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Development of a Vibrometer from Locally Available Materials for Laboratory Applications

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Abstract: This study reports a vibrometer that was designed and developed from locally available materials for laboratory applications. The three main components mechanical, electrical and visual are integrated for higher sensitivity and accuracy. The height-to-length ratio of the active component (quartz) was chosen to be 5 and a typical sensitivity of 25 pC g^{-1} was assumed at the design stage. The conducting electrodes measure 40×40×1 mm while the mechanical component weights 220 g. From the test conducted, the vibrometer has a static output and sensitivity of 340 and 16.7 mV g^{-1}, respectively while the amplification gain of 100 is obtained. The calibration test based on a vibrating turning fork of 485 Hz frequency shows that the instrument performs <6.3%, the actual value and such can be used as the basis for other measurements. The vibrometer will fill the missing link of low frequency seismic instruments suitable for low frequency vibration of laboratory equipment.

Key words: Vibrometer, accelerometer, design and development, sensitivity, laboratory, Saudia Arabia

INTRODUCTION

Vibration of laboratory equipments are largely attributable to dynamic effect of manufacturing tolerance as well as rolling and rubbing contact between machine parts and out-of-balance force in rotating and reciprocating machines (Bruel and Kjaer, 1983). Usually, shaft imbalance and misalignment, developed during equipment operation or sometimes inadvertently incorporated at the design stage, contribute immensely to vibration (Joyti, 2003). Vibration is often unwanted except in few cases when it is purposefully generated and its consequence, especially for laboratory equipments, spans from error reading with consequential poor judgment to equipment failure.

Even the scientists, laboratory attendants and students could adversely be affected if they are directly exposed to vibration source. Human vision may become blurred and loss of balance and concentration may be experienced. Detailed effects of vibration on human are available (Bruel and Kjaer, 1983). Vibrating sources are usually defined by their amplitude and frequency while acceleration, velocity and displacement found in most harmonic motions are often the measurable quantities (Scalise and Di Sante, 2001). Though, there are various ways in which these parameter can be measured depending on the nature of the source and the magnitude of the expected frequency. For measurement of small degree of vibration, the conversion of the mechanical vibration into electronic signals followed by subsequent signal analysis remains the best approach currently available (Zhao *et al*., 2008; Jurevichius *et al*., 2007). A vibration measurement system may include an accelerometer (or displacement sensor), a signal amplifier, an integrator and data acquisition devices (Jurevichius *et al*., 2007).

A block diagram of a typical vibration measurement system is shown in Fig. 1. It consists of a pre-amplifier, a signal conditioner, a detector and indicating meter or a print-out block which are often combined in a single unit (Eldon and Robert, 2002). The AC output can be recorded in a tape or perceive as audio. The choice of appropriate parameter to be measured depends largely on the application of the instrument. Cyril (2002) considered velocity measurement because velocity spectrum is more uniform than displacement spectrum. However, Johnson (2006) preferred measurement of acceleration because both displacement and velocity can be obtained

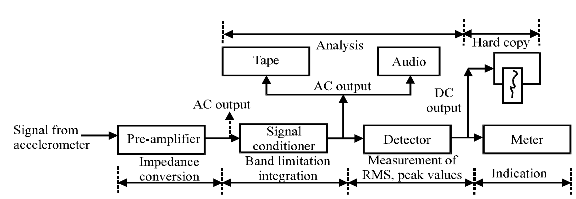

Fig. 1: Vibration measurement system (Eldon and Robert, 2002)

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therefrom. Most modern vibration meters are equipped to measure displacement, velocity and acceleration (Bruel and Kjaer, 1983).

Since, acceleration measurement is the most preferred technique for vibration measurement, its applications have gained immense popularity. For instance, sensitive accelerometers are widely used throughout engineering both as research and development tools and as components of control systems (James, 2000). Five categories of accelerometers have been identified based on their operation theories. They are potentiometer accelerometer (Johnson, 2006), linear variable differential transformer accelerometer (Figliola and Beasley, 1995), variable reluctance accelerometer (Eldon and Robert, 2002), piezoresistive accelerometer (Eldon and Robert, 2002; Cyril, 2002) and piezoelectric accelerometer (Figliola and Beasley, 1995). Details of these accelerometers are available in their respective references. Of these categories, piezoelectric accelerometers have gained immense applications and will be described further here. Piezoelectric accelerometer works on the principle of piezoelectricity (Duval *et al*., 2007; Maluf and William, 2004) and often requires some forms of preloading. Based on the designs by two research groups (Figliola and Beasley, 1995; Eldon and Robert, 2002), a preload is applied to the piezoelectric material with the mass tightened to the piezoelectric element via a nut. The design of Bruel and Kjaer (1983) applied preloading helical spring set to particular value of compression. The static frequency response of an accelerometer may range from 0.03-10 kHz with a static sensitivity ranging from 1-100 mV g^{-1} (Figliola and Beasley, 1995). The resonating frequency of 30 Hz is typical for most accelerometers and total weight of 30 g is commonly achievable.

