Vibration Data Acquisition and Visualization System using MEMS Accelerometer

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***Abstract*—Vibration measurement and its real-time graphical representation is often required for analysis of physical conditions of machines, engines as well as in scientific researches, earth-quake amplitude measurement etc. This project work was intended to develop a system for measurement and real-time visualization of vibration. An electronic accelerometer sensor facilitates the vibration sensing procedure. The measured value is then transmitted to the visualization software installed in a personal computer which provides quantitative and qualitative information about the vibration phenomena in addition with a real-time graphical visualization feature. Two test cases were selected to verify the performance of the system. The first one was implemented to visualize and measure vibration parameters of a simple plastic stand, and the second one was intended to test the system performance on an induction motor for measurement and visualization of its horizontal vibration parameters. The performance analysis in the above mentioned cases confirms the stability and reliability of the system in vibration analysis for frequency range up to 5 kHz. This concludes to a low cost vibration analysis system for uses in medium range vibration analysis like earth quake monitoring, machine vibration level monitoring etc. Though there are many available vibrations analysis systems are available, this paper work is intended to derive the process of building a low cost PIC microcontroller and C# .NET based vibration analysis system for general purpose uses like laboratory equipment or study material from commercially available equipment**

***Keywords*— C# .NET; Data Acquisition; Serial Communication; Real-time Visualization; Mechanical Vibration Measurement**

I. INTRODUCTION

Vibration measurement has a wide range of applications like in industrial or domestic use machines [1], ground, naval or aerospace vehicle engine vibration, transport comfort [2], earth quake measurement [3] etc. . Vibration is an inevitable result of any rotating machine. Vibration measurement and its analysis can be a way for condition based maintenance of machines. Conventionally machines are considered for maintenance with respect to working hour or run time. But condition based maintenance provides a rational way for maintenance according to the actual condition rather than run time which saves time, effort and cost for maintenance. Vibration measurement is also important tool for analyzing transport vehicle comfort and its engine performance. Vibration measurement is the only way of analyzing data of earthquake. . Vibration can be measured using accelerometer which provides acceleration data of an object it is attached to. Acceleration can be vibration, motion or shock. Depending on acceleration type and range of frequency of vibration different types of accelerometer can be used. In general for vibration measurement peizo-electric accelerometers are used but these are costly. . Hence many researches has been taken place for finding accelerometers which are cheaper than conventional accelerometers but can provide same or better performance than these. MEMS (Micro Electro Mechanical System) technology paves the way for that. MEMS accelerometers are of low cost, better frequency response, wider bandwidth, lower offset voltage etc. [4]. This paper illustrates the procedure of building a low cost vibration analysis and real-time visualization system using MEMS accelerometer, PIC microcontroller and C #.NET programming environment. The system involves two different units- a hardware unit and a software unit. The hardware unit is built using PIC16f73 microcontroller, ADXL335 accelerometer and RS232 communication interface. The software unit is developed using C# .NET in visual studio 2012, which enables the visualization and analysis of the vibration parameters in a user friendly environment. Whereas most of the commercially available vibration analysis systems are bit costly according to their accuracy, frequency range and design complicacy, this work specially focuses on a simple approach to design a low cost medium frequency vibration signals that arise in less complicated environments like industrial machines, transport engine vibration and comfort analysis etc. The test cases described here verifies the reliability and stability of the designed system in medium range applications.

II. METHODOLOGY

The key point of the project is a sensor that measures acceleration of a specific object in terms of analog voltage signal. Once the Acceleration in a specific dimension is found, the velocity and displacement can easily be figured out by simply integrating and double integrating the acceleration with respect to time respectively. As the key feature names for, the project consists of two units of different platforms. First one is a PIC microcontroller based data acquisition unit which measures the output voltage signal of the Acceleration sensor[5] using internal analog to digital converter (ADC) module, perform the basic mathematical manipulation for conditioning the vibration data samples applicable for serial transmission and transmits the conditioned serial data to a desktop/laptop computer via RS232 communication port. The other unit is basically data visualization software built using C# .NET. The software opens a communication port listening for the incoming data from the data acquisition device. Receiving the incoming data, the software plots the values in a 2D (amplitude-time) graphics object representing the vibration signal in a graphical form. The graphics object is updated in a regular manner (each time a new data comes to the port) and thus allows the real time visualization option to be integrated.

