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A Vibration Sensor Design Research

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Abstract: The vibration sensor is one of the key technologies in the test section, and its main function is to down mechanical quantity which s received and converted to electricity in proportion. A request parameter vibration sensor design is researched in this paper. The main principle is to design by the principle of differential capacitance. According to the characteristics of the differential capacitance, its mechanical and circuit characteristics is built, and then the design is achieved by applying the sandwich structure. Ansys simulation is taken by the sandwich structure, and the vibration modes are determined. When parameters are adjusted, sensitive devices meet the requirements. Matlab simulation is performed to acquire the corresponding conclusions in their displacement and output voltage. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Vibration, Sensor, Sandwich structure, Differential capacitance, Simulation.

1. Introduction

In the height development of modern industrial, modern testing technology has become an inevitable trend to digital and information-oriented, while the front of the test system is a sensor, which is the soul of the whole test system and is listed as cutting-edge technology in the world, particularly in recent years, the rapid development of IC technology and computer technology provides a good and reliable scientific and technical foundation for the development of sensors. The rapid development of sensor and digital, multi-functional and intelligent is an important feature of modern sensor development [1, 2].

As we all know, the vibration is widely found in nature and human social life, and it is a physical phenomenon [3, 4]. It is visually described that the vibration is a dynamic phenomenon, and a reciprocating which we have observed in a balance position [5, 6]. Vibration is the transfer and storage of energy which are caused because of one or more of the force effect in the structure. Some vibration is what we need, and these are widely used in terms of industrial and agricultural production, social life, health care, etc. For example, in a construction site, cement mortar is tamped by machine, using ultrasonic vibration cleaning, welding. Some vibration is to be avoided, such as ambient noise, such as bridges resonance. Vibration acceleration, velocity and displacement can been provided by vibration measurements, and the basis is provided for industrial production, equipment is ensured in the safety and reliability, various vibration parameter data can been also provided for the instrument during operation, According to the test data of the control system, the work status of the instrument is controlled, to ensure proper working conditions in order to improve work efficiency [7, 8].

In this paper, a vibration sensor is designed by the principle of differential capacitance, measuring vibration acceleration. The main technical indicators are the detection limit of 0.1 mg, and the frequency range of 100-10,000 Hz.

2. Working Principle of the Capacitive Vibration Sensor

2.1. Operating Principle

Capacitive vibration sensor measuring principle is based on Newton's second law, because the acceleration effects on the sensitive mass, inertia force is formatted, and it is an indirect measurement of acceleration. Micro-acceleration sensor includes an elastic beam, inertial mass, its basic mechanical model is a damper system with mass plus springs, acceleration system is acted by the inertial force on the sensitive mass, as it is shown in Fig. 1 [9, 10].

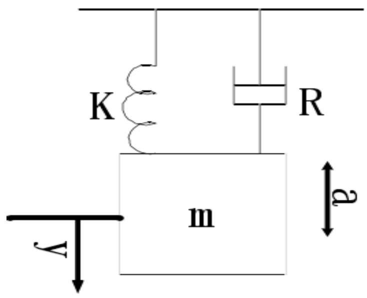

Fig. 1. Basic mechanical model.

Vibration differential equation is established in accordance with Newton's second law [11].

$$m\frac{d^2y}{d^2t}+R\frac{dy}{dt}+ky=F(t)=ma(t), \quad (1)$$

where m is the mass of the vibrating object, *R* is the dynamic damping coefficient, *k* is the spring constant, *a* is the input acceleration, *y* is the displacement of the mass which is relative to the housing.

$m\frac{d^2y}{d^2t}$ represents the inertial force,

$R\frac{dy}{dt}$ represents the dynamic resistance,

F(t) denotes a support beam elastic force.