In most engineering experiments, especially shaft balancing and alignment, the absence of vibrometers is conspicuous and the magnitudes of induced vibration are usually unknown. Absence of these tools is often due to the high purchasing cost. To fill this missing link, the current design aims at design and fabricating a portable vibrometer from locally soured materials for laboratory application. Another justification for this study is that most available seismic instruments are used for high frequency vibration and are proved unsuitable for low frequency vibration of laboratory equipment.

MATERIALS AND METHODS

Theoretical background: Vibration transducers or motion sensors are designed to measure the rate of change of position, location or displacement of an object as given by Johnson (2006):

$$v_t = \frac{dx_t}{dt} \quad (1)$$

$$a_t = \frac{dv_t}{dt} = \frac{d^2x_t}{dt^2} \quad (2)$$

Where:

x_t = The displacement (m)
v_t = The velocity (m sec^{-1})
a_t = The acceleration (m sec^{-2})

Once any of these parameters is measured by the sensor others including vibration amplitude and frequency can be obtained therefrom. Based on design considerations such as availability of material, applicable manufacturing techniques, size and shape and cost of material and production piezoelectric accelerometer is used as the sensor for this design. The piezoelectric accelerometer uses a piezoelectric material as the active component based on the working principle of direct proportionality between the output induced charge and that of input applied force as given by Khurmi and Gupta (2005):

$$Q \propto F \quad (3)$$

From Newton's second law of motion (Singh, 2005):

$$F = ma \quad (4)$$

$$Q = CV \quad (5)$$

Where:

Q = The charge generated
F = The induced force
m = The mass of the body
C = The capacitance of the instrument
a = The acceleration of the body
V = The induced voltage

Combining Eq. 3-5, it can be deduced that:

$$V \propto a \quad (6)$$

This implies that the magnitude of the induced voltage by piezoelectric material depends on the acceleration of the vibrating source as well as the orientation of the polar axes of the crystal with respect to the acting force. This serves as the fundamental principle governing this design. Three different effects can accordingly be discerned. The operations and sensitivity of piezoelectric material depends on how the material is cut that is either transverse, longitudinal or shear. Details of these effects are published elsewhere (Switzerland, 2008; Maluf and William, 2004). For ease of

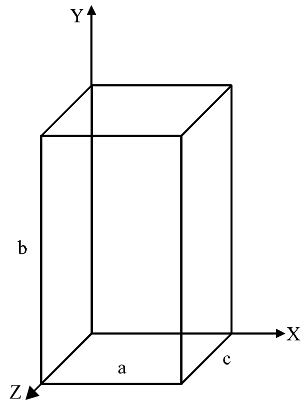

Fig. 2: Quartz material dimensioning

generation of the required shape and to avoid complexities in the generation of the desired form of the quartz element, the transverse configuration is adopted.

Design considerations and calculations: The design considerations mentioned before influence the choice of material, the choice of piezoelectric cut effect, the required electrical amplification and the methods of mounting amongst others. The vibrometer designed has three major parts; the sensor, electrical interphase and computer display. The sensor is a mechanical device that converts vibrating motion into electrical signal. The electrical circuit serves as electrical signal amplifier and an interphase between the sensor and the computer display unit. Taking the transverse cut effect of the quartz material by Eq. 7 (Eldon and Robert, 2002) (Fig. 2):

$$Q_x = -d_{xx} F_y \frac{b}{a} \tag{7}$$

Where:

- Q_x = Charge output of the crystal
- d_{xx} = Piezoelectric coefficient of quartz = -2.3 pC N^{-1}
- F_y = Force along the y-axis
- b = Dimension of the charge generating axis
- a = Dimension of the neutral axis

