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Physical Principles of Vibration and Measurement Techniques

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Abstract: On the fresh fruit transportation, excessive vibration may cause severe damage on fruits. To determine effect of vibration on the quality of fruits, vibration mechanism should be carefully analysed on transports. In the analysis of vibration phenomenon, which occurs during fresh fruits transportation, knowing the physical principles of vibration and selecting the most proper sensors to measure and understand vibration characteristics are very important. This paper investigates the physical principles of vibration and introduces most widely used vibration detection sensors/techniques for vibration measurements on the fresh fruits transportation.
Key words: physics of vibration, vibration measurement techniques

Titreşimin Fiziksel Prensipleri ve Ölçme Teknikleri

Özet: Taze meyve taşımacılığında, aşırı titreşim meyve üzerinde ciddi hasara neden olabilir. Meyvelerin kalitesi üzerinde titreşimin etkisini belirlemek için taze meyve taşıyan araçlar üzerinde titreşim mekanizması dikkatlice incelenmelidir. Taze meyve taşımacılığı esnasında oluşan titreşim olayında titreşimin fiziksel prensiplerinin bilinmesi ve titreşimin özelliklerinin ölçülmesi ve anlaşılması için en uygun sensörün seçimi çok önemlidir. Bu makale titreşimin fiziksel özelliklerini inceler ve taze meyve taşımacılığında en yaygın olarak kullanılan titreşim ölçme sensörlerini/ tekniklerini tanıtır.
Anahtar Kelimeler: titreşimin fiziği, titreşim ölçme teknikleri

1. Introduction

Mechanical vibration is dynamic phenomena, i.e. their intensity varies with time. When the track is stationary and engine is started, vibration usually occurs because of the dynamic effects of manufacturing tolerances, rolling and rubbing contact between machine parts and out-of-balance forces in rotating and reciprocating members. When the track, which carries fresh fruits is mobile extra vibrations may involve to the vibrations phenomena due to road conditions. Although most of roads conditions of Turkey are suitable for fruits transportation, some road conditions are not well qualified. Fruits are damaged during transportation from agricultural production areas to other areas. In practice, it is very difficult to avoid vibration during fresh fruits transportation due to road conditions. Therefore, to know the level of damage on fruits due to road conditions, vibration and shock measurements should be carried out by suitable sensors/transducers.

Accelerometer transducers are used almost all vibration measurements. In market, there are many kinds of option on accelerometer transducers. To measure real vibration and shock effect on road conditions, the most suitable sensor/transducer should be selected. In this paper, most widely used vibration detection sensors are introduced for vibration measurements on the fresh fruits transportation.

2. Theory of vibration

Vibration is an oscillatory motion. A body is said to vibrate when it describes an oscillating motion about a reference position. Motion is a vector quantity, exhibiting a direction as well as a magnitude. By definition, the motion is not constant but alternately greater and less than some average values. The extent of the oscillation determines the magnitude of the vibration and the repetition rate of the cycles of oscillation determines the frequency of vibration (Griffin 1994).

2.1. Periodic Vibration

Oscillatory motion may repeat itself regularly. When the motion is repeated in equal intervals of time *T*, it is called *periodic motion*. The repetition time t is called the *period* of the oscillation, and its reciprocal, $f = 1/T$, is called *frequency*.

2.2. Spring-Mass System

Most vibratory responses of structures can be modelled as single-degree-of-freedom spring mass systems, and many vibration sensors use a spring mass system as the mechanical part of their transduction mechanism.

In addition to physical dimensions, a spring mass system can be characterised by the stiffness of the spring, K, and the mass, M, or weight, W, of the mass. These characteristics determine not only the static behaviour (static deflection, d) of the structure, but also its dynamic characteristics. If g is the acceleration of gravity (Wilson 1999):

$$F = M.A$$

$$W = M.g$$

$$K = \frac{F}{d} = \frac{W}{d}$$

$$d = \frac{F}{K} = \frac{W}{K} = \frac{M.g}{K}$$

2.3. Dynamics of a Spring Mass System

The dynamics of a spring mass system can be expressed by the system's behaviour in free vibration and/or in forced vibration.