The formula (1) is made for the Laplace transform under zero initial conditions, to obtain:

$$m\cdot s^2Y(s)+R\cdot sY(s)+KY(s)=m\cdot A(s),$$

Thus the transfer function can be obtained as follows:

$$H(s)=\frac{x(s)}{a(s)}=\frac{m}{ms^2+cs+k}=\frac{1}{s^2+s(\omega_r/Q)+\omega_r^2}= \\ =\frac{1}{s^2+2s\xi\omega_r+\omega_r^2}, \quad (2)$$

where $\omega_r=\sqrt{\frac{k}{m}}$ is the natural frequency of the vibration mass, Q= $\sqrt{km}$ /c=$\omega_r m$/c is the quality factor; ξ=0.5/Q is the damping factor. Formula (2) is basic research on the system characteristics of the capacitive accelerometer, it has completed a → x, i.e. it is the conversion from the outside acceleration to mass displacement x. When $\omega \ll \omega_r$, the formula (2) can be written as:

$$H(s)=\frac{x(s)}{a(s)}\approx\frac{1}{\omega_r^2}, \quad (3)$$

It is known by the formula (3), when $\omega \ll \omega_r$, the displacement was approximately linear relationship with the acceleration. Sensor mechanical sensitivity is inversely proportional to the square of x / a, with the natural frequency. The natural frequency is lower, it is possible to improve the detection sensitivity of the acceleration sensor, but the bandwidth will be affected, and the intrinsic frequency is limited by the mechanical structure and production conditions, and it can not be lower.

And because $\omega_r=\sqrt{\frac{k}{m}}$, it is substituted into the formula (3), and it can be obtained:

$$\frac{x(s)}{a(s)}\approx\frac{1}{\omega_r^2}=\frac{k}{m}, \quad (4)$$

The following conclusion can be obtained from formula (4): increasing the coefficient of elasticity or decreasing of the inertia mass, natural frequency can be increased on the mass.

2.2. Circuit Model

Fig. 2 shows the circuit model of the capacitive accelerometer's sensing element [12]. A movable plate forms a capacitance C_1 and C_2 with the plates which are fixed to the upper and lower. Initially, the acceleration is zero, then the middle movable plate is located in the middle, there are the same capacitance value in the two capacitors, i.e., $C_1 = C_2 = C_0$. When there is an external acceleration a, the movable plate produces the displacement Δx with the acceleration in the opposite direction, so that a capacitance value increases, the another capacitance value decreases. The difference between C1 and C2 is defined as the differential capacitance ΔC.

$$\Delta C=C_1-C_2=\frac{\varepsilon S}{x_0-\Delta x}-\frac{\varepsilon S}{x_0+\Delta x}=\frac{\varepsilon S 2\Delta x}{(x_0-\Delta x)(x_0+\Delta x)}, \quad (5)$$

where ε is the capacitive dielectric constant, *S* is the area which is faced between the fixed plate and the movable plate, x_0 is the initial distance between the fixed plate and the movable plate. Taking into account the linearity requirements of the capacitance change, the displacement of the movable electrode is typically limited to a small range, under conditions $\Delta x << x_0$, formula (5) can be rewritten as:

$$\Delta C \approx 2\varepsilon S\frac{\Delta x}{x_0^2} = 2C_0\frac{\Delta x}{x_0}, \quad (6)$$

where when $\Delta x << x_0$, $\Delta C \propto \Delta x$. And by the formula (3), when $\omega << \omega_r$, the displacement change is proportional to the acceleration changes outside. The amount of the movable plate displacement is far less than the initial spacing between the movable plate and the fixed plate, and the measured acceleration frequency is much less than the natural frequency of the sensor, the differential capacitance is proportional to the external acceleration, the value is related with the strength and direction of the acceleration. By measuring the change amount of the capacitance difference, it is possible to obtain a signal which is related to the acceleration information [13].

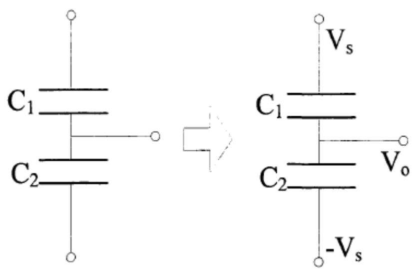

Fig. 2. Equivalent circuit.