From the Eq. 6, the magnitude of the charge produced by the quartz element is proportional to b/a. Based on the available production means, b/a is taken to be Eq. 5 while b is considered to be 40 mm and c = a = 8 mm. With these dimensions, the mass and dimension of the preloading seismic mass required for a specific sensitivity of the sensor can be computed. For this design, the seismic mass is considered as solid material (steel) in which the stud, hexagonal nut, spring and other auxiliary components are integrated. The sensor sensitivity of an accelerometer is defined as:

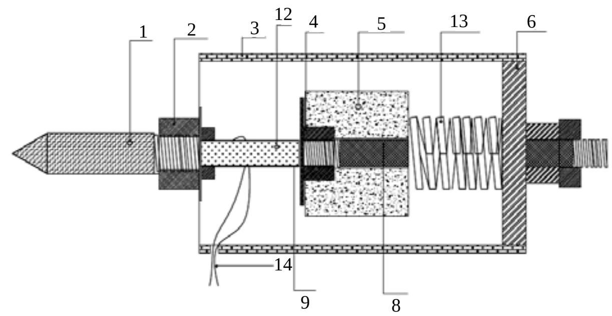

Fig. 3: Cross sectional view of the assembled mechanical components of the vibrometer

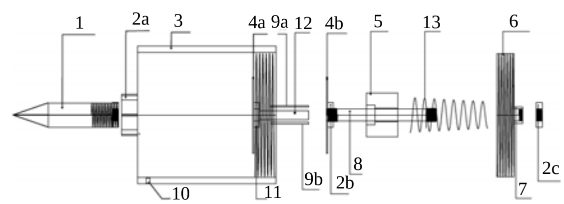

Fig. 4: Cross sectional view of the assembled mechanical components of the vibrometer

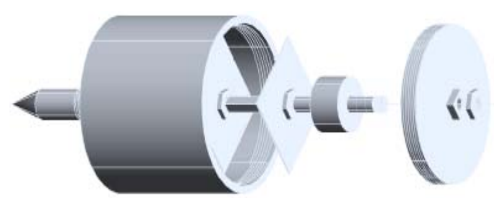

Fig. 5: 3-D exploded view of the mechanical components of the vibrometer

$$S = \frac{Q}{a} \tag{8}$$

Designing for a minimum acceleration of 1 g (where g is the acceleration due to gravity) and a typical sensitivity of 25 pC g^{-1} (Thompson and Dahleh, 1998), the mass of seismic material can be obtained by combining Eq. 4, 6 and 7. With the seismic material made of medium carbon steel (0.3% C) having a density of 7801 kg m^{-3} and mass 0.22 kg (calculated previously), the dimension of the seismic mass is calculated.

Component description and fabrication: Figure 3-5 show the cross-sectional view, 2-D view and 3-D exploded views of the mechanical part of the vibrometer, respectively. The quartz material (labeled 12) is the sensitive part and is rigidly supported by the external braze (4a) and integral component (11). The vibrometer is mounted by hand held probe (1) which is tapered at one end and threaded at the other. With the threaded portion, the probe is fastened to the casing via the nut (2a) threaded on the lower part of the casing (3). The probe is screwed to a point where the flat end touches the flat end of the quartz braze which ensures that the signal from the tip edge of the probe gets to the surface of the quartz. From the other side of the quartz, a flat plate (4b) to which a nut is attached is designed to be on the quartz, the nut serves as a means by which the stud (8) is clamped on to the upper end of the quartz and the combination of the stud and the support (4b) allows the seismic mass (5) to be centralized on the quartz as preloading. The stud is a long rod which accommodates all the attachments and also shoots out.

The spring (13) is placed on the seismic mass to serve as means of absorbing shock and to prevent overloading of the quartz. The upper end of the casing is threaded to accommodate the cover (6) which in turn gives room for passage of the stud to the outside of the casing. Part 7 is an integral component of the cover and serves as a means of holding while screwing. A nut (2c) serves as means of tighten the whole part and located on the stud is a groove used in tightening the support carrying the seismic mass to the sensing element to avoid longitudinal displacement during operation. By the sides of the quartz are the electrodes (9) attached by the means of quartz's support and soldered to these electrodes are the flexible wires (14) which carries signal from the side surfaces of the quartz to the electrical circuit for processing via gap (10).

