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Characteristics evolution of indigenously designed and developed tri-axial force balance accelerometer

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This paper describes indigenously designed and developed tri-axial Force Balanced Accelerometer (FBA) using variable capacitance transduction and electromagnetic feedback. Accelerometer is a highly sensitive, low frequency seismic sensor characterized by rugged construction and proven reliability. It has been designed and developed for ±1g full-scale range with 50 Hz natural frequency mainly for seismic, structural, aerospace and some commercial applications. In a single unit, three accelerometers are orthogonally mounted on a plate and housed in a case for recording all the three components of motion. Characteristics evolution of a natural frequency, damping and noise level, have been done, tested and explained. During designing, most of the technical specifications have been considered for low frequency band from DC to 200Hz applications. Accelerometer is suitable for strong motion recording purpose.

Keywords: Force balanced accelerometer, Frequency, Transduction methods

Introduction

Various transduction methods based on the change in resistance, capacitance or inductance, or any other principle can be used to measure the seismic mass motion with respect to the case[1]. By using these methods, seismic sensors have been developed such as geophone, seismometer and accelerometer as per measurement of displacement, velocity, or acceleration component of earth motion. Geophone and seismometer measure the displacement or velocity and accelerometer measures the acceleration components of the motion.

Accelerometers

Accelerometers based on various techniques and technology are available for different applications. Strain gauge based accelerometer is simplest one to measure the vibration. Solid-state devices based accelerometer gives a higher frequency response. Piezoelectric accelerometer is a self-generating sensor that converts the acceleration into equivalent electrical energy[2]. Another important accelerometer is servo accelerometer or force balance accelerometer (FBA), which measures the acceleration of a structure or vehicle on which it is mounted. In this system, force is needed to prevent the mass movement relative to the instrument frame. A displacement transducer produces a signal proportional to the relative movement of the mass with respect to the instrument frame, and this signal is amplified and fed back as direct current to the force coil suspended in a magnetic field[3]. A flat response from DC to 500Hz can be obtained in these devices with high sensitivities.

Tri-axial Force Balanced Accelerometer

FBA sensor is a spring mass device using variable capacitance transduction and electromagnetic feedback (Fig. 1). The output is fed back to the torque coil, which is an integral part of the mass. From the coil, the feedback loop is completed through resisters R1 and R2, which stiffens the system thereby increasing the natural frequency to 50 Hz. Resister R3 and capacitor C1 control the damping. The acceleration sensitivity is controlled by the gain of the post-amplifier.

The developed tri-axial FBA has three accelerometers (Fig. 2) orthogonally mounted on an internal deck plate. Each of these units, are housed inside the waterproof, anodized cast aluminum housing and sealed to prevent ingress dirt and moisture. There are three capacitor plates A, B, and C (size, 25 mm× 25 mm×0.65 mm). The central plate B is fixed and plate A and C refer to upper and lower plate placed at equal distance (0.65 mm) from the central plate B.

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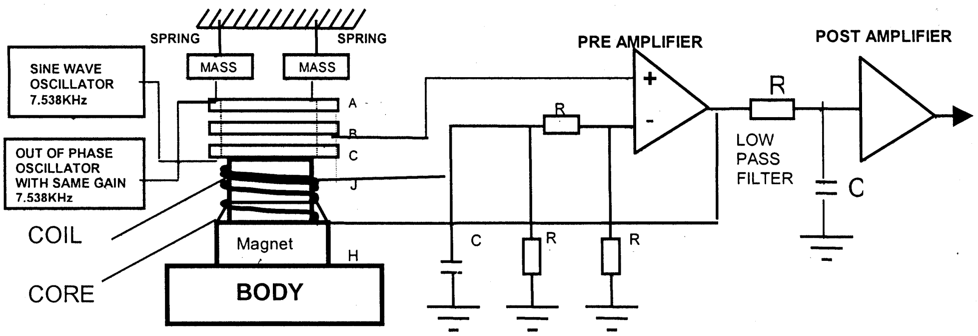

