Design, construction and testing of a vibrometer

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Abstract

A vibrometer that would measure the magnitude of vibrations of power generating sets and sound level with voltages as low as 0.0 2nV was designed and constructed. It was designed to measure very low frequency signals from 0.5 Hz to 200 Hz using a low-pass filter. The vibrometer was tested on three different power generating sets (60kVA, 100kVA and 150kVA), in two locations in the city of Calabar, Nigeria and their vibration analyses were carried out. Results show that the operating speeds of the generating sets were 6799 rpm, 8823 rpm and 3978 rpm respectively. Meaning, they were vibrating at the 5th, 6th and 3rd harmonics, respectively.

Keywords: Vibrometer, vibration measurement, sound level, vibration monitoring.

Resumen

Se diseñó y construyó un vibrómetro que pudiera medir la magnitud de vibraciones de conjuntos generados de potencia y niveles de sonido con voltajes tan bajos como 0.02nV. Fue diseñado para medir señales de muy baja frecuencia de 0,5Hz a 200Hz usando un filtro de paso bajo. El vibrómetro fue probado en tres grupos generadores de energía diferentes (60kVA, 100kVA y 150kVA), en dos lugares de la ciudad de Calabar, Nigeria y se realizó su análisis de vibración. Los resultados muestran que la velocidad de funcionamiento de los grupos generadores fueron 6.799 rpm, 8.823 rpm y 3.978 rpm, respectivamente. Es decir, estaban vibrando en los armónicos quinto, sexto y tercero, respectivamente.

Palabras clave: Vibrómetro, medición de vibraciones, nivel de sonido, monitoreo de vibraciones.

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I. INTRODUCTION

Vibrations are common phenomena of mechanical structures that can be detrimental to many systems. If not monitored, they can cause damage to structures and machines, resulting to malfunctioning, excessive wear and tear and eventually, fatigue failure. Machine condition monitoring is therefore pertinent. Condition monitoring is the process of monitoring a parameter of condition in machinery, such that a significant change is indicative of a developing failure [1]. Some of such monitored parameters are temperature and noise, as well as vibrations, which is the focus of this research.

Readily available electronic components such as resistors, capacitors, a piezoelectric material, etc, are used in the construction of a two–way functional Vibrometer, capable of measuring vibrations of machines (as frequency in Hz or rpm), as well as sound level in an area. The device can also monitor the vibration level of power generating sets.

II. THEORY

A. Vibration and vibration monitoring

Vibration is as an oscillatory motion of a particle or body about a fixed reference point. Mechanically, vibration can also be defined as the motion of rotating/oscillating machine, back and forth from its position of rest or neutral and is considered in displacement mode, frequency mode and acceleration mode [2]. Vibration is therefore the most prominent secondary signal in most machines.

Vibration can be characterized by:

1. The frequency in Hz or revolutions per minute (rpm)
2. The amplitude of the measured parameter.

Units of vibration depend on the following vibration parameters:

i) Acceleration, measured in m/s^2
ii) Velocity, measured in m/s
iii) Displacement, measured in m.

Apart from the damages caused by vibrations on machines, such as wear and tear, crack and fatigue failure, they also have adverse effects on human beings [3]. Some of such effects are motion sickness, breathing and speech disturbances, white finger disease, to mention a few.

B. Causes of machine vibration

Mechanical causes: These may include; a bent or wrapped shaft, loose parts or damaged parts, bad gears, improper design of base plate or foundation, operation at too low a capacity and unbalanced rotating components.

Hydraulic causes: These may include; Pumps/hydraulic motors not operating at rated or best efficiency, vaporization of the product, internal recirculation, Clogged suction strainers or presence of air in hydraulic fluid, non-laminar flow and parallel operation of poorly matched pumps [4].

C. Vibration isolation

Vibration isolation systems serve the purpose of limiting the transmission of vibration to surrounding structures or preventing ambient vibration from reaching machines performing precision work, especially for machines that are sensitive to shock or vibration from other machines. There are two types of isolating systems. One seeks to reduce vibration transmissibility from a machine to its foundation. The other type is employed when it is desired to limit the amount of vibration a machine transmits to the surrounding structures [4].

