High sensitivity cymbal-based accelerometer

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A high sensitivity piezoelectric accelerometer has been developed by replacing the conventional piezoelectric rings with a cymbal transducer. The sensitivity of the cymbal-based accelerometers containing cymbal transducers with different endcap thicknesses and different seismic masses has been measured as a function of driving frequency. Due to the high d'_{33} coefficient of the cymbal transducers, the cymbal-based accelerometers have a high sensitivity of ~97 pC/ms^{-2} with the amplitude rise of 2.85% (<1 dB) at one-third of the mounted resonance frequency (3.38 kHz). The effect of the seismic mass, the resonance frequency, and d'_{33} coefficient of the cymbal transducers on the sensitivity and the frequency range of the cymbal-based accelerometers are reported. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2185487]

Piezoelectric accelerometers are widely used in vibration monitoring and measurements.[1,2] According to the working mechanism, piezoaccelerometers are classified into compression, shear, and flexural beam mode types.[3] The sensitivity of a compression mode accelerometer depends on the d_{33} of the piezoelectric material. Based on this characteristic, methods for improving the sensitivity have been investigated with some success, including the use of piezoelectric transducer (PZT) composites, single crystal materials, and multilayer piezoelectric ceramics.[4–6] The improved accelerometers possess higher sensitivity. Another method for improving the sensitivity of the accelerometer is by installing a smart structure called cymbal transducer which has a high piezoelectric charge coefficient and fast response time, instead of the conventional piezoceramic rings.[7–10] Since the resonance frequency of the cymbal transducer depends heavily on the geometry of the cymbal endcaps and the load masses, the performances of accelerometers with a specific structure containing cymbals with different endcap thicknesses and different seismic masses were evaluated using back-to-back method in this article.

The cymbal transducer consists of a piezoelectric disk sandwiched between two "cymbal" shaped metal endcaps. The two endcaps serve as mechanical amplifiers to convert a small vertical force applied on it into a vertical force with the same magnitude of the applied force and a much larger radial force acting on the piezoelectric disk; with this mechanism, a large charge can be generated under a relatively small vertical force acting on the cymbal transducer, resulting in a high charge coefficient d'_{33}. In our experiments, two cymbal transducers with different endcap thicknesses were used. The d'_{33} of the cymbal transducers with the thickness of 0.25 mm and 0.30 mm endcaps are about 18 200 and 13 800 pC/N, respectively.

The configuration of the cymbal-based accelerometer is shown in Fig. 1, including a seismic mass, a cymbal trans-

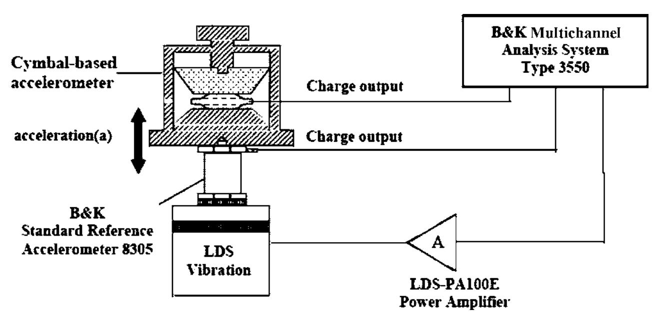

FIG. 1. The experimental setup for the sensitivity measurement of a cymbal-based accelerometer (B&K 8305 was used as a standard reference accelerometer in the back-to-back calibration).

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TABLE I. The geometric dimensions of the cymbal-based accelerometers.

	A	B	C
Diameter of the endcap (mm)	12.7	12.7	12.7
Cavity diameter of the endcap (mm)	9.0	9.0	9.0
Cavity depth of the endcap (mm)	0.35	0.35	0.35
Thickness of the endcap t (mm)	0.25	0.30	0.30
Seismic mass m (g)	5.408	5.408	2.115

ducer, a mounting base, and a metal housing. Three accelerometers were fabricated using different cymbals and seismic masses. In the fabrication of the cymbal transducers, identical piezoelectric disks (PKI 552) with 12.7 mm diameter and 1.0 mm thickness were used. The geometric dimensions of the three cymbal-based accelerometers, named as A, B, and C, are given in Table I. The cymbal transducer was fixed between a seismic mass and the mounting base. During this process, a specially designed jig was used to adjust the position of the seismic mass and apply a prestress for ensuring good adhesion. Due to the direct piezoelectric effect, the cymbal transducer generates an electrical signal (Q) proportional to the force (F) by the seismic mass. Such a cymbal-based accelerometer is a single degree-of-freedom vibration system, where the two endcaps serve as two springs. The equation of motion of the system can be written as[11]

