Design of Industrial Vibration Transmitter Using MEMS Accelerometer

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Abstract. This paper presents the overall design of an industrial vibration transmitter using Micro Electro Mechanical System (MEMS) capacitive accelerometer. It describes the accelerometer sensor interfacing circuit, rms-to-dc converter and voltage to current loop converter circuit design, calibration procedure and mounting methods. The industrial vibration transmitter output can be customized to obtain either acceleration or velocity with root mean square (rms) or peak (pk) value signal. The electronic circuit was designed to measure vibration in motion. The output of the transmitter is a current signal (4-20mA) which is proportional to input acceleration (0-10g rms). The AC coupling circuit for accelerometer sensor interfacing, RMS detector and industrial current loop converter circuit are implemented in a single printed circuit board. The prototype consists of 2 pin top connector for power input (24VDC), current output signal and stainless steel mechanical housing assembly with bottom thread connection for mounting. The loop powered acceleration vibration transmitter is employed for vibration monitoring and control applications.

Keywords: Vibration transmitter, MEMS, capacitive accelerometer, AC coupling, RMS detector, current loop converter, condition monitoring.
1. Introduction

In recent years, machine condition monitoring system is becoming increasingly effective and sophisticated. The condition monitoring techniques mainly rely on the continuous or periodic monitoring of machine vibrations. Vibrations must be converted to an electrical signal which is performed by vibration transducers. The four types of transducers commonly used for vibration measurement are displacement, velocity, acceleration transducers and tachometer. The selection of the right type transducer and location & installation are the key considerations in obtaining a signal that accurately represents the vibrations. Accelerometers are the most popular general purpose vibration transducers. The accelerometers are constructed using a number of different technologies, but for general purpose measurements, the industry relies on the use of piezoelectric accelerometers. The several advantages of piezoelectric accelerometers are self-generating, rugged, and wide dynamic range. The high sensitivity accelerometers can be extremely costly.

The modern condition monitoring systems are employing a new family of sensors called micromachined accelerometers. Micromachining refers to the technique of manufacturing tiny moving mechanical structures out of silicon and other materials. Some of the IC manufacturing techniques such as deposition, photolithography and etching are employed for making micromachined devices. The new accelerometers include both the signal conditioning circuitry and the sensor, fabricated together on a single monolithic chip at very low cost with high reliability. The recent advances in Micro Electro Mechanical Systems (MEMS) have made high-performance, high accuracy, and low cost accelerometers.

2. MEMS Accelerometer

Micromanufacturing processes are capable of creating three dimensional structures in silicon material. The classification of major micromachining techniques are bulk micromachining, surface micromachining, dissolved wafer process, LIGA, and Electro discharge machining. The MEMS devices can be realized by using any of these micromachining techniques. Surface micromachining is based on the sequential deposition and etching of thin films on the surface of a carrier substrate. The fabrication technique uses standard integrated circuit (IC) manufacturing techniques enabling all the signal processing circuitry to be combined on the same chip with the sensor.

The industrial vibration transmitter was designed using MEMS capacitive accelerometer. The ADXL150 is a single axis accelerometer with signal conditioning on a single monolithic IC from Analog Devices, Inc. The ADXL 150 was fabricated using surface micromachining and BiMOS processes. The sensor element is made by depositing polysilicon (2.0µm) on a 1.6µm thick sacrificial oxide layer (B) that is then etched away leaving the suspended sensor (C) elements; Thus resulting in three dimensional structures suspended above substrate (A) and free to move in three dimensions as shown in figure 1. The surface micro machined mechanical element is the combination of springs, masses, motion sensing, and actuation cells. The BiMOS circuitry for on-board signal conditioning has oscillators, demodulators, amplifiers, filters and self test circuitry.

![Figure 1. Surface micromachined sensor structure.](image-url)
The ADXL150 uses a capacitive measurement technique; the deflection of the inertial mass changes the capacitance between the finger beams and the adjacent cantilever beams. The sensor structure is surrounded by supporting electronics, which converts the capacitance changes due to acceleration into a voltage, with appropriate signal conditioning circuits. The differential capacitor sensor is composed of fixed plates and moving plates attached to the beam that moves in response to acceleration. The movement of the beam changes the differential capacitance, which is measured by the on chip circuitry. The proof mass (beam) is supported by tether, which serve as mechanical springs. The voltage on the moving plates is measured via the electrically conductive tether anchors. The simplified view of sensor under acceleration is shown in figure 2.

![Figure 2. Simplified view of sensor under acceleration.](image)

3. Circuit Level Design
The complete electronics circuit design is made on a single printed circuit board (PCB) with proper mechanical slots for mounting with the mechanical housing. It consists of single axis accelerometer, ac coupling circuit, rms-to-dc converter and current loop converter circuit as shown in figure 3.

