 2, 3 \dots) \tag{8}$$

Considering the first-order frequency, that is $i = j = 1$, from equation 8, the first-order inherent frequency of the sensitive element as was gotten as:

$$f_{11} = \frac{\pi}{2} \left(\frac{1}{a^2} + \frac{1}{b^2} \right) \sqrt{\frac{Eh^3}{12(1-\nu^2)\rho h}}$$

To ensure that the system can measure the upper frequency of grain collision, that is the maximum number of grain impacting the sensitive element in unit time, the first-order natural frequency of the sensitive element was $f_{1,1} = 130\text{Hz}$.

That is,
$$\frac{\pi}{2} \left(\frac{1}{a^2} + \frac{1}{b^2} \right) \sqrt{\frac{Eh^3}{12(1-\nu^2)\rho h}} = 130$$

$$\frac{\pi}{2} \left(\frac{1}{(0.3)^2} + \frac{1}{(0.2)^2} \right) \sqrt{\frac{193 \times 10^3 \times h^3}{(10^{-3})^2}} = 130$$

$$\sqrt{\frac{7.75 \times 10^{-3} h}{(10^{-2})^3}}$$

Obtained, $h \approx 1.52(\text{mm})$

The thickness h was taken as 1.5 mm. The sensitive element is seen in Figure 3. The size of the sensitive element was length of 300 mm, width of 200 mm and 1.5 mm thickness, where the ratio of the plate thickness to plane span were much less than 1:6. Therefore, sensitive element based dynamic analysis using the elastic thin plate theory is feasible.

RESULTS AND DISCUSSION

The grain impact experiment was developed to the different thickness of the thin plate on the non-vibrating test bench, so as to test the performance for the sensitive element designed. The thin plates thickness selected were 0.5, 1.5 and 2.5 mm respectively. Other structural parameters and performance parameters were identical. The piezoelectric crystal sensor arrays were pasted on the back of the sensitive elements, the four corners of which were fixed to the test bench. The grains freely fell down from 300 mm above the test bench and impacted the sensitive element at random. Four-channel charge amplifier, with 10 pc/unit sensitivity and a gain of 10, was taken as the pre-signal conditioner for the piezoelectric crystal detection array followed by a gain compensation amplifier to adjust the output signal amplitude. Grain impact signals were recorded by a high-speed data acquisition system with a frequency of 40 kHz. The results are shown in Figure 4.

From Figure 4a, there were seven grains that impacted the sensitive element. With the thickness of the plate as 0.5 mm and low stiffness, the amplitude of vibration signal generated from the grain impacting the sensitive element was large with about 1.5 V and the maximum was 1.8 V, which was easily separated from other signals generated from the glumes and the straws. However, due to the thinner sensitive element, the grain collision signal lasted long and the signal decay time was about 2 s. When the grain collision signal was triggered, the previous grains collision signal attenuation had not finished, which caused grain signals interference and super positioning of one another in the lower resolution, leading to difficulties in the quantitative detection of the grains.



Figure 3. Sensitive element of the grain loss sensor

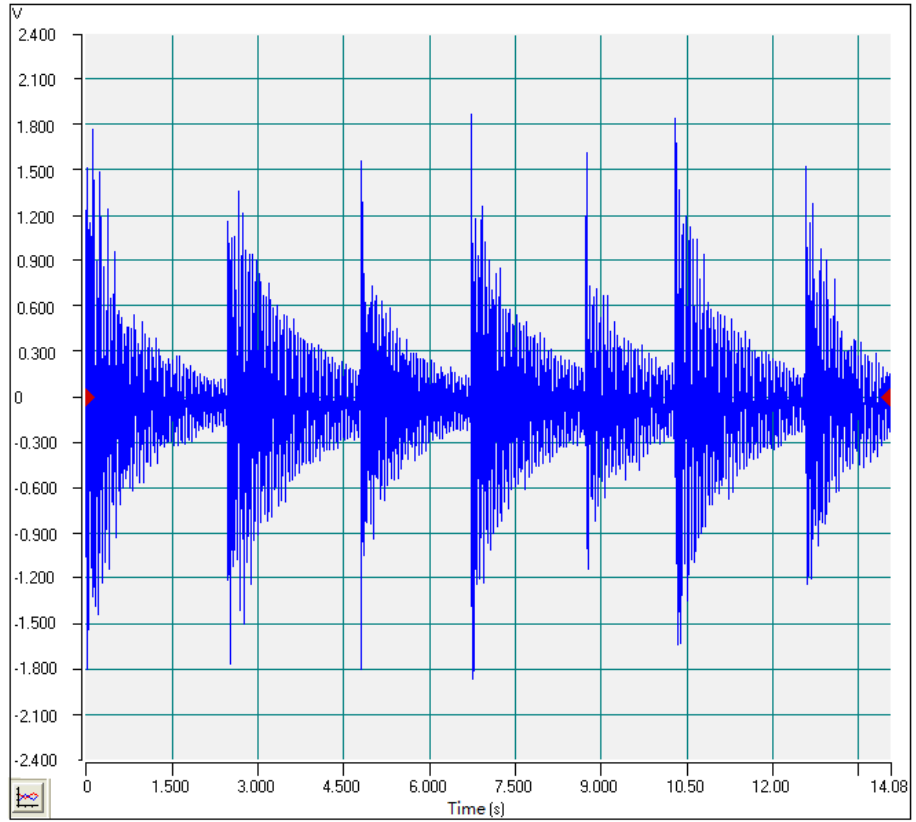
Moreover, the sensitive element radiated noise due to vibration large, which resulted in uneven distribution of sensitivity across the entire plate surface and bad signal-to-noise.

