Proceedings of the 2009 4th IEEE International
Conference on Nano/Micro Engineered and Molecular Systems
January 5-8, 2009, Shenzhen, China

Research on the Output Characteristics of MEMS Convective Accelerometer under Heavy Impact

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***Abstract* — Microelectromechanical system (MEMS) convective accelerometer based on convection heat transfer has many advantages such as simple structure, low cost and great anti-shock property. Due to its great anti-shock property, we research the output characteristics of the convective accelerometer with low measuring range (±5g) (g stands for acceleration of gravity) when the input is heavy impact (500～30,000g). First, we introduce the structure and operating principle of the convective accelerometer and give the reason why it can endure heavy impact. Second, by the study of its structure and operating principle, we analyze theoretically the output characteristics of MEMS convective accelerometer under heavy impact. Grashof number, which governs the convection heat transfer process, is used to determine the output results. We draw the conclusion by qualitative analysis that the output is non-linear extremely to the input, even up to saturation. Then we take a series of impact test to a convective accelerometer. From the results of test, the theoretical analysis we have done is proved correct. Meanwhile, we find that when the amplitude and actuation duration of the impact reach certain value, the output of accelerometer hardly change. We summarize the output law of the convective accelerometer under heavy impact by analyzing the test results. According to its characteristics, we point out the potential application field of MEMS convective accelerometer such as steady threshold switch in the situation enduring heavy impact. The research provides a new idea to use MEMS convective accelerometer in heavy impact field and is a theoretical and testing base for its further research and application.**

Keywords — ***convective accelerometer; Grashof number; heavy impact; MEMS; output characteristic***

I. Introduction

Microelectromechanical system (MEMS)-based accelerometers have many advantages such as small volume, low weight, high sensitivity and so on. So they bring much convenience for system designers and have been widely used in many fields such as inertial guidance, automatic control, auto safety system and so on. Most MEMS-based accelerometers have complex vibration structure and a solid proof mass, so they have poor impact endurance. MEMS convective accelerometer, which is based on the physical phenomenon that the convection heat transfer condition of air changes due to the acceleration, has many advantages such as simple structure, low cost and great anti-shock property. So it has been used in some electronic products. The measuring range of existing MEMS convective accelerometer is mostly low (less than ±50g) (g stands for acceleration of gravity). But because of its unique operating principle, its anti-shock property can reach tens of thousands of g. We are very interested in the output characteristics of MEMS convective accelerometer when the input is heavy impact and have done some research on it. Then we draw some rules and point out its potential application fields.

II. Theoretical Analysis

A. Operating principle of MEMS convective accelerometer

MEMS convective accelerometer consists of a single-crystal silicon cavity, a heater and a pair of temperature sensors. Its structure is shown in Fig. 1. The suspended central heater heats up and lowers the density of the air surrounding it. Two temperature sensors, Temperature Sensor1 and Temperature Sensor2 at equal distance from the heater measure the differential temperature [1]. The sensitive direction of the accelerometer sensor is within the plain consisting of the heater and temperature sensors and perpendicular to the temperature sensors.

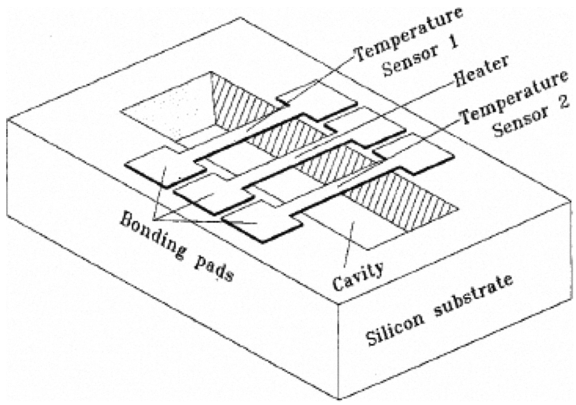

Figure 1. Structure of MEMS convective accelerometer

When MEMS convective accelerometer is in the state of quiescence, the free-convection heat transfer of the hot air is symmetrical to the heater. So the detected temperatures by the two temperature sensors are the same. The symmetrical temperature profile produced by the heater, illustrated in Fig. 2(a), results in no output. When acceleration is applied to the MEMS convective accelerometer, the free-convection heat transfer will change correspondingly. Then the symmetry is disturbed as illustrated in Fig. 2(b). The differential temperature produces an output corresponding to the applied acceleration [1] [2].