Fig. 1—Block diagram of force balance accelerometer

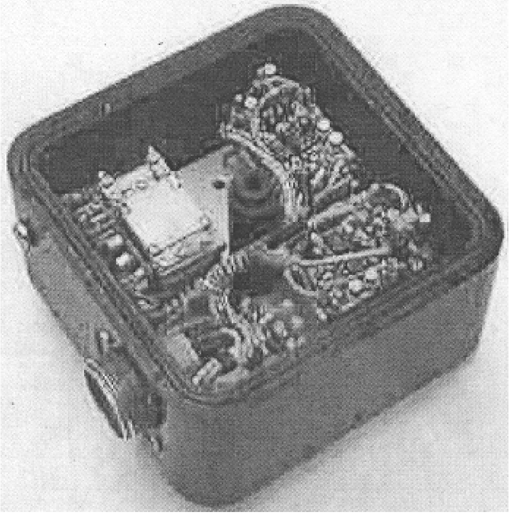

Fig. 2—Newly developed accelerometer

The oscillator (approx 7.5 KHz) applies an AC signal of opposite polarity to the two capacitor plates, also referred to as "the moving mass"; when no acceleration is applied, these plates are symmetrical to fixed central plate and no voltage is produced. Whenever there is acceleration, due to any movement, it causes the coil and the capacitive plate to move with respect to the fixed central plate of the capacitive transducer. The capacitor becoming unbalanced, results in an AC signal on the central plate of the capacitor. This signal is passed to the amplifier. A feedback loop is completed through coil to create a magnetic restoring force to balance the capacitor plates back to their original null position. The current traveling through the coil is directly proportional to the applied acceleration. The current is converted into a voltage and passed through to the low pass filter of desired frequency. The voltage output is set at 2.5V for the acceleration value corresponding to the particular range (acceleration of 1g).

Designing of Some Important Parameters

As per the accelerometer specifications, full-scale range has been considered as ±1 g (where g=980 cm/sec^2). To achieve the full-scale range, the complete distance between the two capacitor plates need to be covered. Maximum distance in one complete cycle, which can be covered by capacitor plates, is equal to 0.65+0.65 =1.3 mm or 0.13 cm, to achieve the full-scale range. Therefore, time taken due to acceleration for full-scale range will be equal to 0.13/980 sec or T= 0.13/980 sec. Therefore, the frequency required to oscillate the capacitor plates f = 1/T =980/0.13 Hz or 7.538 KHz. To achieve the desired frequency, a Wein Bridge sine wave oscillator[4] has been designed for frequency (f_o) = 7.538 KHz and connected to upper capacitor plate mark A. The frequency of the Wein Bridge sine wave oscillator is given by the relation[5]

$$f_o = 1 / (2\pi RC)$$

where, π = 3.14, R and C selected 210K ohms and 0.00001 µF. Therefore

$$f_o = 1/(2\times 3.14\times 210\times 10^3\times 0.00001\times 10^{-6}) = 7.582\text{K Hz}$$

(adjusted to 7.538KHz)

Same sine wave signal, but out of phase, has also been connected to the lower capacitor plate C, so that the signals can be neutralized to each other while plates A and C are at equal distance from center plate B. For considering the other full scale ranges other than ±1g, designer can change the distance between two capacitor plates or oscillator frequency. However, the thickness of the plate has been taken as low as possible to reduce the weight for easy movement of plates due to external force.