2.4. Free Vibration

Free vibration is the case where the spring is freely deflected and then released and allowed to vibrate. Examples include a diving board, a bungee jumper, and a pendulum or swing deflected and left to freely oscillate. Two characteristic behaviours of the system should be noted. First, damping in the system causes the amplitude of the oscillations to decrease over time. The greater the damping, the faster the amplitude decreases. Second, the frequency or period of the oscillation is independent of the magnitude of the original deflection (as long as elastic limits are not exceeded). The naturally occurring frequency of the free oscillations is called the natural frequency, f_n:

$$f_n = \left(1/2\pi\right)\left(K/M\right)^{1/2} = \left(1/2\pi\right)\left(K.g/W\right)^{1/2} \quad (1)$$

2.5. Forced Vibration

Forced vibration is the case when energy is continuously added to the spring mass system by applying oscillatory force at some forcing frequency, f_f. Two examples are continuously pushing a child on a swing and an unbalanced rotating machine element. If enough energy to overcome the damping is applied, the motion will continue as long as the excitation continues. Forced vibration may take the form of self-excited or externally excited vibration. Self-excited vibration occurs when the excitation force is generated in or on the suspended mass; externally excited vibration occurs when the excitation force is applied to the spring. This is the case, for example, when the base to which the spring is attached is moving.

2.6. Displacement, Velocity, and Acceleration

The simplest form of periodic vibration is the so-called harmonic motion which when plotted as a function of time, is represented by a sinusoidal curve (Broch 1980). Since vibration is defined as oscillatory motion, it involves a change of position, or displacement (Figure 1). Velocity is defined as the time rate of change of displacement; acceleration is the time rate of change of velocity.

2.7. Sinusoidal Motion Equation

The single-degree-of-freedom spring mass system, in forced vibration, maintained at a constant displacement amplitude, exhibits simple harmonic motion, or sinusoidal motion. If the vibration has the form of pure translational oscillation along one axis only, the *instantaneous displacement* of the particle (or body) from the reference position can be mathematically described by means of the equation:

$$x = X \sin 2\pi \frac{t}{T} = X \sin(2\pi.f.t) = X \sin(\omega.t) \quad (2)$$

where $\omega = 2\pi f$ = angular velocity

X = peak displacement,

f = frequency,

x = instantaneous displacement,

t = time

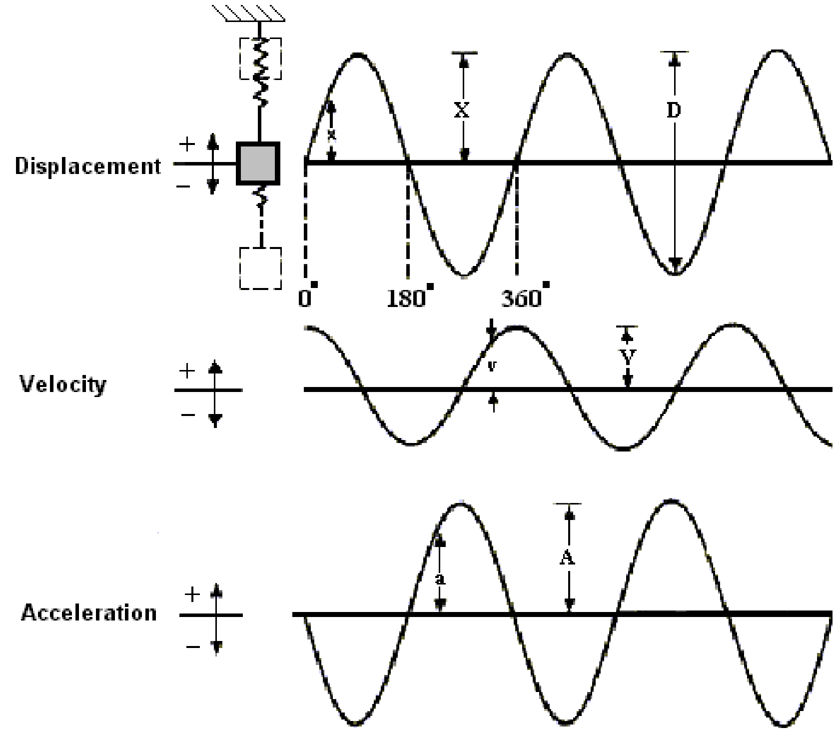

Figure 1. Phase relationships among displacement, velocity, and acceleration

As the velocity of moving particle (or body) is the time rate of change of displacement, which is the derivative of the time function of displacement, the motion can also be described in terms of velocity. For *instantaneous velocity*, *v*:

