Chapter VI

Study of FE Transducer for Vibration Analysis
6.1 INTRODUCTION

Vibration is the to and fro motion of a machine or its mechanical parts from its central position of rest. All machines vibrate under dynamic operation and vibration is the key to know the machinery conditions. Vibration measurement plays a very important roll in determining the level of machines. Unbalance is the most common source of vibration found in fans, blowers, centrifuges, rolls, grinding, wheels and other rotating equipment. Employing vibration analysis study with ferroelectric transducer devices were planning as follows.

The research activities on piezoelectric material for vibration detection and measurement started in 1950s. It has reached a stage of an established technology today. Because of many demands of military aircraft, seismography and medical applications several sophisticated vibration sensors/systems have been developed and are currently available for a wide variety of applications. As all piezo-electrics are ferroelectrics the study was thought to be relevant transducer study for this thesis research work.

For measuring vibration by mean of piezoelectric accelerometer it is necessary to incorporate a preamplifier between the transducer and the measuring system. It balances the impedance matching also amplifying the relatively weak output signal from transducer. This type of vibrational measurement was done by Tungal1 et.al. PLZT based micro-electro mechanical system (MEMS) was developed by Goel2 et al. They showed possibility of integration of piezoelectric films silicon with metal oxide capacitor for vibrational measurement. Tiersten3 et. al. gave linear theory of vibration for piezoelectric transducers. Yu4 showed that study of vibration best possible by non linear sandwiched laminated composites with piezoelectric layered material. Taylor5 gave the theory of electrometrical phenomena in piezocrystal.
The applications to ultrasonic and different piezoelectric biomedical devices are made by Cady\textsuperscript{6}. Air couple capacitor transducer utilized for high frequency operations given by Schindai\textsuperscript{7} et al. They had used etched silicon back-plates and dielectric film as transducer. In present investigation special circuit were designed based on digital technique to get vibration by direct read output. The new technology build emerging with their approach is mechatronics.

Thin film layered structure for integrated piezo-acoustic device has immense utility to produce ultrasonic. A wide variety of devices have been successfully fabricated using bulk materials in the form of single crystals and ceramics for vibration measurement. In recent years with the availability of ferroelectric oxide materials in thin film form layered structures have attracted considerable attention for integrated device applications. In recent years with the advent of superior thin film growth techniques, layered structures utilizing the ferroelectric materials has gradually increased and are being extensively studied for achieving improved properties. [8-12]

6.2 ACCELEROMETER AND VIBRATION PICK-UP

The special type of sample holder is design for capacitor which is compression type accelerometer. The accelerometer is fabricated with a mass mounted in direct contact with crystal element. The mass is preloaded with a stiff spring. It is simplest form of a piezo-electric disc with a mass placed on a frame. In this configuration seismic mass is supported by a solid structure. Where piezo crystal is placed it is a disc type. The supporting structure acts as the spring. The whole assembly mounted in a metal housing with a sturdy base. When the device is subjected to acceleration, the mass exerts a variable force on the piezo electric disc which is linearly proportional to the acceleration. The charge developed across the disc is in turn proportional to the acceleration of the mass. Piezo crystal is self generating sensor which converts the dynamic force or acceleration into equivalent electrical energy. The sensitivity of an
accelerometer is the ratio of its electrical output to applied acceleration usually expressed as pC per g or mV per g.

While measuring vibration by means of piezoelectric accelerometer it is necessary to incorporate a preamplifier between the transducer and the measuring system. The preamplifier is introduced into the measuring circuit for two reasons:

i) To convert the high output impedance of the accelerometer to a lower value, suitable for input to the measuring system; and

ii) Amplify the relatively weak output signal from the accelerometer, if the following instrumentation does not have sufficiently high sensitivity.

The system described can be used for the measurement of the response of any structure under vibration using the accelerometer as the transducer. It can also be used for the measurement of the input force to the structure using the piezoelectric force transducers. It can also be used as a sensitive indicator for velocity pick ups and as a sensitive voltmeter.[13-16]

The accelerometer in its simplest form consists of a piezoelectric disc and mass placed on a frame. In this section circuit is described in block diagram in figure (6.1) which is used for vibration measurement study. Each blocks of the circuit is given in brief in following section one by one.