In Fig. 2, if the voltage of the vertical fixed plates are + V_s and - V_s, the movable electrode plate output voltage is:

$$V_0 = -V_s + \frac{C_1}{C_1 + C_2}(2V_s) = \frac{C_1 - C_2}{C_1 + C_2}V_s, \quad (7)$$

If the external acceleration direction is downward, the movable plate is the upward movement, they are substituted into equation (7), it can be obtained.

$$V_0 = \frac{C_1 - C_2}{C_1 + C_2}V_s = V_s\frac{\Delta x}{x_0}, \quad (8)$$

where $V_o \propto \Delta x$ can be obtained, the output voltage of the movable electrode is proportional to the displacement of the movable electrode. From the above analysis, when $\omega << \omega_r$, $\Delta x \propto a$. When $\omega << \omega_r$, $V_o \propto a$, and the output voltage of the movable electrode is proportional to the external acceleration.

From the above analysis, the natural frequency of the design is extremely important in the design of capacitive acceleration sensor. When the frequency of the measured acceleration is much less than the natural frequency, the output voltage of the movable electrode is linear with the external acceleration. The output voltage of the movable electrode is read out by a subsequent read-out circuit, so that the final output voltage of the sensor is a linear relationship with the measured acceleration.

2.3. Equivalent Electrical Analog of the Sensing Element

Capacitive accelerometer can be modeled as a second-order spring-damper system, as is shown in Fig. 1. The vibration differential equations of the capacitive acceleration sensor are given in equation (1), it is rewritten as follows:

$$mx'' + cx' + kx = ma, \quad (9)$$

The damping coefficient c, elasticity coefficient k, the movable plate displacement x, m the vibration mass and the outside acceleration are replaced by corresponding equivalent electrical parameters, the sensitive components of the capacitive acceleration sensor can be converted to the RLC resonant circuit which is shown in Fig. 3. Differential equation of the RLC resonant circuit is:

$$CV_{out}'' + \frac{1}{R}V_{out}' + \frac{1}{L}V_{out} = \frac{1}{L}V_{in}, \quad (10)$$

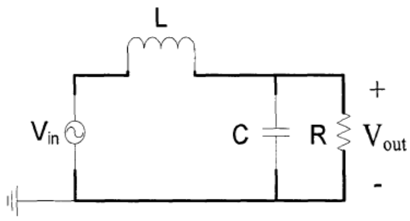

Fig. 3. Equivalent Circuit.

The corresponding relationship between the electrical parameters of equivalent circuit and the mechanical parameters of the sensor sensitive components is shown in Table 1.

Table 1. The correspondence between the mechanical parameters and electrical parameters.

Mechanical model parameters	Electrical model parameters
Inertial mass module m	Capacitance C
Damping coefficient c	Impedance 1/R
Elasticity coefficient k	Inductance 1/L
Displacement x	output voltage V_{out}
Inertial force ma	Vin/L

The displacement of an acceleration sensor is simulated by the voltage across the capacitor in the circuit model, the expression (6) of the capacitance difference can be rewritten as follows:

$$\Delta C \approx 2C_0 \frac{V_{out}}{x_0}, \tag{11}$$

When the equivalent RLC electrical model of sensitive components are used, the acceleration sensor is designed with system simulation in the same environment, and the micro-electromechanical systems are optimized, and the vibration displacement response is researched conveniently, and the mechanical parameters of the sensing element are optimized in their design.

3. Structural Design

Design is shown in Fig. 4 and Fig. 5. Because the size of the mass and the thickness of the cantilever has been determined, that is the thickness of the SOI device layer, in order to meet the requirements of the natural frequency and the first order and vibration mode which is desired, the width of the cantilever is changed.

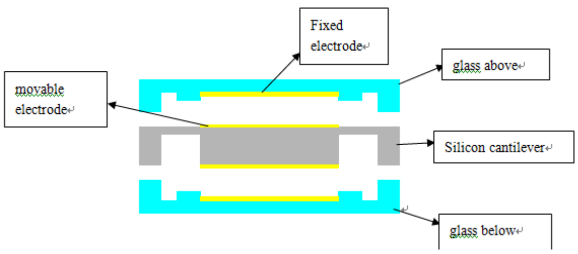

Fig. 4. Overall Structure FIG.