$$v = \frac{dx}{dt}$$

$$= \omega X \cos(\omega . t)$$

$$= 2\pi . f . X \cos 2\pi . f . t \qquad (3)$$

Since vibratory displacement is most often measured in terms of peak-to-peak, double amplitude, displacement $D = 2X$:

$$v = \pi . f . D \cos 2\pi . f . t \qquad (4)$$

If we limit our interest to the peak amplitudes and ignore the time variation and phase relationships:

$$V = \pi . f . D \qquad (5)$$

where:

V = peak velocity

The acceleration (a) of the motion is the time rate of change of velocity, the derivative of the *velocity* expression:

$$a = \frac{dv}{dt} = \frac{d^2x}{dt^2}$$

$$= -\omega^2 . X \sin(\omega . t)$$

$$= 4\pi^2 . f^2 . X(-\sin 2\pi . f . t) \qquad (6)$$

and

$$A = 2\pi^2 . f^2 . D \qquad (7)$$

where:

A= peak acceleration

It can be shown that:

$$V = \pi . f . D$$

$$A = 2\pi^2 . f^2 . D$$

$$D = \frac{V}{\pi . f}$$

$$D = \frac{A}{2\pi^2 . f^2}$$

It can be seen that the form and period of vibration remain the same whether it is the displacement, the velocity or the acceleration that is being studied. However, the velocity leads the displacement by a phase angle of 90° (π/2) and the acceleration again leads the velocity by a phase angle of 90° (π/2). It can also be seen that low-frequency motion is likely to exhibit low-amplitude accelerations even though displacement may be large. A further descriptive quantity, which does take the time history into account, is the *average absolute* value, (Figure 2) defined as (Broch 1980),

$$X_{Average} = \frac{1}{T}\int_0^T |x| dt$$

Even though this quantity takes into account the time history of the vibration over one period (T) it has been found to be of limited practical interest. A much more useful descriptive quantity which also takes the time history into accounts, is the *RMS* (*root mean square*) value (Figure 2):

$$X_{RMS} = \sqrt{\frac{1}{T}\int_0^T x^2(t) dt} \qquad (8)$$

The major reason for the importance of the RMS-value as a descriptive quantity is its simple relationship to the power content of the vibrations. For a pure harmonic motion the relationship between the various values is:

$$X_{RMS} = \frac{\pi}{2\sqrt{2}} X_{Average} = \frac{1}{\sqrt{2}} X_{peak}$$

A more general form of these relationships may be given by:

$$X_{RMS} = F_f . X_{Average} = \frac{1}{F_c} . X_{peak}$$

$$F_f = \frac{X_{RMS}}{X_{Average}} \qquad F_c \frac{X_{peak}}{X_{RMS}} \qquad (9)$$

The factors F_f and F_c are called “Form-factor” and “crest-factor”, respectively, and give some indication of the vibrations being studied.