In this configuration seismic mass is supported by a solid structure. Where piezo crystal is placed it is disc type. The supporting structure acts as the spring. Piezo crystal is self generating sensor which converts the dynamic force or acceleration into equivalent electrical energy. The complete diagram of piezo crystal is shown in fig. (6.2)

The sensitivity of the piezo-crystal is a complex value it is defined as the ratio of electrical output to the mechanical input.
The basic diagram of vibration measurement circuit are as follows:

- Power Supply
- Transducer (PZT)
- Impedance matching LM108
- High Low Range Toggle Switch
- Integrator LM324
- Display Unit
- ADC 7106
- RMS Detector 1N4148
- Amplifier LM324

Fig. (6.1)a

The flow of Integrator Circuit in vibration measurement:

Vin → 2 Log → \( \Sigma \) → Log → \( \Sigma \)

Fig. (6.1)b
Input Amplifier

\[ U_1 = \text{LM108} \]
\[ C_1 = 10\mu F \]
\[ C_2 = 30\text{ PF} \]
\[ R_1 = 10M \]
\[ R_2 = 10M \]
\[ R_3 = 22M \]
\[ R_4 = 100K \]
\[ R_5 = 1K \]

1. Mounting stud
2. Frame
3. Piezoelectric Disks
4. Mass

Piezoelectric transducer holder

Fig. (6.2)
6.3 MATHEMATICAL FORMULA BASED ON VIBRATION MEASUREMENT

Vibration is basically simple harmonic motion which follows the displacement pattern.

\[ X = X_0 \sin(2 \pi f t) \quad \text{--------- (6.1)} \]

\[ f \rightarrow \text{frequency of simple harmonic motion} \]

\[ X_0 = \text{amplitude} \]

\[ \omega = 2 \pi f \text{ (angular frequency)} \]

\[ X' = \text{Velocity} = X_0 (2 \pi f) \cos(2 \pi f t) \]

\[ = X_0 \omega \cos \omega t \]

\[ X'' = \text{acceleration} \]

\[ X'' = -X_0 (2 \pi f)^2 \sin(2 \pi f t) \quad \text{------- (6.2)} \]

\[ = -X_0 \omega^2 \sin \omega t \]

\[ X'' = X_0 \quad \text{--------- (6.3)} \]

\[ X' = 2 \pi f \times X_0 \quad \text{------- (6.4)} \]

\[ X'' = (2 \pi f)^2 \times X_0 \quad \text{------- (6.5)} \]

The sensitivity of the piezo crystal is a complex value it is defined as the ratio of electrical output to the mechanical input.

The voltage sensitivity \( S_e(f) \) and charge sensitivity \( S_q(f) \) can be written as

\[ S_e(f) = \frac{u(f)}{a} \quad S_q(f) = \frac{g_o(f)}{a} \]

The piezoelectric equation in term of output voltage is
\[ E = -g_{33} T + \frac{D}{\varepsilon} \]

E = output voltage

D = Dielectric Displacement

\( g_{33} \) = Piezo electric voltage constant (stress const.)

T = Mechanical stress

\( \varepsilon \) = Permittivity of crystal material at constant stress

When open circuit condition the dielectric displacement current is zero.

\[ [E]_{D=0} = -g_{33} T \]

\( T(t) \) = a (t) m/A (Compression)

\( S_{e0} \) = \( e/a = g_{33} h/A. m \) & \( S_{e0} \) = \( g_{33} h/A. m/2 \) \( \rho g_{33} \) \( h^2 \)

m = Seismic mass

m' = mass of Transducer disc

\( \rho \) = density of crystal material.

