Analysis and experimental study on force balance accelerometer

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ABSTRACT: Force balance accelerometer is in expanding need recent years. Because of the short history and limited application past, the relevant theory of this type of accelerometer is not studied well. Theoretical analysis and experimental study results are introduced here. For Force Balance Accelerometer, a pair of back-to-back electrical signal is added to the fixed up and down plates of difference variable capacitor. The input acceleration will cause relative movement (displacement) of the movable middle plate, this displacement induces unbalance of the capacitor, this capacitor variation, which is proportional to the input acceleration, is converted into a voltage by successive circuit, a feedback circuit will generate a current through the coil attached to the movable plate, and apply a force which is balanced to that caused by the input acceleration. The voltage will be recorded as the indication of input acceleration.

Based on force balance principal and the design experience of BA-02 accelerometer, the author fully analyzed moving function, mechanical parameters and electronic parameters of accelerometer. As a single particle damping system, three kinds of force applied on the moving part of accelerometer. They are feedback electromagnetic force F_d, damping force F_b and spring restoring force F_k. According to d'Alemberts principal, the mechanical moving function of the accelerometer could be calculated. And from mechanical moving function three key parameters' functions, resonance frequency ω, damping parameter ξ, amplitude frequency response A, could be figured out. The results shows that three components of accelerometer that are mass quality m, proportional resistance R and differentiate capacitor C, settle the resonance frequency, bandwidth and output sensitivity of the accelerometer.

1 INSTRUCTIONS

Force balance accelerometer has many merits, such as large dynamic scale, high precision. Accelerometer of type BA-02 introduced in this paper has good specifications. It can fulfill earthquake measurement and all kinds of low frequency vibration measurement. The specifications are as follow. The measurement scale is ±2.0g_n. Its' effective frequency bandwidth is 0~120Hz(3dB). There are three kinds of sensitivity, ±2.5V/g_n, ±100.0V/g_n and ±1000.0V/g_n. And the supply power is DC ±12V.

Normal designing principal of force balance accelerometer is as follow. Driving signal modulate, demodulate, and through feedback circuit force feedback were brought into accelerometer. The voltage output is direct proportional to capacitor's movement. And capacitor's displacement is proportional to movement acceleration of accelerator shell. So the voltage output of capacitor stand for moving acceleration of accelerator shell. Reference to analysis materials of single-degree of freedom system, we can calculate specifications of accelerator[1]. But materials that fully describe movement function, mechanical parameters, electrical parameters of accelerometer are rare. So in this paper, we focus on design analysis of force balance accelerometer.

2 DESIGN PRINCIPLE OF FORCE BALANCE ACCELEROMETER

Force balance accelerometer is one kind of vibration sensor which can measure vibration acceleration change and convert it into voltage. Then acceleration can be easily measured. The accelerator introduced here is one kind of close loop sensor that differential capacitor was used as transforming circuit. The sensor is a single pendulum of vibration system. The mass and two fixed electrodes constitute two transformable capacitors. When this is a displacement of mass that produced by mass acceleration, First capacitors can transform displacement changing to static capacitor changing. Second, through differential pulse amplitude modulation circuit, capacitor changing was converted into voltage output. Figure 1 is the schematic block diagram of design principal. Now such products you can get from market that produced by China BeiAo vibration technology company and American Kinematrics company were all designed on this theory.

There are three electrode of capacitor inside the accelerometer. And they were mounted on the base shell through connectors. The up-electrode and down-electrode were complete mounted on the shell so they can not move independently. But only one side of middle-electrode connects with shell through two springs. So the middle-electrode can move up and down inside the accelerometer. Two sine alternating waves with same amplitude and different angle separately drive up-electrode and down-electrode. When accelerometer shell move, the middle-electrode move relatively inside the sensor. Volt V_1 was generated with the movement of the middle-electrode. And through the demodulate circuit, V_1 was magnified several multiple by the amplifier electrocircuit. Then we get volt V.

Through feedback circuit which is made up of proportion resistance R and differential capacitance C, output voltage V was convert to feedback current I_f. The feedback current flows through current-force transformer winding. And the winding lies on alnico. A certain extent electromagnetic force was produced by the reaction between magnetic field and winding. For the winding and middle-electrode were connected together, then feedback electromagnetic force drives middle-electrode to do same directional movement. And so this movement changes the middle-electrode position.

magnitude of drive voltage input on up electrode and down electrode[3]. So we can get the equation (1):

$$V_1 = V_0 \cdot x/L \qquad (1)$$

In equation (1):

V_0 is magnitude of drive voltage input on up electrode and down electrode.

x is relative displacement of middle capacitance electrode.