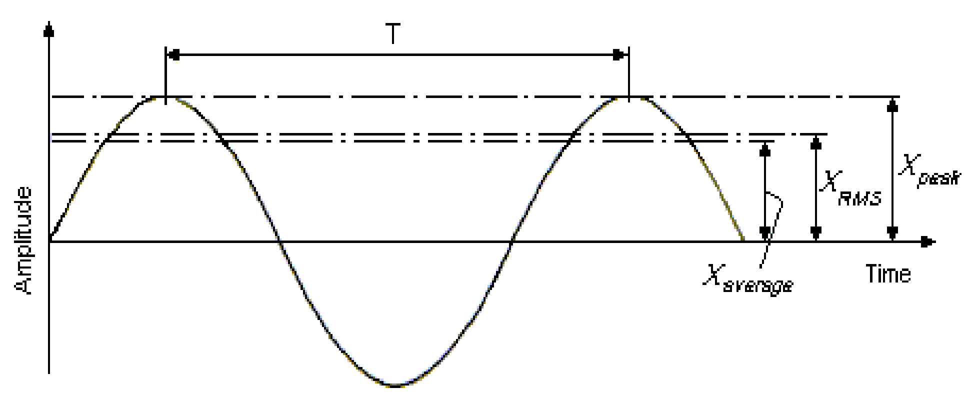

Figure 2. Example of harmonic vibration signal with indication of *the peak, the RMS* and *the average absolute* value

3. Measurement Techniques

3.1. Measuring Vibratory Acceleration

The types of sensor used to measure acceleration, shock, or tilt include electromechanical servo, piezoelectric, bulk micro-machined piezo-resistive, capacitive, and surface micro-machined capacitive. Each has distinct characteristics in output signal, development cost, and type of operating environment in which it best functions.

Transducers designed to measure vibratory acceleration are called accelerometers. Accelerometers (acceleration sensors) are available in a wide variety of sizes, shapes, and performance characteristics.

Despite the different electromechanical transduction mechanisms, all use a variation of the spring mass system, and are classified as seismic transducers.

3.1.1. Seismic Accelerometer Principle

The basic physical principle behind Mass-Spring system accelerometers used for measuring acceleration is that of a simple mass spring system (Figure 3).

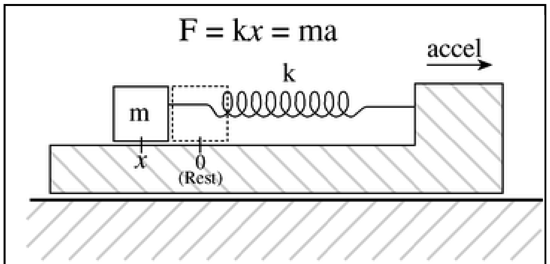

Figure 3. Mass-Spring system used for measuring acceleration

Springs (within their linear region) are governed by a physical principle known as Hooke's law. Hooke's law states that a spring will exhibit a restoring force, which is proportional to the amount it has been stretched or compressed. Specifically, $F=kx$, where k is the constant of proportionality between displacement (x) and force (F). The other important physical principle is that of Newton's second law of motion which states that a force operating on a mass which is accelerated will exhibit a force with a magnitude $F=ma$. Figure 3 shows a mass connected to a spring. If this system undergoes acceleration, then by Newton's law, there will be a resultant force equal to ma. This force causes the mass to either compress or expand the spring under the constraint that $F=ma=kx$. Hence an acceleration a will cause the mass to be displaced by $x = \frac{m.a}{k}$ or alternatively, if we observe a displacement of x, we know that the mass has undergone an acceleration of $a = \frac{k.x}{m}$. In this way we have turned the problem of measuring acceleration into one of measuring the displacement of a mass connected to a spring.

3.2. Accelerometer Types

The most common seismic transducers for shock and vibration measurements are:

- Piezoelectric (PE); high-impedance output
- Integral electronics piezoelectric (IEPE); low-impedance output
- Piezoresistive (PR); silicon strain gauge sensor
- Variable capacitance (VC); low-level, low-frequency
- Servo force balance

3.2.1. Piezoelectric (PE)

These sensors use the piezoelectric effects of the sensing element to produce a charge output. Specifically, when a pressure (piezo means pressure in Greek) is applied to a polarised crystal, the resulting mechanical deformation results in an electrical charge. Because a PE sensor does not require an external power source for operation, it is considered self-generating. The "spring" sensing elements provide a given number of electrons proportional to the amount of applied stress. If a sufficient force is applied to the piezoelectric crystal, a deformation will take place. This deformation disrupts the orientation of the electrical dipoles and creates a situation in which the charge is not completely cancelled (Figure 4). This results in a temporary excess of surface charge, which subsequently is manifested as a voltage, which is developed across the crystal.