The operation of capacitor transducer is based upon the familiar equation for capacitance of a parallel plate capacitor

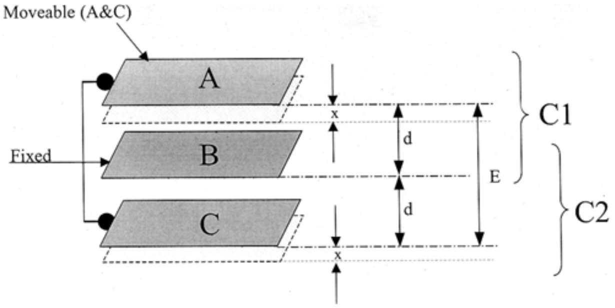

Fig. 3—Parallel plate capacitors transducer

Capacitance $C = \varepsilon A/d$

where, A = overlapping area of plates; d = distance between two plates; and ε = dielectric constant

In a capacitive transducer, the change of capacitance may be caused by: i) Change in overlapping area; ii) Change in the distance d between the plates; and iii) Change in dielectric constant. These changes are caused by physical variables like displacement, force and pressure in most of the cases. This type of a capacitive transducer is suitable for measurement of linear displacements with very high accuracy. In a parallel plate capacitor (Fig. 3), the capacitances are as $C1 = \varepsilon A/d$ and $C2 = \varepsilon A/d$. An alternating voltage E is applied across plates A and C and the difference of the voltage across the two capacitance is measured.

Voltage across $C1$ is $E1 = EC2 / C1 + C2$ and
Voltage across $C2$ is $E2 = EC1/C1 + C2$

When the upper and lower moveable plates are at equal distance from the middle fixed plate B then, $C1 = C2$ and therefore voltage $E1 = E2$. Differential output at this stage will be

$$\Delta E = E1 - E2 = 0$$

Let the movable plates be moved up due to some force to a displacement x. Therefore, the values $C1$ and $C2$ become different resulting in a differential voltage output.

Now $C1 = \varepsilon A/(d - x) C2 = \varepsilon A/(d + x)$

$$\begin{aligned} E1 &= C2E/(C1 + C2) \\ &= E\,\varepsilon A/(d + x)/\{\varepsilon A/(d - x) + \varepsilon A/(d + x)\} \\ &= E\,(d - x)/2d \end{aligned}$$

$$\begin{aligned} E2 &= C1E/(C1 + C2) \\ &= E\,\varepsilon A/(d - x)/\{\varepsilon A/(d - x) + \varepsilon A/(d + x)\} \\ &= E\,(d + x)/2d \end{aligned}$$

Differential output voltage =
$\Delta E = E1 - E2 = [E\,(d-x)/2d - E\,(d-x)/2d] = E\,(x/d)$

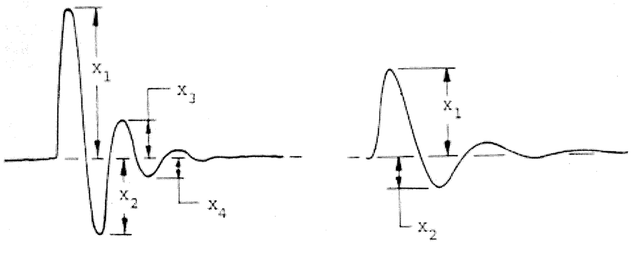

Fig. 4—Damping test results

Therefore, the output voltage varies linearly as the displacement

Sensitivity $S = \Delta E/x = E/d$

The differential method can be used for displacements of 10^{-10} mm to 10 mm with an accuracy of 0.1%. During the design and development, it was found that indigenously available permanent magnet strength is one third as compared to magnet used in FBA-23 of M/s Kinematics USA[6]. To maintain the better output signal, coil with more turns has been designed and used for the development of accelerometer. The full scale output voltage was found 3.5V as compared to 2.5V of FBA-23. The developed accelerometer is more sensitive than FBA-23.

Characteristics Evolution and Calibration of Some Important Parameters

Number of parameters such as damping, natural frequency, noise level and full scale range etc. have been evaluated, calibrated and matched with the designed specifications.