L is distance between up-electrode and down-electrode. And we should subtract thickness of two electrode from the distance.

2.2 *Output voltage*

Through the demodulate circuit output voltage of the sensor's middle electrode was turn into DC voltage. Then the DC voltage be amplified K_a by an amplifier circuit. So we can get the output voltage V of the sensor.

$$V = K_a \cdot V_1 = K_a \cdot V_0 \cdot x/L \qquad (2)$$

We define K_d as the displacement – voltage transformer parameter. So see the equation (3):

$$K_d = K_a \cdot V_0/L \qquad (3)$$

Then there is equation (4):

$$V = K_d \cdot x \qquad (4)$$

Equation (4) means that, the waveform of sensor output voltage V manifests middle-electrode moving displacement. And middle-electrode displacement manifests the acceleration of sensor shell. So waveform V stands for environment acceleration.

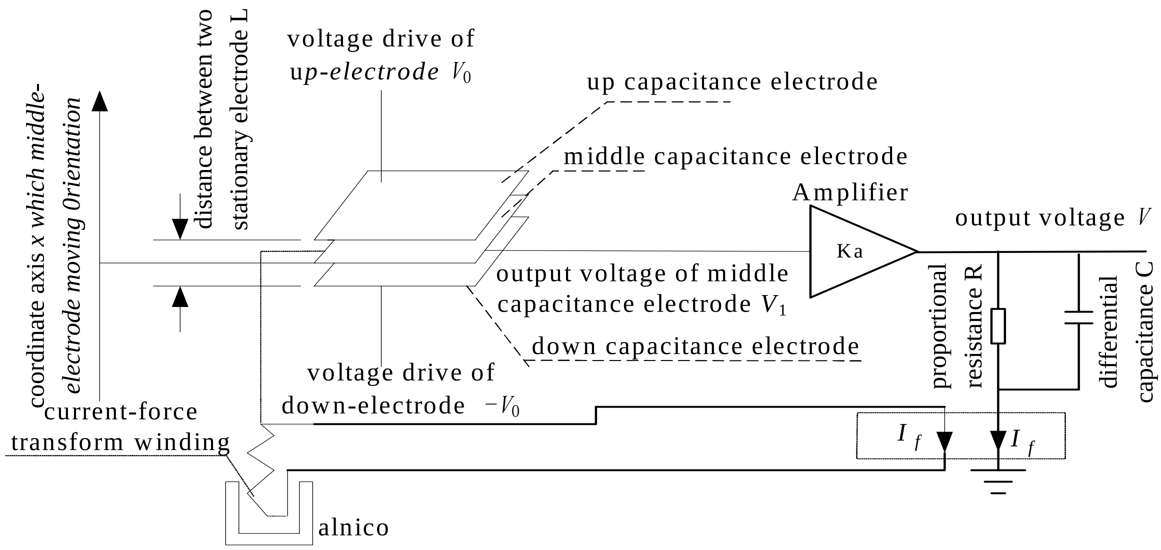

Fig.1 Structure of Force Balance Accelerometer

2.1 *Output voltage of middle capacitance electrode*

Middle capacitance electrode deviate the central position for the movement. That makes the output voltage V_1 of middle capacitance electrode deviate zero volt. The magnitude of V_1 has relation with displacement of middle capacitance electrode, distance between up electrode and down electrode and

There are difference between the magnitude and amplitude of V and the magnitude and amplitude of acceleration. In this paper we focus on the description.

2.3 *Feed-back current in windings*

Trough feedback eletrocirciut, output voltage of accelerometer inflects middle-electrode. Feedback voltage was transformed into current by the proportional resistance and feedback capacitance. This current was called feedback current of winding. See equation (5):

$$I_f = V/R + C \cdot V' \quad (5)$$

In equation (5):

V' stands for deviation of V.