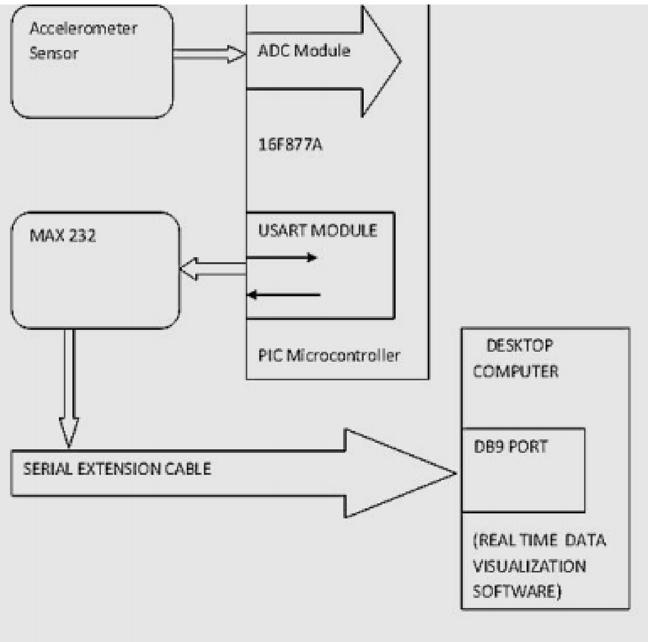

Figure 1: Block Diagram of the System

III. VIBRATION MEASUREMENT USING ACCELEROMETER

Although there are several approaches for measuring vibration signal of target objects, the implementation procedure and technology selection always relates to the environment of implementation and type of object, whose vibration signal is to be analyzed. Using an accelerometer is often a good choice for measuring vibration parameters in industrial or research applications. Once the instantaneous acceleration of the object in one direction is found, velocity can be found by simply integrating acceleration and displacement can be found by integrating velocity.

If, 'a', 'v' and 'd' is acceleration, velocity and displacement respectively. Then

$$v=\int a\,dt \qquad (1)$$

$$d=\iint a\,dt=\int v\,dt \qquad (2)$$

But the equations are valid for only continuous signal. As during data acquisition the analogue (continuous) signal is sampled and quantized, the digital data obtained is discrete in both time and amplitude level. To integrate discrete data, numerical method should be implemented. Using trapezoidal method for numerical integration shows an appreciable result.

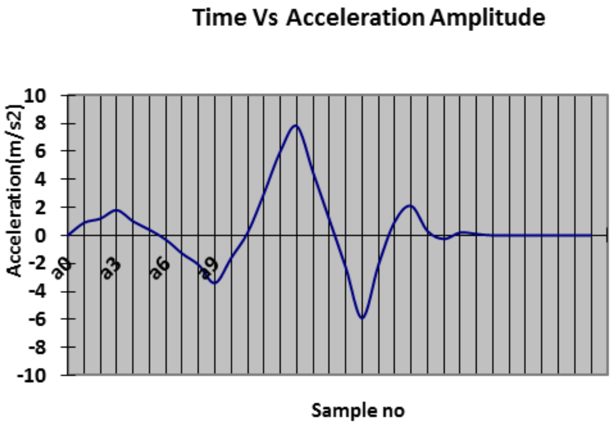

Figure 2: Sampling of acceleration signal for digital processing

. If, $a(t)$ is the continuous analog signal (time domain), Δt is the sampling time interval, $a(i)$ is the i^{th} sample of the analog acceleration signal, 'n' is number of samples of the digitized signal , by using trapezoidal method

$$\int a(t)\,dt = \sum[\{ a(i) + a(i-1) \}/ 2] \times \Delta t \qquad (3)$$

If, $v_c(i)$ is the i^{th} sample of the velocity calculated from the acceleration, $d_c(i)$ is the i^{th} sample of the displacement calculated from the velocity, by using trapezoidal method

$$v_c(i) = v_c(i-1) + \{(a(i)+ a(i-1))/2\} \times \Delta t \qquad (4)$$

$$d_c(i) = d_c(i-1) + \{(v_c(i) + v(i-1))/2\} \times \Delta t \qquad (5)$$

As the acceleration data required to be integrated once for determining velocity and the velocity is integrated further to get displacement, the accelerometer output should have no or least possible dc offset value. If there is any dc offset value it will hamper the actual data more and more with the increase of time. [1]

ADXL335 is an 3 axis MEMS accelerometer of low offset value, which measures the component of the acceleration due to gravity ('g'=9.8 ms^{-2}) or any other forces in the measuring direction indicated on its' surface and provides an output voltage analogous to the acceleration value. In stable conditions, if the measuring direction is placed horizontally (when value of the component of 'g' is zero and no other external force is applied),an electronically fit ADXL335 accelerometer provides an output voltage of 1.5V (when the sensor IC is biased by 3 V single supply voltage source). The output voltage varies linearly (sensitivity = 300 mVg^{-1}, where 'g'=9.8 ms^{-2}) with the variation of the value of acceleration component (in range of ±3)

In stable condition, the angle between the direction of measurement and the direction of gravity, $\theta = \pi/2$ and hence,

$$g \times \cos(\pi/2)=0$$

$$V_{out}(\text{sensor})=1.5\text{ V}$$

Once the output voltage is measured, the acceleration thus can easily be found, as well as the other vibration parameters from equation (4) and equation (5).