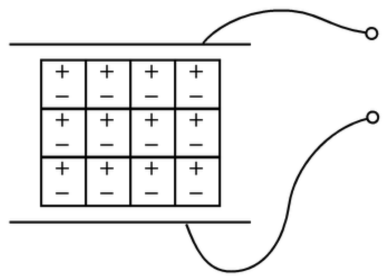

Figure 4. A sensor based on the piezoelectric effect

Figure 4 shows a common method of using a piezoelectric crystal to make a force sensor. Two metal plates are used to sandwich the crystal making a capacitor. As mentioned previously, an external force cause a deformation of the crystal results in a charge, which is a function of the applied force. In its operating region, a greater force will result in more surface charge. This charge results in a voltage $V = \frac{Q_f}{C}$, where Q_f is the charge resulting from a force *f*, and *C* is the capacitance of the device. In the manner described above, piezoelectric crystals act as transducers, which turn force, or mechanical stress into electrical charge, which in turn can be converted into a voltage. A common unit of charge from a PE accelerometer is the picocoulomb.

Because they are self-generating, PE transducers cannot be used to measure steady-state accelerations or force, which would put a fixed amount of energy into the crystal (a one-way squeeze) and therefore a fixed number of electrons at the electrodes. Conventional voltage measurement would give electrons away. Energy would be drained and the output would decay, despite the constant input acceleration (Endevco TP No. 293)

Most PE transducers are extremely rugged. The most common types of this transducer are compression and shear designs. Shear design offers better isolation from environmental effects such as thermal transient and base strain, and is generally more expensive. Beam-type design, a variation of the compression design, is also quite popular due to its lower manufacturing cost. But beam design is generally more fragile and has limited bandwidth (Bruel & Kjaer 1982).

Piezoelectric measuring devices are widely used today in the laboratory, on the production floor, and as original equipment for measuring and recording dynamic changes in mechanical variables including shock and vibration.

3.2.2. Integral Electronics Piezoelectric (IEPE)

Many piezoelectric accelerometer transducers include integral miniature hybrid amplifiers, which, among their other advantages, do not need noise-treated cable. Most require an external constant current power source. Both the input supply current and output signal are carried over the same two-wire cable. The low-impedance output of the IEPE design (Figure 5) provides relative immunity to the effects of poor cable insulation resistance, and stray signal pickup (PCB Piezotronics 1985).

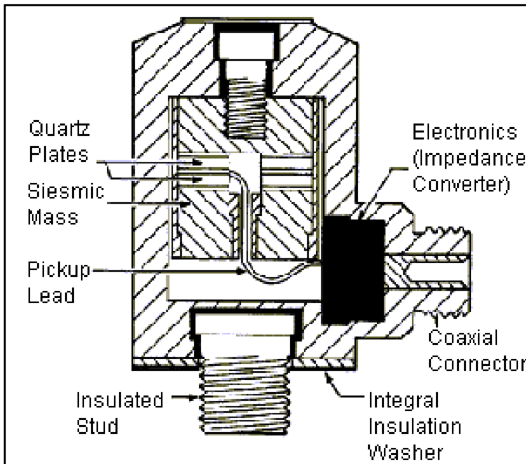

Figure 5. This IEPE accelerometer has an inverted compression seismic system and an electronic module in the connector.

Output-to-weight ratio of IEPE is higher than with PE transducers. The sensitivity of IEPE accelerometer transducers, in contrast to PR, is not significantly affected by supply changes. Instead, dynamic range, the total possible swing of the output voltage, is affected by bias and compliance voltages. Only with large variations in current supply would there be problems with frequency response when driving high-capacitance loads (Endevco, 1995).

A disadvantage of built-in electronics is that it generally limits the transducer to a narrower temperature range. In comparison with an identical transducer design that does not have internal electronics, the high-impedance version will always have a higher mean time between failures rating (Wilson 1999).