$$m\ddot{x}_0 + c(\dot{x}_0 - \dot{x}_i) + k(x_0 - x_i) = 0, \quad (1)$$

where x_0 and x_i are the displacement of the seismic mass and base plate. c and k are the damping and the stiffness coefficient of the system, respectively. Thus, the generated charge signal Q and the sensitivity S of the accelerometer can be expressed as

$$Q = d'_{33}F = -d'_{33}m\ddot{x}_0, \quad (2)$$

$$S = \frac{|Q|}{|\ddot{x}_i|} = \frac{d'_{33}k\sqrt{1+(2\xi\lambda)^2}}{\omega_0^2\sqrt{(1-\lambda^2)^2+(2\xi\lambda)^2}} \approx d'_{33}m \quad \left(\lambda = \frac{\omega}{\omega_0} \ll 1\right), \quad (3)$$

where $\ddot{x}_0$ is the acceleration of the seismic element, $\ddot{x}_i$ the input acceleration, ξ the damping ratio, ω the frequency of the input acceleration, and $\omega_0 = \sqrt{k/m}$ is the fundamental frequency of the cymbal-based accelerometer. From these equations, it can be seen that the sensitivity of the accelerometer is proportional to both the d'_{33} of the cymbal transducer and the seismic mass.

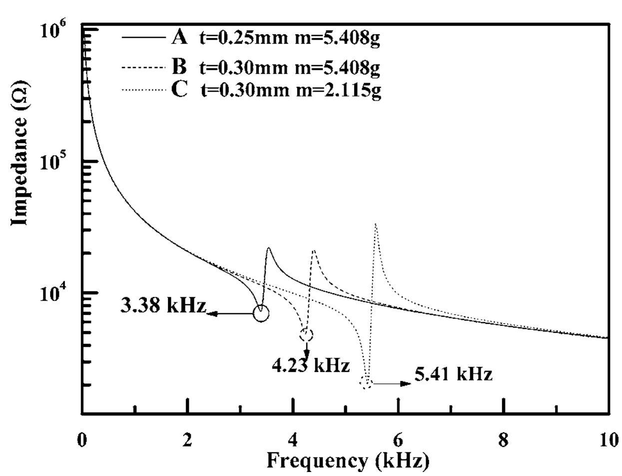

FIG. 2. Impedance spectrum of the cymbal-based accelerometers.

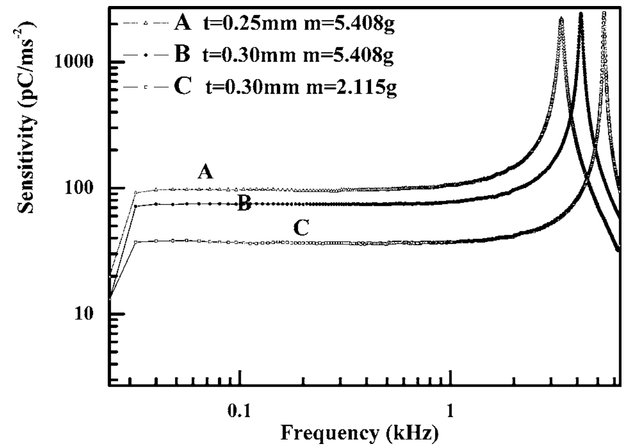

FIG. 3. The sensitivity of the cymbal-based accelerometers as a function of frequency.