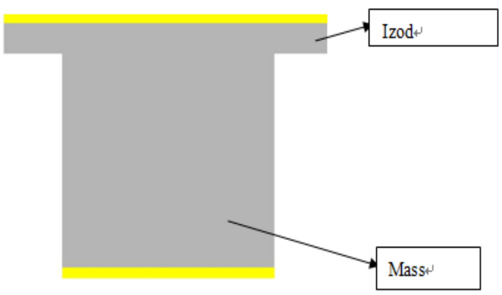

Fig. 5. Mass cantilever diagram.

As shown in Fig. 6, it only needs to change the *D* size [14].

Sensitive devices are designed according to the following structure:

The key size of the structure is shown in Fig. 6. X = 2 mm, X1 = 0.1 mm, X2 = 0.675 mm, Y = 0.685, Z = 2, D = 0.3 mm. The initial position d0 is 1 mm, which is set from the movable electrode to the fixed electrode.

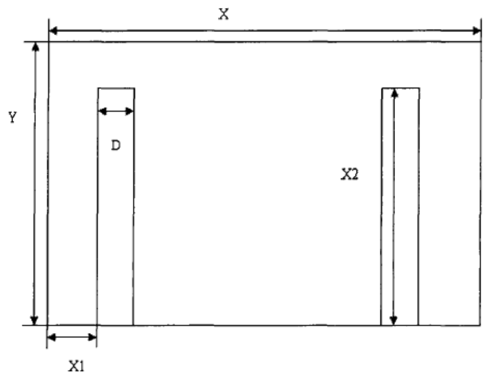

Fig. 6. Structure size chart.

4. Simulation

First, each mode of the sensitive element is solved according to the simulation of the structural design, and then the structural parameters are adjusted as required. Structural modeling is analyzed and mesh is made by using Ansys, which is shown in Fig. 7.

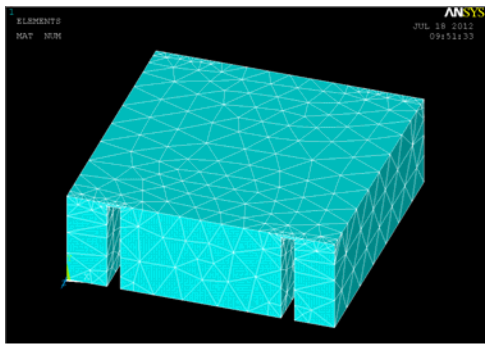

Fig. 7. Graphical Modeling.

Table 2. Set the parameters.

Monocry-stalline	Young's modulus	Poisson's ratio	Density	Structural units	
MKS	$1.65*10^{11}$	0.3	$2.33*10^{3}$	solid45	
X	X_1	X_2	Y	Z	D
2	0.1	0.675	0.685	2	0.3

Table 3. Ansys simulation results according to the data in Table 2.

Set	Time/FREQ	Load Step	Substep	Cumulative
1	3294.9	1	1	1
2	3883.6	1	2	2
3	4791.2	1	3	3
4	5594.1	1	4	4
5	6221.2	1	5	5

Displacement results are shown in Fig. 8.

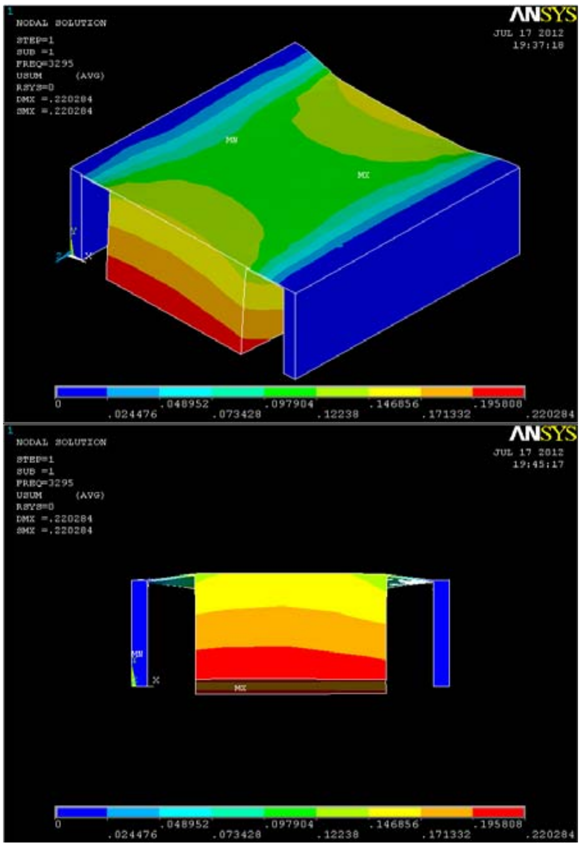

Fig. 8. Displacement of device vibration in Z-axis direction.