Thus the voltage sensitivity of the piezoelectric crystal sensor without seismic mass increases as the square of the disc thickness h and is independent of the surface area A. [17-20]

6.4 CIRCUIT DESCRIPTION

The actual circuit diagram is used in vibration measurement is represented in fig.(6.3) as discussed in following section.

6.4.1 Impedance Matching Circuit

In our circuit configuration piezoelectric accelerometer is a high impedance a-c transducer. Such a transducer requires high input resistance amplifier to prevent loading error. LM108 can provide input resistance in the range of 10 to 10 mega ohms using simple circuitry. Here we introduced impedance matching circuit. In this circuit controlled positive feedback is used.
called boot strapping. The lower cutoff frequency of the capacitive transducer is determined by RC, product of R and C resistances and the equivalent capacitance of the transducer.

6.4.2 Isolator and Follower

As vibration sensor does not have any current driving capacity, it requires the voltage controlled or voltage operated device, which will not draw any current from the sensor and hence loading of sensor is avoided. The only remedy for this is use of isolated gate FET or MOSFET IC, which act as a voltage follower.

As it was required to follow the sensor output, it is needed to use amplifier with unit gain so we use the easily available MOSFET IC CA 3140 that is pin compatible to the normal OP-AMP. The IC CA 3140 have very high input impedance about 1.5 Tera-ohm and bias current is also very low about 1 pico-Ampere, hence it avoids any loading on sensor. Practically CA 3140 has better current driving capacity and act as an insulator at the input stage, its speed of operation is also very high because of the FET's used in it.

A follower is used in the non-inverting mode so its gain depends on input resistances and feedback resistance which approximately equals to the unity because the input resistance is very high as compare to feedback resistance. The offset null is achieved by feeding the appropriate voltage at the inverting terminal. Thus this stage is to follow the same voltage that is fed by the vibration sensor.

6.4.3 Range Selector

The first block is a piezo electric transducer whose output voltage is proportional to input acceleration pick is very small. The first stage may have high input impedance hence preamplifier is used for impedance matching. By potential divider circuit high and low range can be selected. The signal is then
Integrator

Frequency Response of an Integrator
given to an integrator. The accelerometer pickup acceleration of transducer for digital conversion of signal is possible only when this vector is converted to velocity.

6.5.4 Integrator

This unit is followed by isolator unit to bypass some of the noise pickups by 1μf capacitor are incorporated at input. To make integrator an op amp LM 324 with capacitor of value 33μf is in feed back path. Integrator has resistance of 1.2 MΩ in feed back path.

This circuit is forwarded to range selector unit which is made of 1M pot in feed pack path of LM 324 op-amp. Integrator unit convert acceleration into velocity.

6.4.5 Amplifier

After this operation signal become much weak. This must be amplified before rectification. IC LM 324 is applied here to impliment amplifier unit. This amplifier is shown in fig. (6.5). in which one amplifier is of logarithmic type. The output of this section depends on RMS detector and integrator together.

6.4.6 RMS Detector

This RMS detector is made up of two diodes to convert ac signal into d.c. It is then amplified by two amplifiers. Vibration is random phenomenon. True R.M.S. converter is used to convert signal to d.c. Then signal is converted to digital form using an ADC. This can be taken to display unit or can be measured on computer too.
Amplifier Circuit

Fig. (6.5)
6.4.7. Analog to Digital Converter

This unit comprises of IC 7106ADC converter chip. Analog to digital converter chip 7106 is CMOS. It is necessary to incorporate unit TTL to CMOS conversion circuit before connection. This arrangement is obtained by chip and transistor matching is also employed. The circuit diagram is illustrated in fig. (6.6)

6.5 TESTING AND CALIBRATION CIRCUITS

Calibration is an important aspect for any measuring system and its instrumentation. It is the output of a system for a known input as in the case of transducer and help to establish the accuracy of the measuring system in order to validate the measurements undertaken using the system.

6.5.1 TESTING

A 40 mV a.c. signal was supplied to U1 and its output was tested. It was observed that the circuit picked up a 10 KHz noise from the power supply circuit. Capacitor is connected to bypass the noise. Improvement has been tested.