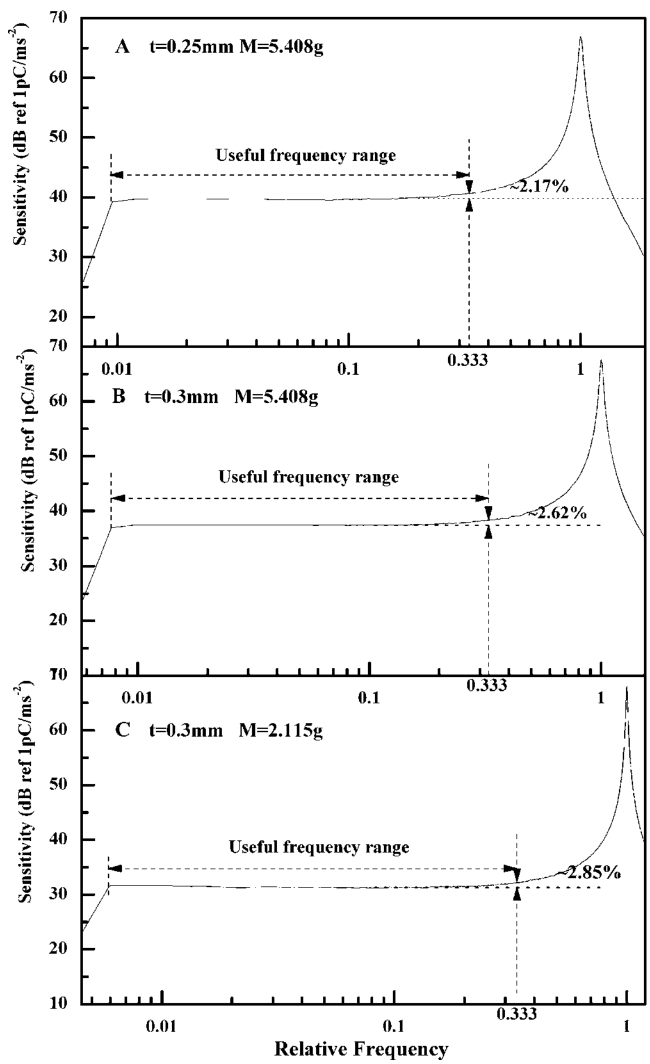

FIG. 4. The typical frequency response of the cymbal-based accelerometers in a logarithmic plot.

Two tests were carried out to evaluate the performance of the cymbal-based accelerometers including the useful frequency range and the sensitivity. To estimate the fundamental resonance frequency of the cymbal-based accelerometers, an HP 4294A impedance analyzer was used. Figure 2 shows the impedance spectra of the cymbal-based accelerometers with different endcap thicknesses and seismic masses. The fundamental resonance frequencies of the cymbal-based accelerometers (A, B, and C in Table I) were 3.38, 4.23, and 5.14 kHz, respectively. In the useful frequency range, the accelerometer gives a constant amplitude output signal when subjected to a constant acceleration from very low frequency up to a frequency limit set by the fundamental resonance frequency of the accelerometer.

Then, the sensitivity spectrum of the three cymbal-based accelerometers A, B, and C was measured using a conventional back-to-back method as shown in Fig. 2. A standard accelerometer (Brüel & Kjær 8350) installed below the cymbal-based accelerometer was used to measure the input acceleration. The accelerometers were excited using an electromagnetic shaker (LDS V406). The signal used to drive the shaker was generated by a multichannel analyzer (Brüel & Kjær type 3550) and then fed into a power amplifier (LDS-PA100E). The input acceleration measured by the standard accelerometer and the charge response from the cymbal-based accelerometer were collected simultaneously by the analyzer. Thus, the sensitivity spectrum of the cymbal-based accelerometer can be calculated using the analyzer. Figure 3 shows the measured frequency spectra of sensitivity for different cymbal-based accelerometers under an input acceleration of 0.9 m/s^2 in the frequency range of 0–6.4 kHz with a frequency resolution of 8 Hz. Sensitivities of the cymbal-based accelerometers A, B, and C are ~97, ~75, and ~37 pC/ms^{-2}, respectively. From these results, it is seen that the sensitivity of the cymbal-based accelerometer increases as the seismic mass and the d'_{33} of the cymbal transducer increase, which shows a good agreement with Eq. (3).

In order to evaluate the useful frequency range, the typical frequency response of different cymbal-based accelerometers was replotted in the logarithmic coordinate as shown in Fig. 4. As a rule of thumb, the accelerometer can be used up to one-third of its resonance frequency. This can ensure that the amplitude rise error in that frequency range does not exceed approximately 12% or 1 dB. For the cymbal-based accelerometers A, B, and C, the amplitude rises at one-third of the mounted resonance frequency are about 2.17%, 2.62%, and 2.85% (<1 dB) as shown in Fig. 4, respectively. It means that the useful frequency ranges of three cymbal-based accelerometers A, B, and C are 0.032–1.13, 0.032–1.41, and 0.032–1.80 kHz, respectively. The error below 0.032 kHz is the systematic error of the whole measurement system. These results demonstrated that the frequency ranges of the cymbal-based accelerometers are related to both the mass of the seismic element and the cymbal transducers. Using the same cymbal transducer, the frequency range of the cymbal-based accelerometer will be narrower with increasing seismic mass. Besides, using the same seismic mass, the frequency range of the cymbal-based accelerometer would be broadened with increasing endcap thickness of the cymbal transducers.

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