The dynamic response of grains collision to the sensitive element is shown in Figure 4b; there were six grains that impacted the sensitive element. As the plate thickness increased to 1.5 mm and the stiffness was enhanced, the duration of vibration signal generated from the grain impacting the sensitive element was reduced and the signal decay time was within 1 s. When the grain collision signal was triggered, the previous grains collision signal attenuation had been completed. Interaction between grain signals decreased and resolution was enhanced. In addition, the maximum grain collision signal amplitude was about 1.2 V and the output signal amplitude was large, easily separated from other signals generated from the glumes and was not liable to disturbance. The thickness was calculated by the maximum number of grain impacting the sensitive element in unit time, which ensured that the system could measure the highest frequency of grain collision. As shown in Figure 4c, there were two grains impacting the sensitive element. Because the plate thickness increased to 2.5 mm and the stiffness was strengthened, the duration of vibration signal generated from the grain impacting the sensitive element was reduced and the signal decay time was about 0.5 s. When the grain collision signal was triggered, the previous grains collision signal attenuation had been finished. In this case, the interaction between

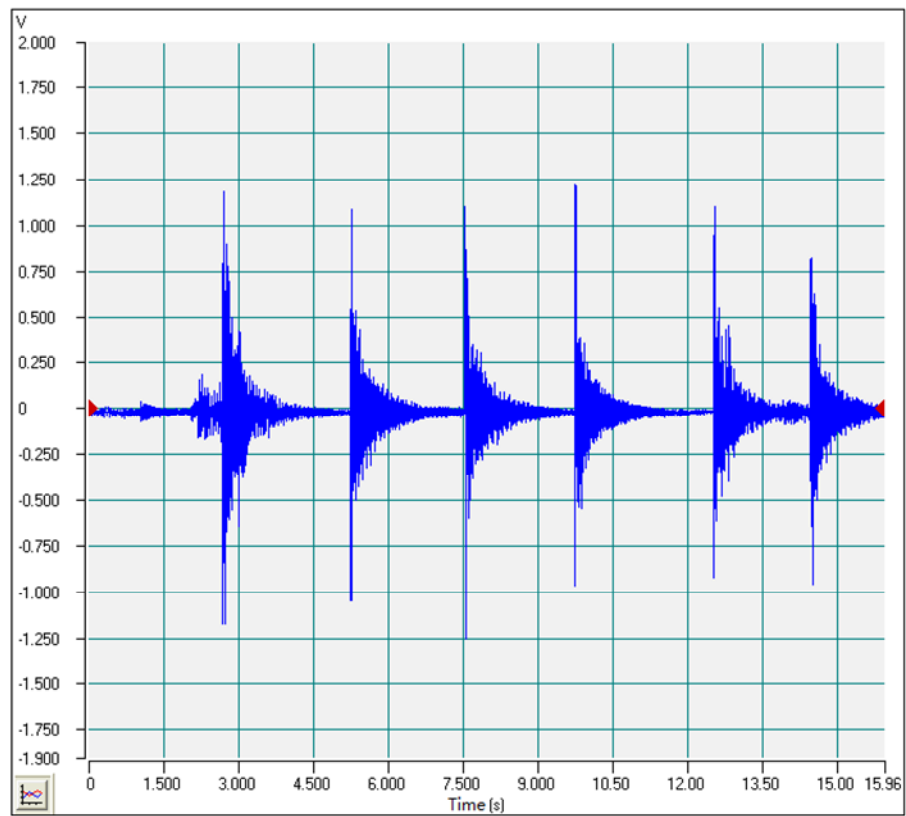
grain signal decreased and resolution was enhanced. However, the maximum of grain collision signal amplitude reduced to around 0.5 V owing to the thicker sensitive element. Output signal was smaller and was liable to disturbance; the grain collision signal was not easily distinguished.