From the results in a modal, the maximum displacement is about 0.220284 mm. It can be seen from the above results that the device frequency is 3294.9 Hz, and it does not match with the requirements of frequency 10000 Hz. So the size of the device is changed, in order to increase the natural frequency and to achieve the results which are required. The following table shows the modified device parameters, the simulation again.

Table 4. Parameter setting after the change.

Monocry-stalline	Young's modulus	Poisson's ratio	Density	Structural units	
MKS	$1.65*10^{11}$	0.3	$2.33*10^{3}$	solid45	
X	X_1	X_2	Y	Z	D
2	0.3	0.655	0.685	2	0.1

Table 5. Ansys simulation results.

Set	Time/FREQ	Load Step	Substep	Cumulative
1	16631	1	1	1
2	19492.	1	2	2
3	25074.	1	3	3
4	27070.	1	4	4

Vibration displacement [15] is obtained on the Z-axis direction, as is shown in Fig. 9. The maximum displacement is 0.854485 mm. In order to avoid that the moving plates are met with the fixed plates, so d_0 is 1 mm and barrier is set to prevent the collision which is occurred when overloaded.

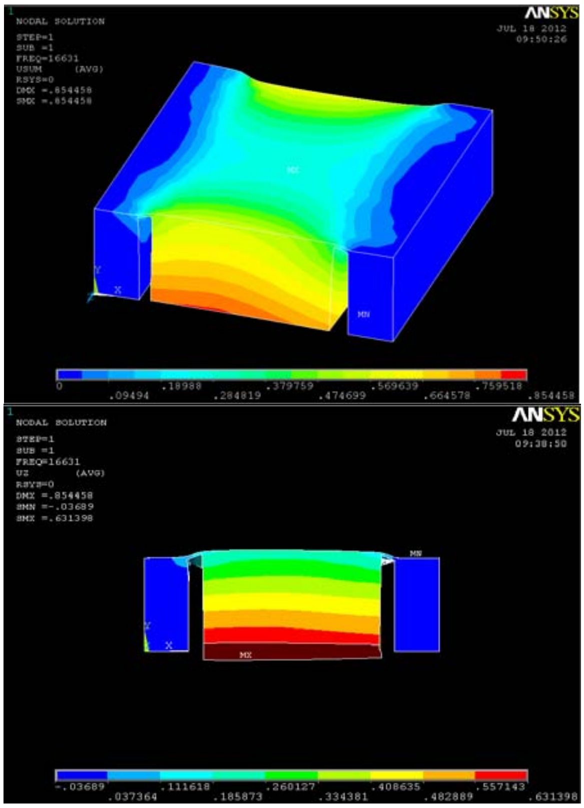

Fig. 9. Device Z-axis displacement map and a side view of the device displacement.

The transfer function of the sensing element has been obtained by the preceding analysis. In order to analyze the electrode displacement with external acceleration action, the sensitive elements are simulated by the MAILAB.

When the selected frequency is 500 Hz, a = 1, a = 2, a = 10, a = 20, when a frequency of 1000 Hz, a = 1, a = 2, a = 10, a = 20, their displacement changes are in Fig. 10.

As can be seen from the above simulation, output displacement is proportional to acceleration, and frequency affects the output density.

The sensor output voltage and the ΔC output are simulated from formula (5) to formula (11).

When the selected frequency is 500 Hz, a = 1, a = 10, when a frequency of 1000 Hz, a = 1, a = 10, their output voltages are in Fig. 11.

Simulation shows, the higher the frequency of the acceleration, the smaller the displacement of the sensitive element. In order to obtain high sensitivity, the test acceleration frequency should be away from the natural frequency of the sensing element. The displacement output of the sensitive element is related with the size of damping factor ξ. It can also be seen from the simulation results that, after amplification circuit, the output voltage can be detected in mV level, and the output voltage is alternating current, and the corresponding acceleration is obtained after the circuit can be processed, and velocity, displacement and their related information can be obtained through the integration.