![Figure 3. Block diagram of industrial vibration transmitter.](image)

The circuit components are based on SMD ICs so that the overall size of the transmitter unit with mechanical assembly is small. The overall circuit is designed for 0-10g rms acceleration sensing, with current as the output of the circuit. It is a loop powered transmitter with 4-20mA current output corresponding to 0-10g rms acceleration input. There is no separate power supply for neither sensors or any other ICs. The internal current loop circuit supplies power for all the ICs. The design aspects of various parts of the accelerometer are discussed in the following sections.
3.1. Acceleration Sensor with AC Coupling

The ADXL150, a single axis MEMS accelerometer is used as an acceleration sensor which measures accelerations that result from an applied force. Its typical signal-to-noise ratio is 80 dB with resolution of signals as low as 10mg. For full scale range of ± 50g, the sensitivity S is 38mV/g and the frequency bandwidth is dc to 1000Hz. The sensitivity of the chip is the output voltage change per g unit of acceleration applied, specified at the $V_o$ pin in mV/g. The output voltage, $V_o$, of the sensor is a function of both the acceleration input g and the power supply voltage ($V_s$) as given by equation (1).

$$V_o = V_s / 2 - (S \times g \times V_s / 5)$$

The accelerometer chips need to be physically positioned and aligned in a manner which allows the desired acceleration to be measured. The accelerometer chip (U1) is operated with positive power supply of 5 volt. The full scale (FS) acceleration range [2] considered here is ± 10g. The full scale range can be set by the resistor values of 1MΩ, 332kΩ, and 249kΩ for the FS range of ± 25g, ± 12.5g and ± 10g respectively. The circuit component U2 is OP196GS - Micro power, operational amplifier. The FS range can be changed by the resistor settings as described in the AC coupling circuit.

The AC coupling used for vibration measurement, is employed between the ADXL150 (U1) accelerometer’ output and the external OP196GS (U2) op amp’s input. The series combination of capacitor and resistor together form a high pass filter (HPF) with corner frequency given by equation (2).

$$f_c = 1/(2\pi R_2 C_3)$$

The high pass filter (or ac coupling) reduces the signal from the accelerometer by 3 dB at the corner frequency ($f_c$) and it continues to reduce it at a rate of 20 dB per decade for signals below the corner frequency. The corner frequency can be set by the proper selection of capacitor and the resistors. The most common corner frequencies are 1 Hz, 3 Hz, 10 Hz and 20 Hz. In case of velocity measurement, the preferred lower (corner) frequency considered is 10 Hz. For almost all the machinery, the frequency bandwidth of 1.5 Hz to 1000 Hz will catch all the normal vibrations. The acceleration sensor with AC coupling circuit is shown in figure.4. The proper selection of accelerometers is needed to sense those high frequency vibrations. In this design, the corner frequency considered is 3 Hz. The value of the resistor is 249kΩ and capacitor is 0.22µF corresponding to this frequency. The output voltage $V_1$ is applied to the RMS detector circuit.

![Figure 4. Acceleration sensor with AC coupling.](image-url)
3.2. RMS to DC Converter Circuit

The AD737 rms detector chip is employed to detect the root mean square value of acceleration. The AD737JR (U3) is a low power, precision, true rms-to-dc converter. It can compute the rms value of both ac and dc input voltages. It is capable of measuring ac signals by operating as either average or a true rms-to-dc converter. The working principle of this chip is given. It computes the average absolute value of an ac voltage or current by full wave rectifying and low-pass filtering the input signal; this approximates the average. The resulting output, a dc average level, is then scaled by adding a scale factor to convert the dc average reading to an rms equivalent value for the waveform being measured. The rms detector circuit is shown in figure 5.

![RMS-to-DC converter circuit.](image)

Both the ICs (U3, U4) are operated with positive power supply of 5 volt. The rms converter has two inputs namely a high impedance 1012Ω input at pin 2 and an 8kΩ, wide dynamic range input via pin 1. The rms converter’s full scale input range is normally 200mV. The input scale factor (input range) is increased by adding an external resistance namely the resistors R3, R4 and R5. The AD737 rms converter drives an AD8541AR (U4) op amp with a negative-flowing output current. The op amp operates as a current to voltage converter and also inverts the signal. The resistor R8 value is equal to the effective external input resistance of the AD737 in order to make the input and output scaling factor to unity. The resistors R6 and R7 are used for output zero adjustment. The output voltage V2 is fed as input to current loop circuit.

3.3. Current Loop Circuit

The output voltage of the rms detector section is fed to the current loop converter, shown in figure 6. The current loop circuit converts the input voltage (V2) into loop current (I_L) of 4-20mA, which is the commonly used industrial standard current signal level. For minimum input voltage (corresponds to 0g rms), the current in the loop is 4mA and at maximum input voltage (corresponds to 10g rms), the loop current is 20mA. The output current is directly proportional to the input voltage, which is directly proportional to the input acceleration. The zero (4mA) adjustment is done by the series combination of the resistors R13, R14, R15 and R16. The span (20mA) adjustment is done by the series combination of the resistors R9, R10, R11 and R12. The circuit components U7 & U8 are LM317M - three terminal adjustable regulators.
4. Prototype
The prototype of an industrial vibration transmitter was developed with other signal conditioning circuits. The size of the card is approximately 44mm by 22mm. Two small slots are provided in the PCB card which is used for mounting this card with the 2 pin top connector. The connector consists of two male pins (A & B); one is for signal/power (+ve) and the other for ground (-ve) connection. The top connector has a diameter of 24mm, height of 23.5mm and has male threads of 5/8”. The top connector is specially designed with better precision to hold the card rigidly. The mechanical housing unit is provided with internal hole for holding the card and tapped hole (female threads ¼”-28UNF-2B) at the hexagon bottom for mounting the instruments. Its height is 59mm and diameter is 26.5mm. The overall product dimension is 26.5mm by 76mm.

5. Conclusion
The prototype of an industrial vibration transmitter was designed using MEMS capacitive accelerometer. The complete electronic circuit level design is described. These loop powered vibration transmitters are employed for vibration monitoring and control applications.

6. References
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