Vibration isolation reduces the level of vibration transmitted to or from a machine, building or structure from another source. The degree of isolation achieved depends on the ratio

$$\frac{\text{Frequency of disturbing vibration}}{\text{Natural frequency of isolation}} = f_e/f_n = R\,. \qquad (1)$$

The ratio f_e/f_n should be greater than 1.4 and ideally greater than 2 to 3 in order to achieve a significant level of vibration isolation.

The degree of isolation is given as transmissibility (T) which is the amount of vibration transmitted at a specific frequency f_e as a fraction of the disturbing vibration at the same frequency f_e [5].

For undamped systems,

$$T = 1/1\text{-}R^2. \qquad (2)$$

For damped systems,

$$T = \left(\frac{1 + \frac{R^2}{Q^2}}{(1 - R^2)^2 + R^2 + \frac{R^2}{Q^2}} \right)^{1/2}. \qquad (3)$$

And

$$Q = \frac{1}{2C/C_C}\,. \qquad (4)$$

Where Q is the maximum transmissibility T_{max} at resonance and C_c is the critical damping which is the value of damping at which a system will not oscillate when disturbed from equilibrium and is related to the system mass and natural frequency thus: $C_c = 78.96(mf_n^2)$.

C/C_C is the level of isolator damping [6].

$$T_{max} = Q = 1/2C_c\,. \qquad (5)$$

Where;
T > 1 = Increased transmitted vibration.
T = 1 = No vibration isolation.
T < 1 = Vibration isolation. [7]

Isolation efficiency, E relates to transmissibility as:

$$E = 100\,(1\text{-}T)\,\%. \qquad (6)$$

D. Vibration transducers

A transducer is a device that accepts an input of energy in one form and produces an output of energy in some other form, with a known, fixed relationship between the input and output. The output, most times is in the form of electrical signals. Vibration transducers convert vibration input of the machine to electrical signal outputs in various forms giving required information. Accelerometers, velocity transducers, piezo-resistive accelerometers, low-resonance geophones, fast Fourier transform (FFT) analyzer, lead zirconate titanate (PZT) actuators, etc, are some of the types of vibration transducers.

III. MATERIALS AND METHODS

A. Concept of design

The vibrometer constructed in this research measures very low frequency vibrations (within the range of 0.5Hz to 200Hz) of certain machines (power generating sets in this case). A sensor that picks up the vibration signals from an operating generating set does this. This sensor is a piezoelectric crystal. The quartz type piezoelectric crystal used as the sensor has a good temperature tolerance therefore it can function well within temperature ranges of 0 to 121°C.

The vibrometer has six units and two channels namely: The power supply unit, Instrumentation amplifier/filtering unit, Microprocessor unit, Sensor/detector unit, Control unit and Display unit.

The two channels are; Channel 1 for vibration measurements and Channel 2 for sound level measurements. Both channels have the same circuit design but different values of resistors. Each channel has amplification and filtering unit.

Figure 1 shows the print out of the design for this device. Software called DIPTRACE was used to design this circuit.

1) Power supply unit: This unit is made up of a 12V transformer, a 6V rechargeable battery that is on charge when AC voltage is in use and provides DC voltage in the absence of AC voltage. It has a rectifier, a 100μF capacitor for smoothening and filtering the DC voltage, and LM 7085 IC for regulation. Once the AC line voltage of 220/240V is applied to the step down transformer, it is rectified to charge

the input DC battery and it is also regulated by the LM 7805 IC to produce a V_{cc} of 5V to power the microprocessor chip and other ICs. An operational amplifier (4558 IC) generates ½Vcc, to power the amplifier/filter unit in the device using a voltage follower.