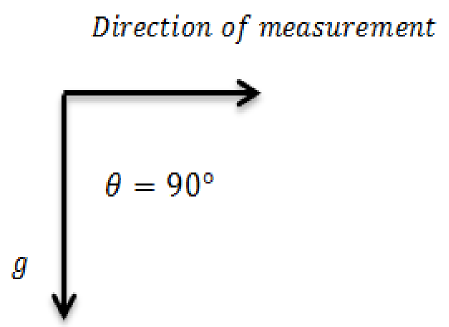

Figure 3: Component of 'g' in stable mechanical condition

IV. System Design and Implementation

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The system requires development in two different platforms-

- Hardware Development
- Software Development

A. Hardware Development

The hardware development of the system involves the measurement of vibration signal in terms of acceleration using appropriate sensor, conversion of the measured analog signal to digital format (Analog to Digital Conversion-ADC) for further digital processing and the transmission of acquired digital data to the software installed in a personal computer. ADXL335-MEMS technology based three axis accelerometer is used for the measurement of vibration signal in one direction. The sensor provides an analog voltage signal as output relative to the instantaneous acceleration. The sensors output voltage is read by the internal ADC module of a midrange PIC microcontroller. Microchip's midrange PIC microcontrollers are featured with built in ADC modules and USART module for facilitating A/D Conversion and Serial Communication process, which requires minimum level of peripheral circuitries. Reading the ADC value, the microcontroller sends the raw digital data to its UART Terminal to be transmitted to the host software. The data transfer process follows UART protocol to communicate with the PC. A MAX232 signal level converter IC based RS232 communication circuit performs the signal voltage level conversion between the microcontroller terminal and the COM port terminal of PC. A firmware installed in the microcontroller's program memory takes care of the overall data acquisition process and makes the system functional.

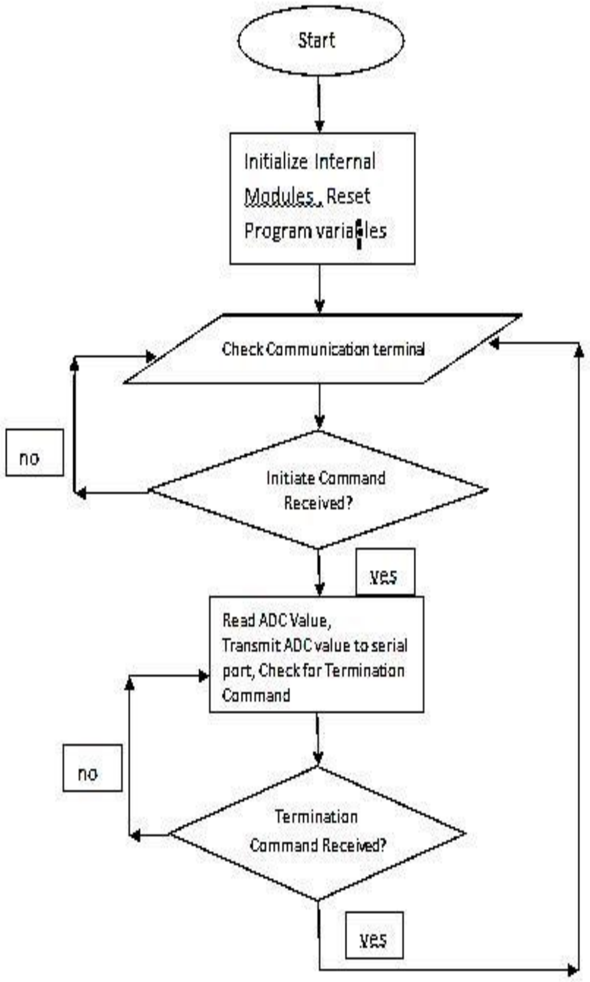

Figure 5: Flowchart of Microcontroller Firmware

B. Software Development

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The software development for the vibration data visualization system involves the firmware development and implementation for the microcontroller of the data acquisition unit as well as developing the data acquisition and visualization software for personal computer.