Figure 6 shows the electrical component of the vibrometer which serves as a signal processing unit. It comprises of oscillation circuit, phase lock and times frequency for signal amplification, frequency differential forming circuit for signal extraction and compensating output circuit. Some of the basic electronic components fixed to the Ferro-board are variable load resistor for variable amplification, programmable integrated circuit, capacitor, Light Emitting Diode (LED), field effect transistor among others. These components work together to perform both signal conditioning process and hardware inter-phasing function. Among the inter-phasing functions are the detection of port, communication of signal from circuit to software program, activation of the LED during signal reception and controlling the power package for the amplification. The main computational code is written in Microsoft® visual basic environment.

It retrieves data from the computer serial port and writes them as m-files that are accessible to Matlab®. Lastly, Matlab® code is written to handle the generated m-file and plot the values of the function for visual appreciation.

Table 1 shows the fabrication of most mechanical components of the vibrometer. These components are fabricated from locally available materials and assembled in the university workshop. The electronic components were also assembled in the same workshop.

Operating principles: Prior to measurement, the electrodes of the mechanical part are connected to the electronic circuit via the connection cables while the electronic circuit is connected to the PC where software and drivers are pre-installed. The whole components are

Fig. 6: Electronic component of the vibrometer

Table 1: Summary of the fabrication process of some components of the vibrometer

Parts	Operation	Machine tool/equipment	Tools
Quartz	Quartz of irregular dimension was grounded to the designed shape. The surfaces were equally machined to achieve a smooth flat surfaces	Grinding machine	Grinding wheel
Seismic mass	A steel bar was turned to 3 cm in diameter and then smoothly faced to 5 cm length. It was thereafter bored and a groove was made at one end of the mass	Lathe machine	Facing tool, hacksaw and drill bit
Stud	A 9 cm long steel bar was turned to 1 cm diameter and then threaded at both ends	Lathe machine	Dice and facing tool
Probe	A steel bar of length 10 cm was turned into 1 cm diameter. It was then threaded at one end turned at the other end to form a conical tip edge	Lathe machine	Facing tool and dice
Bolt	A bolt of 10 mm diameter was welded to the metal sheet. This serves as a means of accommodating the stud and to hold the quartz in place	Welding machine	-
Casing	A galvanized pipe of 37 mm in diameter was cut and threaded at the upper part for ease of assemblage and disassembling	Welding machine and Lathe machine	Hacksaw and tap
Wire	Two wires of equal length were soldered along the surface of the electrode	Soldering iron	-

initialized through a Microsoft® visual basic code and a display of connected is obtained if all components are functioning correctly. To measure the vibration amplitude of a source, the source is touched with a probe held in a vertical position just after the components are initialized. The quantity of data extracted depends on the data acquisition period and is often minimized to reduce the data size.

When a source is vibrating with acceleration and is touched by the vibrometer probe, the probe transmits the vibration to the surface of the quartz. This causes compression in the quartz as the other surface is tightened by the stud and the seismic preloading. The compression induces charges on the surfaces of the quartz and is collected by the electrodes and transferred through the flexible cables to the electronic circuit. The electronic circuit receives the signals in the form of a charge and is extracted by the oscillating circuit and then transformed by a frequency differential. This induced voltage is amplified by a phase lock and times frequency circuit. The output signal is linearized to have a linear relationship with the acceleration. The magnitude and polarization of the digital signals are processed to reflect the magnitude and direction of the acceleration of the vibrating source (Hidemichi, 1995).

RESULTS AND DISCUSSION

Testing procedure: The testing procedure is designed to evaluate the characteristic of the vibrometer especially the vibration frequency using a particular vibrating source and a turning fork. An initial result without a vibrating source was obtained to characterize the preloading of the mechanical spring. Then, the set-up was subjected to a vibration from a source. The vibration spectrum of the source was thus obtained from the difference of the two results. Another test was conducted with a vibrating turning fork to calibrate the vibration frequency of the instrument.

Figure 7 shows the plot of the data obtained without a vibrating source and reflects the intrinsic vibration in the system. The vibrating spectrum is observed to vary between 340 and -340 mV and the static output of the instrument is 340 mV since, the preload is a static seismic mass. The voltage induced by the quartz is equal to 340×4.9 mV/100.