3.2.3. Piezoresistive

A PR accelerometer (Figure 6) is a Wheatstone bridge of resistors incorporating one or more legs that change value when strained. A piezoresistive material's resistance value decreases when it is subjected to a compressive force and increases when a tensile force is applied.

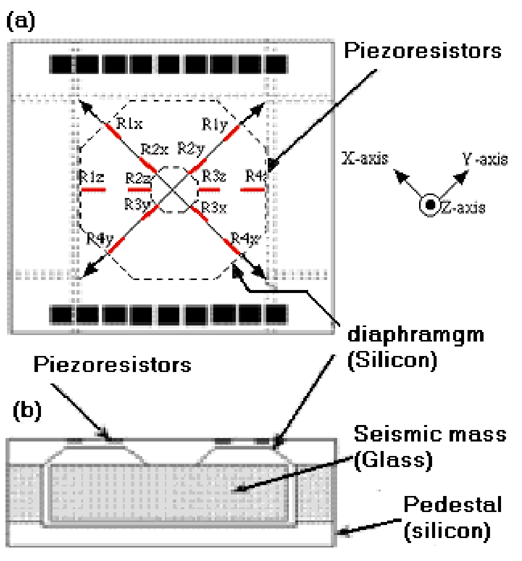

Figure 6. The 3-axis silicon piezoresistive accelerometer is shown from the top (a) and in a cross-sectional view (b).

On the surface of the first layer of silicon, three sets of Wheatstone bridges are separately formed for use as detection circuits. Each circuit consists of four piezoresistors made by the semiconductor planar process. On the reverse side is a thin silicon diaphragm fabricated by anisotropic etching. The glass layer is anodically bonded to the diaphragm side of the first layer. By dicing from the reverse side of the glass, a seismic mass is fabricated at the centre of the sensor die. This mass behaves like a pendulum, responding to acceleration and causing deflection of the diaphragm. Anodic bonding attaches the silicon third layer to the glass second layer. This final silicon layer limits the travel of the seismic mass, preventing the sensor diaphragm from being damaged by excessive acceleration and serving as a base to which the unit is attached (Wu and Ko. 1989).

Most PR sensors use two or four active elements. Voltage output of a two-arm, or half-bridge, sensor is half that of a four-arm, or full bridge. The response of strain gauges with higher gauge factors is dominated by the piezoresistive effect, which is the change of resistivity with strain (Endevco 1978, Entran 1987).

3.2.4. Capacitance Technique

Capacitors are electrical components which store charge. A simple capacitors is formed by placing two metal plates in parallel with each other as shown in Figure 7. The amount of capacitance that a device such as this would exhibit is given by $C = \frac{k}{x_0}$, where k is a property of the material between the two plates. Using this, if one knew k and could measure capacitance, they would be able to determine x_0, the spacing between the plates.

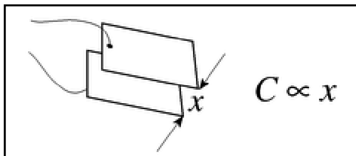

Figure 7. A simple capacitor

Variable Capacitance: VC transducers are usually designed as parallel-plate air gap capacitors in which motion is perpendicular to the plates. In some designs the plate is cantilevered from one edge, so motion is actually rotation; other plates are supported around the periphery, as in a trampoline. Changes in capacitance of the VC elements due to acceleration are sensed by a pair of current detectors that convert the changes into voltage output (Wilson 1999). In a VC accelerometer, a high-frequency oscillator provides the necessary excitation for the VC elements. Changes in capacitance are sensed by the current detector. Output voltage is proportional to capacitance changes, and, therefore, to acceleration. (Endevco- TP 296).

The sensor of a typical micro-machined VC accelerometer is constructed of three silicon elements bonded together to form a hermetically sealed assembly (Figure 8).