The firmware for the microcontroller is developed using "Mikro-C Pro for PIC 2011" embedded C compiler. Rich library of built-in routines for different hardware interfaces made the compiler well suited for the firmware development. A simple algorithm implemented in the firmware takes the charge of appropriate data measurement and communication interface between the hardware unit and desktop software according to the algorithm shown in the flow chart of figure 5.While running, the firmware firstly initializes the required internal modules and variables for system operation, i.e. the Analog to Digital Converter (ADC) module for sensor response measurement, Universal Asynchronous Receiver Transmitter (UART)module for serial communication establishment, and variables associated with storing and calculation purpose. PIC16F877A has a 10 bit ADC module with configurable sampling rate and result data orientation facilities and internal serial communication interfaces the UART module, which allows asynchronous communication interface (SCI) between digital devices with a wide range of baud-rate configurable programmatically. For the system implementation, the baud-rate was set to 128000 bit per second (bps) which offers a data acquisition rate of minimum 64 kHz, considering the required instruction cycles.

The desktop software for the proposed vibration data visualization system is developed on .NET platform using C# .NET programming language. The developed software is mainly a Windows Form Application, which provides a friendly user interface (UI) for operating and monitoring the data acquisition unit, figures out the vibration information (Instantaneous amplitude of vibration) from raw accelerometer data by use of proper mathematical equation mentioned earlier and plots the data in a graph object in the Form. The overall software development process was highly facilitated by built in classes for serial communication interface (serial port class), graphical object (Chart class), program threading (thread class) and useful delegate and event options. The desktop software processes the system parameters by maintaining the algorithm shown in the flowchart of figure 6.

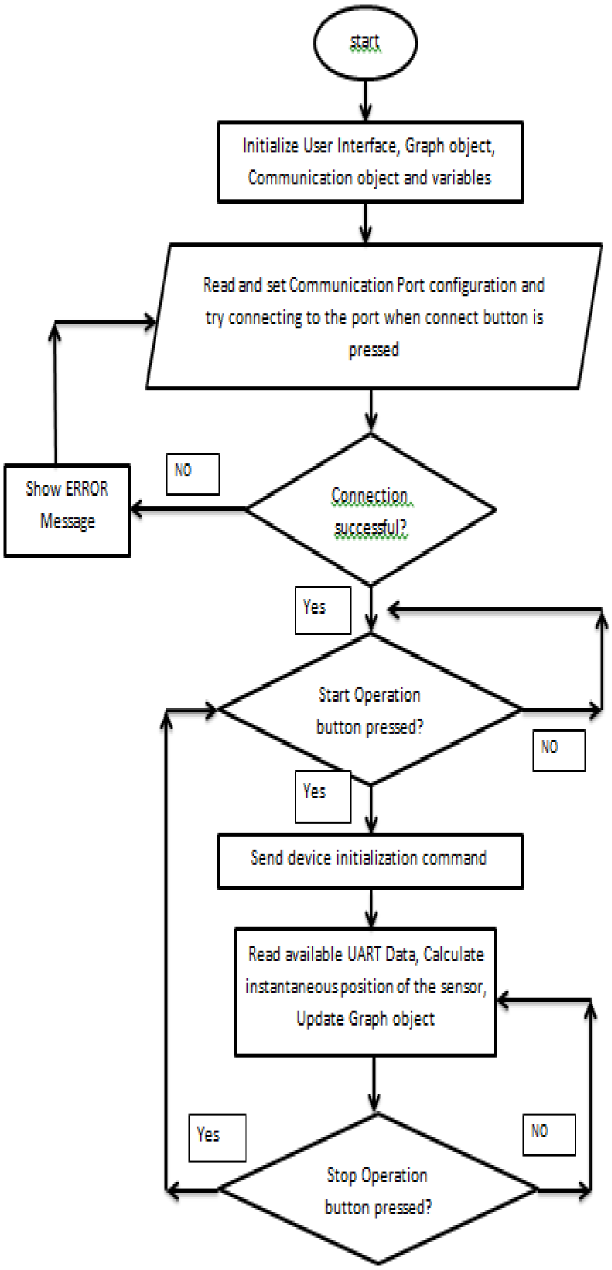

Figure 6: Flowchart of the Desktop Software

V. Performance Evaluation

Performance of the system can be analyzed in different view-points.