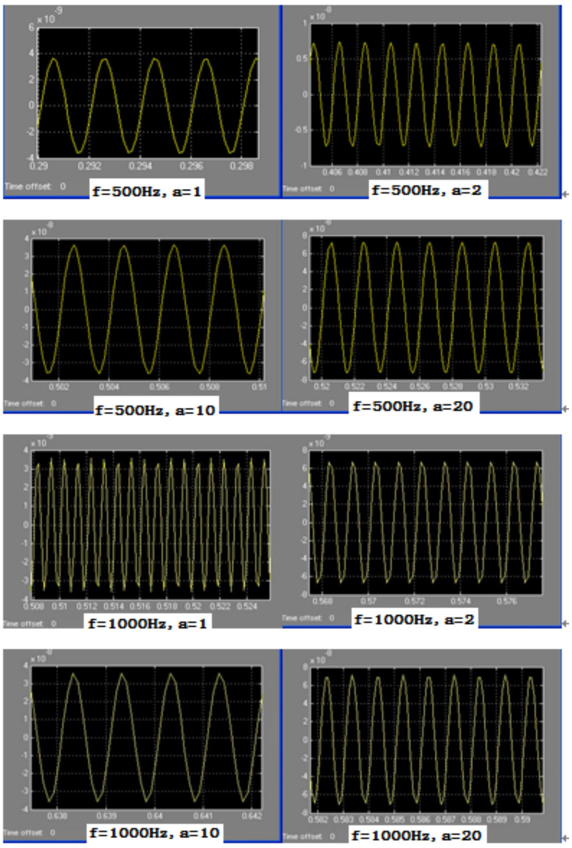

Fig. 10. The displacement with different frequencies, different a value.

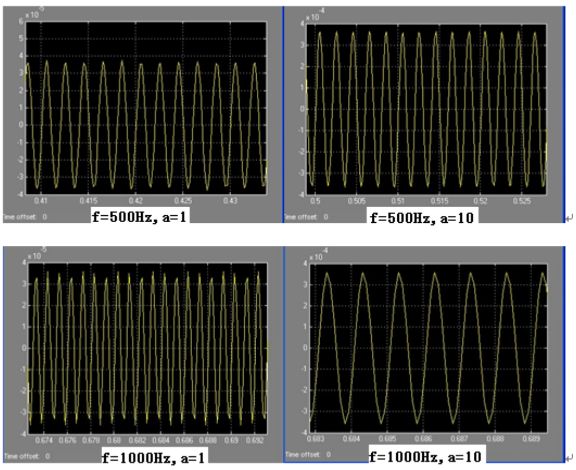

Fig. 11. The output voltage with different frequencies, different a value.

5. Conclusion and Outlook

It has shown by studies that the sensitivity of the differential capacitor and linearity are better than single capacitor. On the basis of the article, the selected sensitive structure is typical differential capacitive structure, the specific configuration parameters are as follows: X = 2 mm, X_1 = 0.1 mm, X_2 = 0.675 mm, Y = 0.685, Z = 2, D = 0.3 mm, and an initial position d0 from the movable electrode to the fixed electrode is set to d_0 = 1 mm. Structure modal analysis is made by annoys software, its output characteristics is simulated by using Matlab software. The result follows that the structure modal is 16631 Hz, the maximum displacement is 0.854485 mm. The Matlab simulation result is that the higher the frequency of acceleration, the smaller the sensitive components displacement. In order to obtain high sensitivity, the frequency of the test acceleration is required away from the natural frequency of the sensing element. The size of the damping factor ξ is related with the displacement output of the sensitive element. When ξ is less than 1, the displacement response curve of the sensitive element will vibrate, the smaller the ξ, the greater the peak vibration, the longer the time period when vibration is eliminated. When ξ is larger than 1, the vibration does not occur, and with the ξ increase, the time is longer when system reaches a stable value. The size of the sensitive elements is designed, and the damping factor is adjusted, so that the response time of the sensor displacement is less than half of the acceleration measured period, the final output of the displacement is proportional to the acceleration.

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