Damping

Testing and calibration of damping has been done by recording number of cycles by hammering near the sensor (Fig. 4) and comparing the result output of second cycle with the first cycle output and third cycle output with second cycle and so on i.e. $X2/X1 = X3/X2 = X4/X3 = 0.7$. The ratio comes out 0.7; it indicates that the critical damping is adjusted to 70%.

$X2/X1 = X3/X2 = 0.7$ (Approx 70% critical damping)

Noise

The noise of the output has been checked with 8½ digital multimeter after the final adjustment of capacitor plates. Whenever the output signal approaches to minimum possible towards zero voltage level, the shaft adjustment is completed. At this stage, the output has been checked and found less than 2 µV. Therefore, the noise level is within the technical specification.

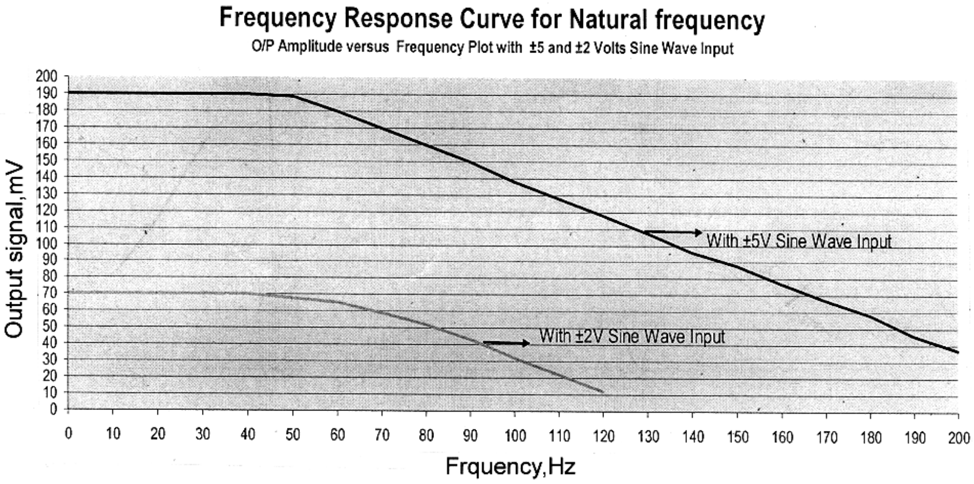

Fig. 5—Testing of natural frequency with ± 2 volts and ± 5 volts input signal

Natural Frequency

By applying different sign wave signals at calibration point D, the output has been recoded by varying frequencies from DC to 200 Hz. The number of output signal sets has been recoded by selecting voltages ±1, ±2, ±3, ±4, and ±5 volts and graph has been plotted between frequencies at input voltages ±2 & ±5 (Fig. 5). It established accelerometer natural frequency at 50 Hz.

Output (full scale)

The full range has been checked by pressing the capacitor plate to move downwards up to full capacitor gap (distance 'd'), and the output of accelerometer has been checked with multimeter. Output was found 3.5 volts, as per following technical specifications: Full scale range, ±1.0g; Natural frequency, 50 Hz; Normal damping, 70% critical; Output (full scale), ±3.5 volts; Zero offset, < 25 mV; Cross-axis sensitivity, <0.03g/g; Noise, 0-50Hz, <±2.5μV; Dynamic range, 130 dB, 0-50Hz.

Conclusions

The developed tri-axial Force Balance Accelerometer has been interfaced with Seismic Data Recording System and results, compared with similar type of Accelerometer (FBA-23) of M/S Kinematrics USA, were found comparable. The output voltage is 3.5 volts as compared 2.5 volt of FBA-23; therefore, sensitivity of developed accelerometer is better than FBA-23. Some important parameters such as natural frequency, damping and noise level etc. have also been tested and verified separately, and the results were found as per the technical specifications. The developed accelerometer has been put in operation for the application of strong motion recording in Seismological Observatory at CSIO, Chandigarh. It can also be used for other applications, which falls under the technical specifications of described accelerometer.

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