The spectra variation is attributed to noise and interference of the AC power unit of the system. Figure 8 is the spectrum of the vibration obtained due to a vibrating source. The letter a shown in the Fig. 8 is the recursive distance between the peak-to-peak values of the amplitudes of the vibration. This defines the period and is measured to be 30×50 µs. The vibrating frequency is thereafter obtained to be:

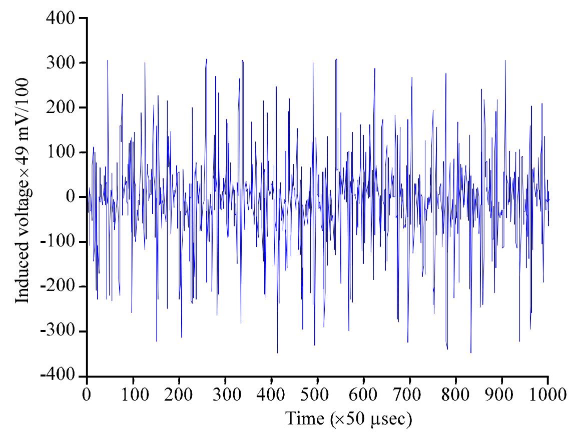

Fig. 7: Graph of the data obtained without a vibration source

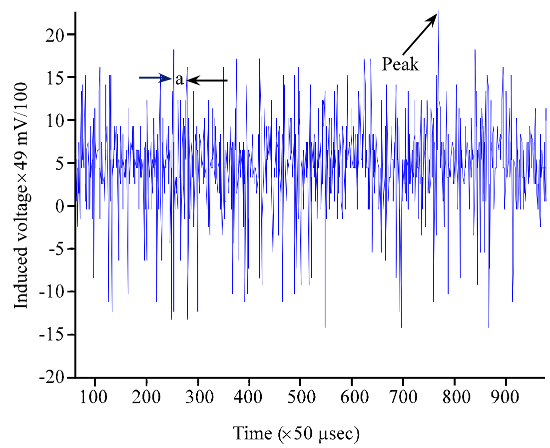

Fig. 8: Graph of the data obtained due to a vibrating source

$$f = \frac{1}{a} = 667 \text{ Hz} \quad (9)$$

Figure 9 is a plot of the vibration data obtained from a tuning fork of frequency 485 Hz. The period of vibration T is determined to be 0.00022 sec with a vibration frequency of 454.5 Hz. This calculated frequency is very close to the turning fork frequency but for an error of 6.3%.

This error is due to the slight differences in the period of the cycles, noise and the damping in the tuning fork. The peak value is measured to be 350 mV given an output voltage of the transducer to be 350×4.9 mV/100 = 17.15 mV.

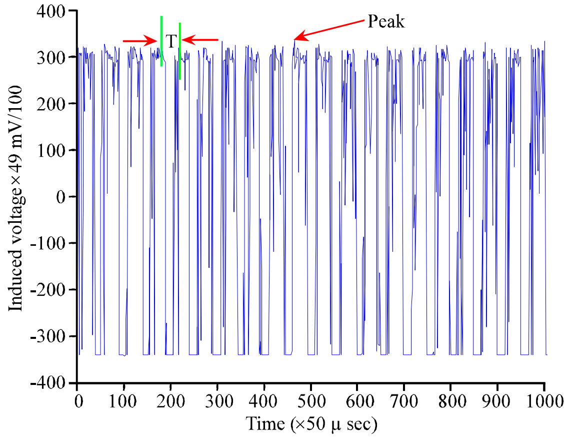

Fig. 9: Graph of the data obtained with a tuning fork of 485 Hz frequency

Since, the output voltage was 16.7 mV and the transducer was kept vertically upward with an acceleration of 1 g therefore the static sensitivity of the transducer as obtained from Eq. 9 is found to be 16.7 mV g^{-1}. The total mass of the vibrometer is 500 g.

CONCLUSION

A vibrometer was designed and developed from locally available materials for laboratory applications. It consists of three main components; mechanical, electrical and visual and are all integrated for higher sensitivity and accuracy. From the test conducted, the vibrometer has a static output and sensitivity of 340 and 16.7 mV g^{-1}, respectively and an amplification gain of 100. The calibration test conducted on a vibrating turning fork of 485 Hz frequency shows that the instrument performs 6.3% lower than the actual value and such can be used as the basis for other measurements. More calibrations might be needed to accurately discern the deviation of the vibrometer from the actual value.

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