B. Analysis of the Output under Heavy Impact

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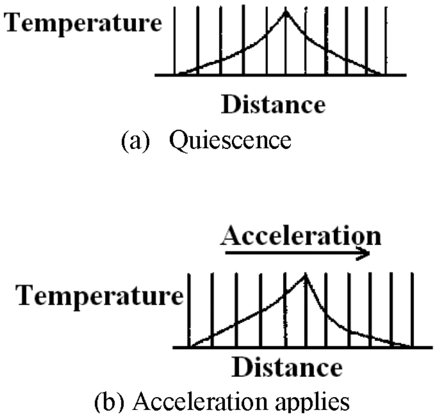


Figure 2. Temperature profile of convective accelerometer

The operating principle of MEMS convective accelerometer is based on the free-convection heat transfer of the fluid. Grashof number, *Gr*, which governs the free-convection heat transfer process, determines the output of convective accelerometer [3]. The temperature difference of the two temperature sensors in MEMS convective accelerometer is mainly affected by *Gr*. *Gr* can be determined by:

$$Gr = \frac{ap^2x^3\beta(\Delta T)}{\mu^2} \tag{1}$$

In this equation, a stands for acceleration; p stands for density of fluid; x stands for length of the heater; β stands for coefficient of expansion; μ stands for viscosity of fluid; ΔT stands for temperature of heater. From (1), we can see that once the convective accelerometer is made, a will do definitive effect to *Gr*. When *Gr* is between 10^{-2} and 10^{-3}, the differential temperature of two sensors, δT is proportional to applied acceleration, a [4].

The structure of 2–axial MEMS convective accelerometer is shown in Fig. 3. In X (or Y) axis, the output signal of two temperature sensors are differential amplified and then low pass filtered [5]. From (1), in the measuring range of accelerometer, the output is proportional to applied acceleration. And the sensitivity is related to the nature of fluid, thermal element and differential amplification factor.

Compared to capacitive, piezoelectric or piezoresistance accelerometer, convective accelerometer have no movable solid structure. So it can endure heavy impact. When applied acceleration is much higher than the measuring range, the output will be no longer linear to applied acceleration. Known from the structure and operating principle of convective accelerometer, there are two causes to the non-linearity:

First, free-convection heat transfer in accelerometer changes acutely and nonsymmetry of temperature profile reach certain degree. So that δT is up to saturation. At this time, applied acceleration $a \gg a_{MMR}$ (Max Measuring Range of accelerometer), so $Gr \gg 10^3$, and δT is no longer linear to *Gr*.

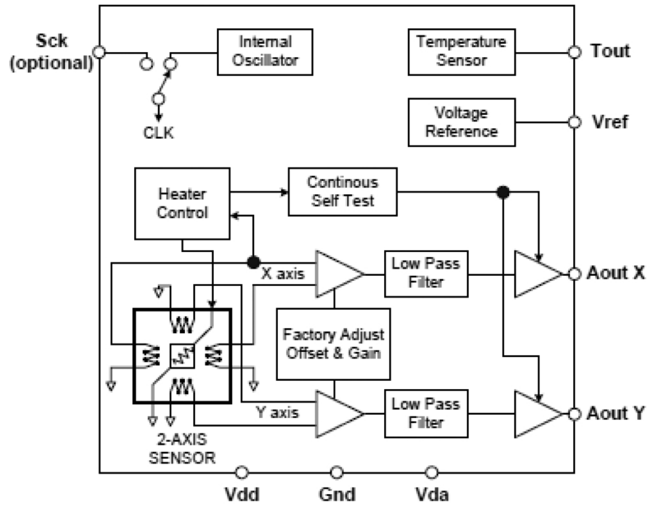


Figure 3. Structural schematicof 2-axial MEMS convective accelerometer

Second, the differential temperature of two sensors is too large. So after differential amplification, theoretical output voltage reaches or exceeds maximum output voltage of the amplifier.

These two reasons both make the output of convective accelerometer turns to saturation. At this time, the output of the accelerometer is no longer proportional to applied acceleration. And the saturation value and saturation time need experiments to determine.

At the same time, compare to other types of accelerometer, operating principle of MEMS convective accelerometer is based on free-convection and heat transfer. So its response frequency is low (usually dozens of Hz) and can be regarded as low pass filter. And the output law under heavy impact also needs to be determined by experiments.