Amplifier:– Potentiometer P₁ is used to set the gain of the amplifier.

Integrator:– After the buffer amplifier stage the signal is given to a integrator. The integrator integrates the input acceleration signal and converts it to a velocity signal at the output. As a design input signal is must between 10 to 1000 Hz.

After the high input impedance stage the signal is given to a potential divider. Where the high or low range can be selected using the switch. The signal is then given to a buffer amplifier and then to an integrator.
Dual Supplies using 7660 chip

ICL7660 which is CMOS voltage converter IC

Fig. (6.6)
The integrator integrates the input acceleration signal and converts it to a velocity signal at the output as the design input signal is most between 10 to 1000 Hz.

Here is given the output of the integrator at different frequencies for 8mV input.

<table>
<thead>
<tr>
<th>Frequency Hz</th>
<th>Output (MV)</th>
<th>Av</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>370</td>
<td>46.56</td>
</tr>
<tr>
<td>100</td>
<td>37</td>
<td>4.56</td>
</tr>
<tr>
<td>1000</td>
<td>3.56</td>
<td>0.445</td>
</tr>
</tbody>
</table>

6.5.2. CALIBRATION

R.M.S. Circuit- RMS Circuit gives d.c. output equivalent of RMS of a.c. input signal. Due to mismatching in transistor, it is necessary to calibrate the circuit. Calibration is done by feeding a small offset into amplifier U4/1 by varying P2 till desired output is obtained.

Display driver The input to the driver circuit is adjusted to 200 mV by varying the input signal. Calibration of display circuit is carried out by varying P4 till full scale reading (1999) is available on the LCD.

Op-amp in the circuit designed for low input bias current Ib, requires special attention while wiring. Leakage current may exist across the PC board guards is used.

6.6 CIRCUIT OPERATION

The piezoelectric accelerometer output is fed to the charge amplifier. The charge amplifier produces output voltages (mV) proportional to the charge input fed to it. The output of charge amplifier passes to impedance matching circuit mode of LM 108. It is range selector circuit which constitutes a
calibrated attenuator. The output can be attenuated in steps one third, one tenth and one thirtieth. This output signal passes to the sensitivity full scale in 2 ranges 10 - 100 pc/g and 1 - 100 pc/g respectively. This output is again amplified by LM324 Then fed to RMS detector. Then normalized output can be directly got through the input terminal for recording display purpose. The purpose of precision rectifier to convert true dc output which can display the value of g directly on digital panel meter.

The digital panel meter consists of IC 7106. It is designed to interface with 3 1/2 liquid crystal display (3 1/2 LCD) unit. It includes a back plane driver necessary for this type of display. It is CM03 IC package which are 3 1/2 digit single chip A/D converters. 7 segment decoders, display drivers and reference and clock. Its pin diagram is shown in fig (6.7)

6.7 SIMULATION AND MEASUREMENT OF VIBRATION

As Vibration is a sudden, non-periodic excitation of a mechanical system it is characterized by a short but definite period of time. It is characterized by suddenness and severity and usually causes significant relative displacement in the system vibration, its simulation is an important environmental testing for product qualification and development. Recently different techniques are employed including VRS testing, computer simulation methodology for vibration testing in laboratory. In order to develop digital technique for measurement of frequency we reached on the point of measuring vibration also. For the selection consideration of the transducer and signal conditioner with respect to amplitude and frequency response mounting consideration, we developed idea of measuring vibration. In this chapter we discuss digital circuit for measurement of vibration in detail. To ensure that the equipment is sufficiently rugged and of quality measurement testing is necessary. The severity and nature of vibration is not always similar in working field. However with VRS (Vibration response spectrum) the field condition

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Fig. 6 Pin configuration of 7106 and 7107.
cannot be defined exactly and therefore vibration simulated can never exactly duplicate same conditions that occur in the field. Therefore machine has been tested at different field. The goal of vibration testing is that the equipment, which survives the test condition, is acceptable under service or field conditions.