Conclusions

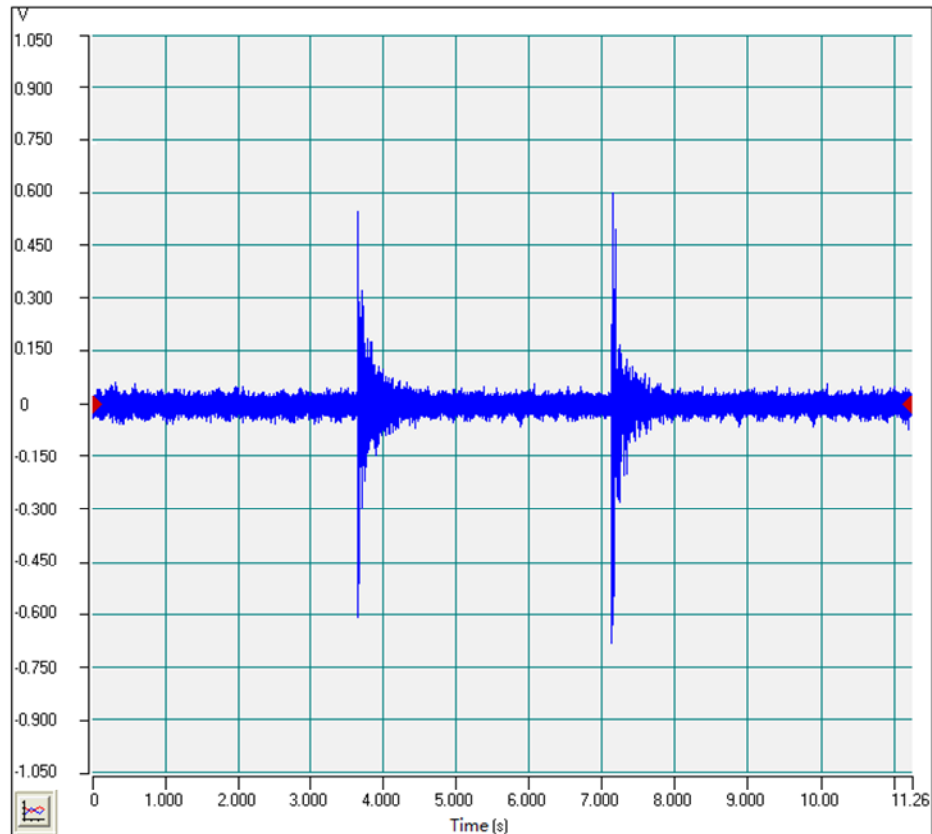
The dynamic model for grain collision sensor array was established by using elastic thin plate theory and also the best structural parameters of sensitive element were determined to make out the grain and the stems momentum. The structural parameters of the thin plate were length of 300 mm, width of 200 mm and thickness of 1.5 mm, respectively, plate structural style and four corners fixed. The experiment grains freely fell down from 300 mm and impacted sensitive elements with the thickness of 0.5, 1.5 and 2.5 mm, established on the test bench. The results showed that, with increasing thickness of the sensitive element and strengthening of the stiffness, both the amplitude of the grain collision signal and the signal duration decreased. When the grains impacted the sensitive element with the thickness of 1.5 mm, decay time of the vibration signal was 1 s and the maximum signal amplitude was about 1.2 V, which caused signal resolution to be high and not easily disturbed, meanwhile, the designed sensitive element could measure the highest frequency of grain impact.



a



b



c

Figure 4. Response of the sensitive element with different thickness to grain impact; (a) Thickness was 0.5 mm (b) thickness was 1.5 mm and (c) thickness was 2.5mm.

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