III. Experimental Results and Discussion

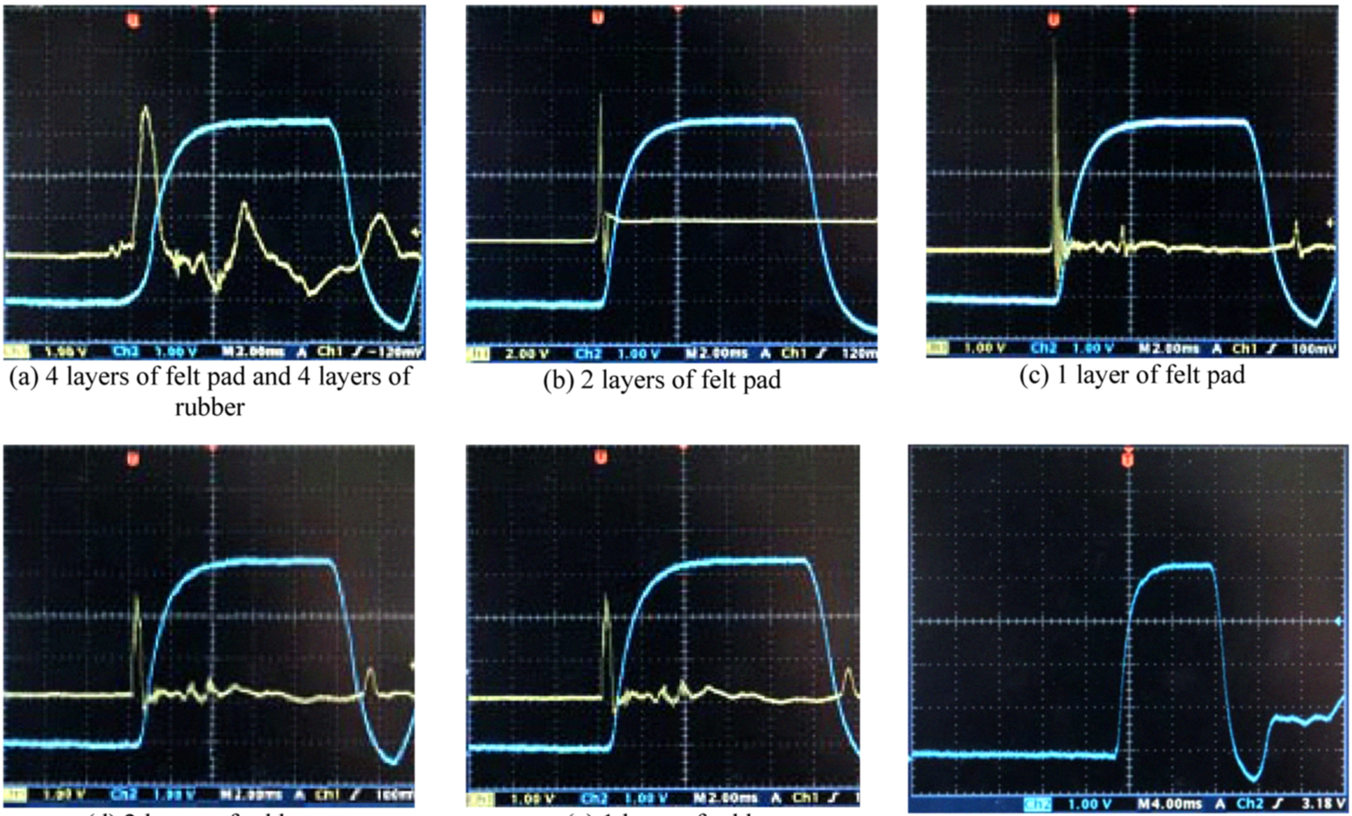
For validating our theory analysis and getting the output characteristics under heavy impact exactly, we take a series of impact experiments using MEMS convective accelerometer. We use MXA 2100A, which is made by MEMSIC, Inc. Its main technical parameters are shown in TABLE I [5]. From TABLE I, we can see it can endure 50,000g acceleration.