2.4 *Electromagnetic force of capacitor's middle-electrode*

For there is a current in the current-force transformer winding, and there is a magnetic field in the alnico, so one feedback electromagnetic force, F_d, were formed in the winding of the sensor. And this force is proportional to feedback current. See equation (6):

$$F_d = K_f \cdot I_f \quad (6)$$

K_f stands for force produced by one unit of current. And it only has relationship with winding number and alnico intension. You can put equation (5) into equation (6), and get following equation:

$$F_d = K_f \cdot (V/R + C \cdot V') \quad (7)$$

3 FORCE ANALYSIS OF ELECTRIC CAPACITOR'S MIDDLE-ELECTRODE

There are three kinds of force applied on sensor's middle-electrode. They are damp force, spring restoring force and feedback electromagnetic force. And we define initial moving direction as positive direction.

Damp force:

The accelerometer is single-particle-with-damp vibration system. So there is energy dissipation that prevents the capacitor's middle-electrode moving until stop. In the force balance accelerometer if we suppose the damp coefficient is b, then the damp force of the accelerometer is F_b. The direction is minus.

$$F_b = b \cdot x' \quad (8)$$

Spring restoring force:

The sensor is a spring system so there is a spring restoring force. And the spring restoring force prevents the middle-electrode of capacitor moving and draws it back to the balance position. We suppose the sensor elasticity coefficient is k. Then the spring restoring force is F_k, see following equation:

$$F_k = k \cdot x \quad (9)$$

Feed-back magnetic force:

See equation (7), the direction is minus.

4 MOVING EQUATION ANALYSIS OF FORCE BALANCE ACCELEROMETER

Take space fixed coordinate as base, earth surface displacement which installed the sensor is y. The moving displacement of sensor's middle-electrode is x which is measured relative to earth surface. So variable $x + y$ is the absolutely displacement of the sensor. Then we can get the sensor's movement acceleration $\xi = x'' + y''$. The inertial force of the sensor is F_m, see equation (10):

$$F_m = m(x'' + y'') \quad (10)$$

According to force balance theory, equation (11) exists.

$$F_m = F_d + F_k + F_b \quad (11)$$

From equation (7) ~ (11), we can get mechanical moving function of force balance accelerometer.

$$m \cdot (x'' + y'') = -b \cdot x' - k \cdot x - K_f \cdot (C \cdot V' + V/R) \quad (12)$$

Put equation (4) into equation (12),

$$m \cdot (V''/K_d + y'') = -b/K_d \cdot V' - k/K_d \cdot V - K_f \cdot (C \cdot V' + V/R)$$

Then

$$m/K_d \cdot V'' + m \cdot y'' + b/K_d \cdot V' + K_f \cdot C \cdot V' + k/K_d \cdot V + K_f/R \cdot V = 0 \quad (13)$$

In equation (13), the function of b and k are so small that can be neglected. So it can be simplified to following equation:

$$V''/K_d + K_f \cdot C/m \cdot V' + K_f/(R \cdot m) \cdot V = -y'' \quad (14)$$

Supposes $Y = -y''$, then formula (14) can be transform to formula (15) or (16):

$$V''/K_d + K_f \cdot C/m \cdot V' + K_f/(R \cdot m) \cdot V = Y \quad (15)$$

Or

$$V'' + (K_f \cdot K_d \cdot C)/m \cdot V' + (K_f \cdot K_d)/(R \cdot m) \cdot V = K_d \cdot Y \quad (16)$$

Do Laplace transformation:

$$V(s)/Y(s) = K_d \cdot 1/(S^2 + K_f \cdot K_d \cdot C/m \cdot S + (K_f \cdot K_d)/(R \cdot m)) \quad (17)$$

5 ANALYSIS OF ACCELEROMETER'S PARAMETER

The specifications of accelerometer are crucial for the application range is depends on its. So we must fully analyze parameters of accelerometer. From moving function (16) and (17), and with the help of standard moving function, we can calculate three key parameters, resonance frequency, damp parameter and amplitude response. Referring to these parameters we can get accelerometer's other parameters.

5.1 *Rresonance frequency*

Referring to accelerometer's moving function (16), we can get the resonance frequency of accelerometer, see equation (18).

$$\omega^2 = (K_d \cdot K_f)/(m \cdot R) \quad (18)$$

In equation (18), feedback electromagnetic coefficient K_f and displacement – voltage transformer parameter K_d are constant. So accelerometer's resonance frequency depends on mass quantity m and proportion resistance R. Increasing the mass quantity or proportion resistance, the resonance frequency will be enlarged. Adversely, reducing the mass quantity or proportional resistance, the resonance frequency will be lessened.