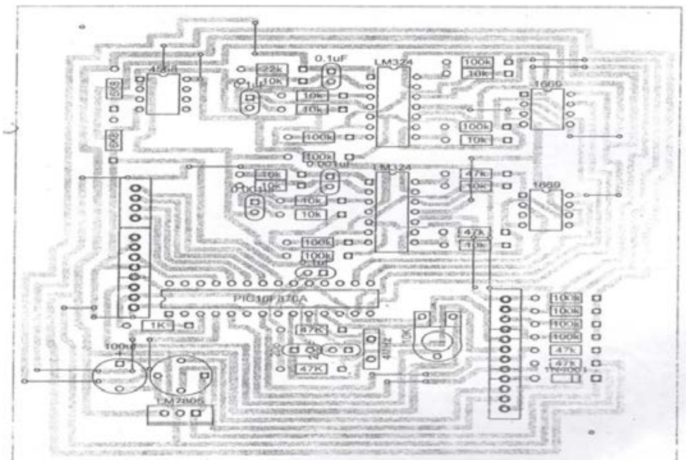

FIGURE 1. Printed circuit board design for the Vibrometer.

2) The instrumentation amplifier/filtering unit: The instrumentation amplifier unit is made up of two single-ended amplifiers and a fully differential amplifier (LM 324 ICs). The circuit also consists of a DS 1669 - 10 IC that is a memory chip for gain selection. The filtering unit is an active low-pass filter and its circuit consists of an operational amplifier, resistors and capacitors. The function of the amplification circuit is to amplify the signals picked up by the sensors. The amplification unit is designed with a high common mode rejection ration (CMRR) which takes care of the offset voltage and eliminates unwanted signals that may introduce some errors. After amplification, the signal is fed into the low pass filter. The cut-off frequency (f_c) for the low pass filter was calculated using the formula below:

$$f_c = 1/\,2\pi RC\ . \qquad (7)$$

Where R = 10kΩ and C = 0.1μF. Therefore

$$f_c = \frac{1}{2 \times 3.142 \times 10 \times 10^3 \times 0.1 \times 10^{-6}}$$

$$= 200\text{Hz (Approx)}.$$

Therefore, the low-pass filter will pass low frequencies within the range of 0.50 and 200Hz. The function of the DS 1669-10 IC is to help the user select a gain before taking measurements.

3) The microprocessor unit: The microprocessor unit mainly consists of a microprocessor chip called PIC 16F876A. This works using a fixed 0-4MHz crystal oscillator that enables the different multiplexers in the chip to have a standard of measurement and interpretation of data acquired. It enables the chip to measure the vibrations in terms of frequency. This unit is controlled by software designed to take care of the measurement process.

4) Sensor/detector unit: This unit consists of a piezoelectric crystal that picks up vibration signals. There is also a port created for a microphone that would pick up audio signals. The piezo-electric device is connected to channel 1 while the microphone would be connected to channel 2.

5) Control unit: This unit consists of touch buttons that carry out the task of gain selection (either up or down). Two other buttons provided are for other functions that may arise in future, such as trouble shooting, mathematics operations etc. The software designed also controls this unit.

6) Display unit: The display unit is a Liquid Crystal Display (LCD) that allows the viewing of the readings taken during measurements.

B. Materials used for construction

The components used in the construction of this device were; Piezo-electric crystal, Ds 1669-10 microchip, PIC 16F876 AIC, LCD Display, LM324 IC chip, 12V transformer, 6V rechargeable, Capacitors, O-4MHz crystal, Resistors and 4588 IC chip.

IV. RESULTS AND DISCUSSIONS

A. Testing and troubleshooting of vibrometer

The completed processor board was tested for continuity using a multimeter. Contacts were noticed to be lost at some points and these were corrected. The vibrometer was connected to an oscilloscope that was set to a time base of 2ms. When the vibrometer was switched on, it read the natural frequency of the environment that was 49Hz and its frequency waveform as seen on the oscilloscope (Figure2).