6.8 RESULT AND DISCUSSION

Digital control systems afford an attractive capability for classical vibration testing. These systems through the use of high speed transfer function measurement and subsequent shaping techniques are capable of producing high quality and reproducible waveforms with minimum setup time. Most commercially available digital control systems can generate a variety of pulses including half-sine, triangular, terminal peak, saw tooth and rectangular pulses. In the market electronic circuit maker and simulation software are available. We built our digital vibration measurement circuit on that. The type of pulses that can be produce a on computer yields both initial condition \((t = 0)\) and final conditions \((t = \text{pulse duration})\) also zero value for the magnitude of acceleration, velocity and displacement. To achieve the final conditions constraints of the vibration synthesizer conditions the desired pulse by adding pre and post pulse of proper duration and amplitude is applied on different stages of circuit. These conditioning pulses are referred to as tails. These tails provide a negative area under the acceleration time history, which is equal to the area of the required classical pulse assuring zero final velocity.

The typical vibration ratings for 25 mm, 50mm and 63.5 mm displacement with maximum acceleration of 225g and maximum velocity of 5m/sec shown in figure.

Input pulses applied on system is shown in fig a, b, c

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Fig. (6.9) Computer Simulation Measurement for PZT Transducer
Fig. 6.10 Computer Simulation Measurement for PLZT Transducer
The output pulse before going to display unit is shown in figure d, e, f which is exact replica of input signal in terms of output digitization of signal.

This shows that the vibration measurement system is efficient for input signal variations. The system described is also capable of providing high input impedances so that the accelerometer and force transducer can be used without any decrease in sensitivity the g, or force of vibration can be directly read by setting the sensitivity of the transducer. The system is capable of measuring vibration upto 300 g in the 10 - 100 pc/g range and 30 g in the 1 - 10 pc/g range in four steps.

Figure depicted on (6.9a) is showing output of low range. This is exact replica of transducer pickup. This figure belongs to PZT material.

Fig.(6.9b) shows output of HIGH RANGE which is exactly same as figure (a).

(c) Shows output of voltage follow for PZT is here again it is same.

(d) And (e) curve shows the output of amplifier. (f) Figure shows the input output pulses on same scale.

(g) Figure shows the input output of Integrator. AC response of integrator is shown in figure (h)

(i) Output of rectifier is in this curve tracer shows the ac ripples are these.

(j) The output of RMS converter is quite independent of a.c. ripples. This gives the dc value of voltage pickup of transducers.

The next figure (6.10) is belongs to PLZT material. This shows good response in compare to PZT.

The specifications of the circuit are as under:

1) Display: 3½ Digit LCD

2) Range High: 100mm/sec to 1mm/sec
3) Low Range: 2mm/sec to 0.1mm/sec

4) Frequency range: 10Hz to 100Hz.

5) Signal Input: From Piezoelectric pick-up having 40mV/g sensitivity.

The accelerometer calibration is a passive calibration procedure. Here we are concerned with establishing the output sensitivity of the accelerometer and also in finding whether it is stable under the various operating conditions. The output sensitivity of the accelerometer is recorded for a given unit of mechanical input at discrete frequencies of interest selected within the frequency range of operation. The other calibration operation relates to the frequency response of the accelerometer.

So was our effort of circuit design and software developed computation are invaluable when used in conjunction with computer simulation. Our efforts and study is believe in a way will be useful in technology development for accelerometer and vibration measurement.

The outcome of vibration study in our work is for better understanding of the ferroelectric transducer materials for practical device application in vibration measurement system. We have tried to utilize their pressure sensitivity to implement vibration meter as our practical approach by digital circuit design, but also and more important to utilized simulation technique for deeper understanding of device suitability. By the formula of integration calculated values are in good agreement with those measured by vibration measurement circuit.

Our circuit developed for vibration measurement suit to all factors like low cost, construction with same ICS and minimum component which may produce adaptability for MEMS as future contribution of ferroelectric devices in modern development of technologies and industrial applications.
6.10 REFERENCES

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