5.2 *Damp*

Referring to accelerometer's moving function (16), we can get accelerometer's damp, see equation (19).

$$\xi^2 = K_d \cdot K_f \cdot R \cdot C^2/(4 \cdot m) \quad (19)$$

In equation (19), accelerometer's damp has relation with proportion resistance, feedback capacitor and mass quantity. If we adjust one of these three parameters the damp will change. Then it will inflect accelerometer's specification.

5.3 *Relationship between damp and frequency*

From equation (16) and standard moving function we can get equation (21).

$$2 \cdot \xi \cdot \omega = (K_f \cdot K_d \cdot C)/m = C \cdot R \cdot \omega^2 \quad (21)$$

And from equation (21) we can get following result.

$$C \cdot R = 2 \cdot \xi/\omega \quad (22)$$

In equation (22), if $\xi = 0.707$, $\omega = 6.28 \cdot 100$, the damping frequency $\omega_z = 70Hz$, so there is below equation.

$$C \cdot R = 0.002252$$

Then $R = 225$, $C = 10uF$.

5.4 *Relationship between resonance frequency and response*

From equation (18) and equation (20), we can get following equation. That is $A \cdot \omega^2 = K_d$. K_d is displacement and voltage transform parameter. When K_d is a constant, A has reverse proportion relation with ω. If ω be enlarged to 100 times, then A decreased to 0.1 times.

6 INTRODUCTION OF ACCELEROMETER'S SPECIFICATION AND EXPERIMENTAL DATA

Type BA-03 accelerometer was designed on the force balance theory. And the detailed specification is in table 1.

In engineering application, accelerometer's magnitude response, linearity curve have great effects on the reliability of measuring data. So in this paper we give these two data. Table 2 is ba-03 accelerometer's magnitude response from 3Hz to 130Hz. Table 3 is BA-03 accelerometer's 10 Hz linearity data. From real calibration data, this kind of accelerometer can be used to measure the low frequency earthquake or vibration.

7 CONCLUSION

Force balanced accelerometer is very durable. It can endure overload, bump. The accelerometer's volume and weight are very small. And it has good temperature characteristic. The sensor shell is designed as one sealed box so it can work in atrocious environment. So it be used to measure acceleration in earthquake, buildings, aviation, traffic, mechanical industry.

Table 1 Specification of Force Balance Accelerometer

	Single axial accelerometer	Triaxial accelerometer
range	$\pm 2.0g_n$	$\pm 2.0g_n$
resonance frequency	100Hz	100Hz
bandwidth	0-120Hz (3dB)	0-120Hz (3dB)
damp	0.6~0.7	0.6~0.7
sensitivity	±2.5V/g（low） ±100.0V/g（high）	±2.5V/g（low） ±100.0V/g（middle） ±1000.0V/g（low）
zero drift	<10mV	<10mV
dynamic scope	126dB	126dB
power	±12V（DC）	±12V（DC）
weight	0.262Kg	1.95Kg

Table 2 Magnitude Frequency Magnitude Data of Force Balance Accelerometer

Frequency(Hz)	Input Acceleration(g)	Accelerometer Output Voltage(V)	Accelerometer Sensitivity(V/g)
2.99	0.1	0.249	2.49
4.98	0.2	0.498	2.49
9.97	0.5	1.255	2.51
19.9	0.98	2.479	2.53
29.9	0.97	2.474	2.55
39.95	1.01	2.586	2.56
59.95	1.03	2.657	2.58
79.73	0.99	2.534	2.56
99.54	0.98	2.421	2.47
110.1	1.03	2.472	2.40
120.1	1.07	2.279	2.13
129.5	1.02	1.775	1.74

Table 3 Linearity Data of Force Balance Accelerometer(10Hz)

Input Acceleration (g)	Accelerometer Output Voltage(V)	Accelerometer Sensitivity(V/g)
0.1	0.2551	2.551
0.2	0.5102	2.551
0.5	1.2755	2.551
1.0	2.5480	2.548
1.3	3.3098	2.546
1.6	4.0704	2.544
2.0	5.0860	2.543

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