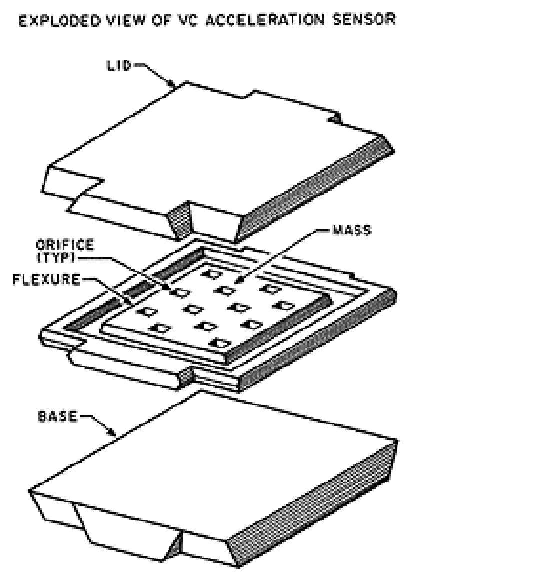

Figure 8. An exploded view of a variable capacitance accelerometer shows its primary elements.

Two of the elements are the electrodes of an air dielectric, parallel-plate capacitor. The middle element is chemically etched to form a rigid central mass suspended by thin, flexible fingers. Damping characteristics are controlled by gas flow in the orifices located on the mass.
Disadvantages are the cost and size associated with the increased complexity of the onboard conditioning (Wilson 1999).

3.2.5. Servo (Force Balance)

Servo accelerometers are used predominantly in inertial guidance systems, some of their performance characteristics make them desirable in certain vibration applications. All the accelerometer types described previously are open-loop devices in which the output due to deflection of the sensing element is read directly. In servo-controlled, or closed-loop, accelerometers, the deflection signal is used as feedback in a circuit that physically drives or rebalances the mass back to the equilibrium position. Servo accelerometer manufacturers suggest that open loop instruments that rely on displacement (i.e., straining of crystals and piezoresistive elements) to produce an output signal often cause non-linearity errors. In closed-loop designs, internal displacements are kept extremely small by electrical rebalancing of the proof mass, minimising non-linearity (Wilson 1999).

The servomechanism (see Figure 9) was primarily based on electromagnetic principles. Force is usually provided by driving current through coils on the mass in the presence of a magnetic field. In the pendulous servo accelerometer with an electromagnetic rebalancing mechanism, the pendulous mass develops a torque proportional to the product of the proof mass and the applied acceleration.

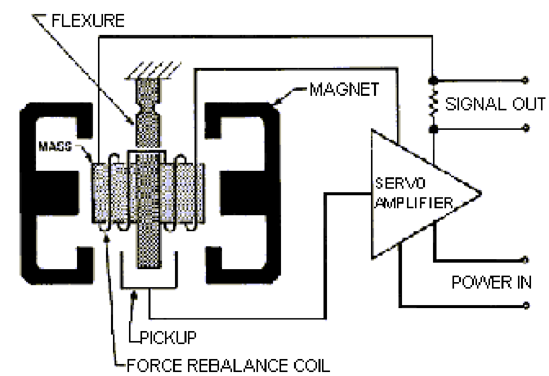

Figure 9. The servo force balance accelerometer produces an output proportional to the force required to maintain the mass in an equilibrium position.

Motion of the mass is detected by the position sensors (typically capacitive sensors), which send an error signal to the servo system. The error signal triggers the servo amplifier to output a feedback current to the torque motor, which develops an opposing torque equal in magnitude to the acceleration-generated torque from the pendulous mass. Output is the applied drive current itself, which, analogous to the deflection in the open-loop transducers, is proportional to the applied force and therefore to the acceleration.

Bias stability of these accelerometers depends solely on the characteristics of the sensing element (s), it is the feedback electronics in the closed -

loop design that controls bias stability. In general, they are designed for use in applications with comparatively low acceleration levels and extremely low frequency components (Wilson 1999).

4. Conclusion

The sensor/transducer types introduced in this paper have many advantages and disadvantages for any specific purpose use. When the road conditions are considered, most of the selection criteria such as frequency response, acceleration level, noise free signal, robustness, portability and usability are satisfied by piezoelectric sensors for fresh fruits transportation even though some of the other type sensors can be adaptable. For more specific purpose, to select right sensor, attention should be given to sensitivity (mV/g), weight (small size is recommended), shock limit and frequency response characteristics.

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