In order to obtain heavy impact, we use shocking hammer to get heavy impact. Its operating principle is using gravity to accelerate the hammer to strike ferric object. And it can generate 200～50,000g impact acceleration [6]. We fix a MEMS convective accelerometer MXA 2100A and a piezoelectric accelerometer whose measuring range is 30,000g on the shocking hammer. The output of piezoelectric one is used to provide true impact status. The power supply voltage of MEMS convective accelerometer is 5V. We lay layers of cushioning material such as felt pad and rubber between shocking hammer and ferric object to change the amplitude and actuation duration of the impact. The output curves of the two accelerometers are shown in Fig. 4.

In Fig. 4, yellow curve is the output of piezoelectric accelerometer and blue curve is the output of convective accelerometer. Abscissa stands for time and ordinate stands for output voltage. Because the condition of every experiment is not the same, the unit abscissa or ordinate stands for in every figure has some difference. In Fig. 4(f), we don't use any cushioning device and the impact acceleration is about 30,000g. To avoid damaging the piezoelectric accelerometer, it's not used. The specific result of the test is summarized in TABLE II.

TABLE I. MAX2100A TECHNICAL PARAMETERS

Parameter	Measuring range (g)	Sensitivity (mV/g)	Bandwidth (Hz)	0 g voltage (V)	Maximum acceleration rating (g)	Supply voltage (V)
Typical Value	±5	100	30	1.25	50,000	5



(a) 4 layers of felt pad and 4 layers of rubber
(b) 2 layers of felt pad
(c) 1 layer of felt pad
(d) 2 layers of rubber
(e) 1 layer of rubber
(f) no cushioning device

Figure 4. The ouput of accelarometers under heavy impact using different cushioning device. Yellow curve is the output of piezoelectric accelerometer and blue curve is the output of convective accelerometer

TABLE II. RESULTS OF CONVECTIVE ACCELEROMETER TEST UNDER HEAVY IMPACT

Cushioning Device	**Amplitude of Impact (g)**	**Actuation Duration of Impact (ms)**	**Saturation Time of Output Signal [a] (ms)**	**Actuation Duration of Output Signal [b] (ms)**
4 layers of felt pad and 4 layers of rubber	600	2.3	6	11
6 layers of felt pad and 2 layers of rubber	750	2.0	6	11
2 layers of rubber	2,500	0.7	6	11
1 layer of rubber	5,000	0.5	6	11
2 layers of felt pad	8,000	0.3	6	11
1 layer of felt pad	10,500	0.2	6	11
None	about 30,000	—	6	11

a. Time duration when output voltage is above 4.8V (power supply voltage is 5V). b. Time duration when output signal is from responding to the first return to 0.

From Fig. 4 and TABLE II, we can draw the conclusions:

First, when the input is heavy impact, the output voltage of MEMS convective accelerometer reaches a certain value and no longer change (saturation). And the saturation value is close to the voltage of power supply.

Second, piezoelectric accelerometer has high response frequency so it can sense high-frequency vibration in heavy impact. Convective accelerometer has low response frequency and long response time. Its output curve is very smooth. So its output signal is easy to process (especially in the situation needing for high-speed signal processing).

Third, when the amplitude and actuation duration of the impact reach certain value, the output will not change with the enhancing of impact. And the curve has obvious feature: saturation time is about 6 ms; actuation duration is about 11 ms.

IV. CONCLUSIONS

By taking a series of experiments with it, we obtain some output characteristics of MEMS convective accelerometer under heavy impact. And the experiment results validate the correctness of our theoretical analysis. MEMS convective accelerometer has stead response characteristic under heavy impact and its output is very regular. At the same time, MEMS convective accelerometer has many advantages: first, small volume, light weight, low cost and easy to use; second, great anti-shock property; third, smooth output curve, high SNR (signal to noise ratio) and the signal is easy to process; fourth, steady response to heavy impact and obvious output feature. In the field of heavy impact, conventional accelerometers have some disadvantages such as large volume, high cost, and low reliability. Based on above-mentioned advantages, in some signal measuring field for heavy impact, we don't need to measure exact impact signal, and just need to estimate if the impact reaches a certain threshold, MEMS convective accelerometer can replace conventional accelerometer. Especially in high-speed signal processing field it can be widely used.

In the future, we will take more experiments using other convective accelerometers with different measuring range. And we will try to establish exact threshold.

ACKNOWLEDGMENT

The authors would like to thank Asso. Prof. Jun Wang in Beijing Institute of Technology for his support in experiments.

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