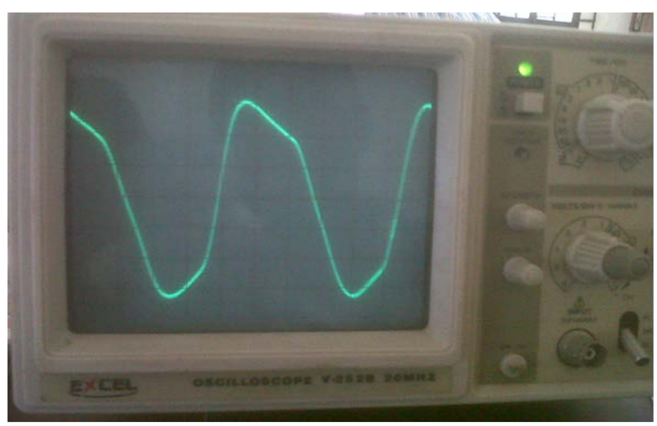

FIGURE 2. Output characteristics at 49 Hz.

The piezo-electric crystal was then mounted (using adhesive tapes) on a table where an operating drilling machine was placed and the vibrometer read the vibrating frequency as 58

Hz. This modulated frequency waveform as seen on the oscilloscope is shown (Figure 3).

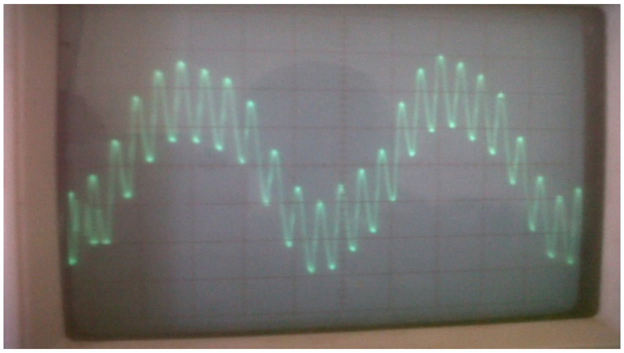

FIGURE 3. Output characteristics at 58 Hz.

As the speed of the drilling machine was increased, values of frequencies increased up to 69 Hz and the modulated waveform as seen on the oscilloscope (Figure 4).

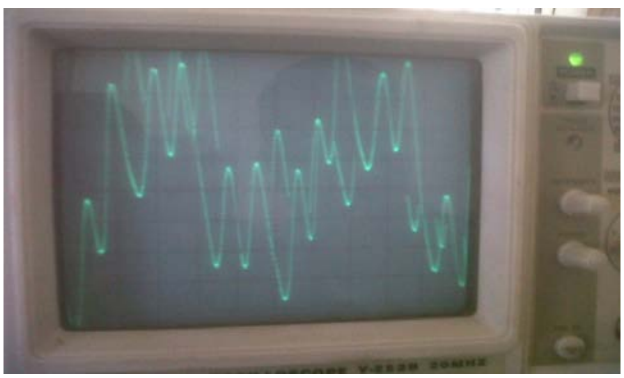

FIGURE 4. Output characteristics at 69Hz.

The picture of the constructed vibrometer is shown in Figure 5.

FIGURE 5. The constructed vibrometer.

V. CONCLUSION

This vibrometer is a handheld instrument that has a detachable sensor (the piezoelectric crystal). The sensor is mounted on the machines under test using adhesive tapes. This instrument is programmed to pick signals with voltages as low as 0.02nV, its threshold voltage being 4V. It measures very low frequencies within the range of 0.5 to 200Hz and functions well within temperature ranges of 0 to 121°C. The vibrometer was constructed in Enelec-GS Laboratory, Uyo, Nigeria with a total cost of #50,000. The price of a vibrometer in the market ranges from $1,000 to $3000 depending on the manufacturing company. Therefore, this research has produced a vibrometer that is more affordable.

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TABLE I. Summary of results for tested machines.

Machines tested	**Measured mean value of amplitude ± uncertainty (V)**	**Measured mean value of frequency ± uncertainty (Hz)**	**Running speed of machine (rpm)**	**Present operating frequency (rpm)**	**Most likely cause**
60KVA Generating set	0.386 ± 0.006	113.32 ± 1.27	1500	6799 (5xRPM)	Machine part problem
100KVA Generating set	(0.09 ± 0.01) X 10-9	147.05 ± 0.33	1500	8823 (6 x RPM)	Machine part problem
150KVA Generating set	(0.072 ± 0.008) X 10^{-9}	66.29 ± 0.08	1500	3978 (3xRPM)	Misalignment