A. Performance in Frequency Domain

Performance of the system in the frequency domain is unfortunately limited by the frequency response of the sensor installed within it. Whereas, most modern vibration measurement systems allows relatively larger bandwidth which is around or above several kHz, the implemented sensor ADLX335 allows a measurement bandwidth from 0.5 Hz to 1.6 kHz in x and y axis and from 0.5 Hz to 550 Hz.

Frequency performance of the system can be improved by substituting the sensor by more responsive sensor units. The visualization software developed on the windows platform allows real-time visualization software developed on the windows platform allows a real-time visualization of signals consisting up to minimum of 5 MHz. (Considering dual core processor with 2.6 GHz clock frequency and possible assembly instructions required to execute a complete plotting function.) The microcontroller unit limits the frequency response of the system bellow 250 kHz because of low processing speed (20 MHz on PIC16f877A microcontroller). The maximum data communication rate supported by UART protocol implemented further limits the safe real-time plotting of data to 50 kHz. Hence, sensors responsive up to 50 kHz can easily be implemented on the existing measurement system without worrying about signal distortion.

B. Interfacing Simplicity

ADXL335 is a 3 axis accelerometer build upon 3D MEMS (Micro Electro Mechanical System) technology which provides output in analog voltage form. This makes the interface procedure simplest without requiring any advanced digital communication protocol like other advanced sensor which implements specialized communication protocol like I^2C or SPI. Again, simple UART protocol used to communicate with PC allows simple understanding, design and analysis of the system.

C. Cost Evaluation

Use of Low cost MEMS accelerometers made the designed system a cost effective solution for vibration analysis up to a 1.6 kHz (datasheet). MEMS technology provides adequate accuracy in relatively much lower cost than commercially available high end accelerometers. The graph bellow shows the similarities between the performance of a high end accelerometer data(velocity showed by blue graph) and a general purpose MEMS accelerometer data (acceleration showed by green line) for an online monitoring system to monitor bearing in a steel production machine. [7]

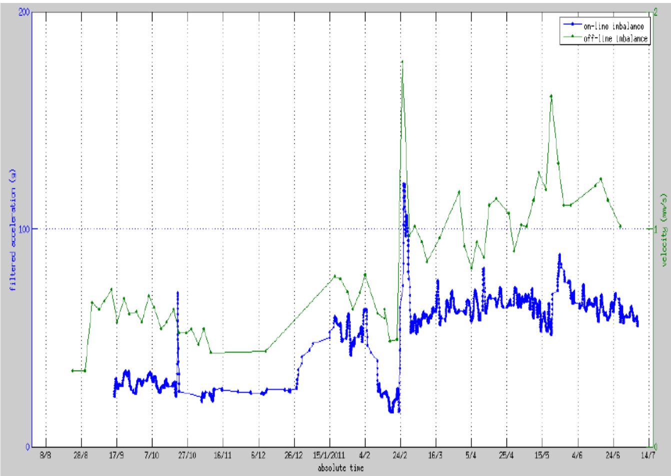

Figure 7: Performance comparison graph for MEMS and High-End accelerometer (installed for bearing alignment monitoring) [8]

The graph bellow shows the performance similarities of the same systems on a different machine. For both the cases, the MEMS accelerometer shows the ability to measure vibration data close to the high end accelerometers. [7]

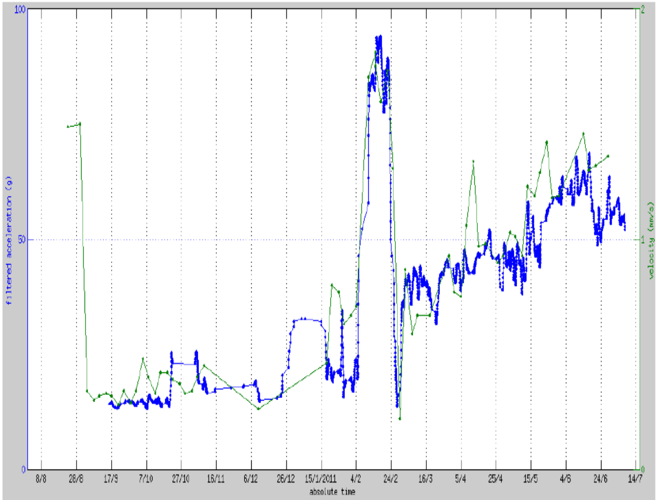

Figure 8: Performance comparison graph for MEMS and High-End accelerometer (installed for online vibration monitoring system on a different machine) [7]

Good performance and sensitivity near high end accelerometers and low manufacturing cost of MEMS accelerometers thus function as key driving factor to consider MEMS accelerometer in place of costly high end sensors.

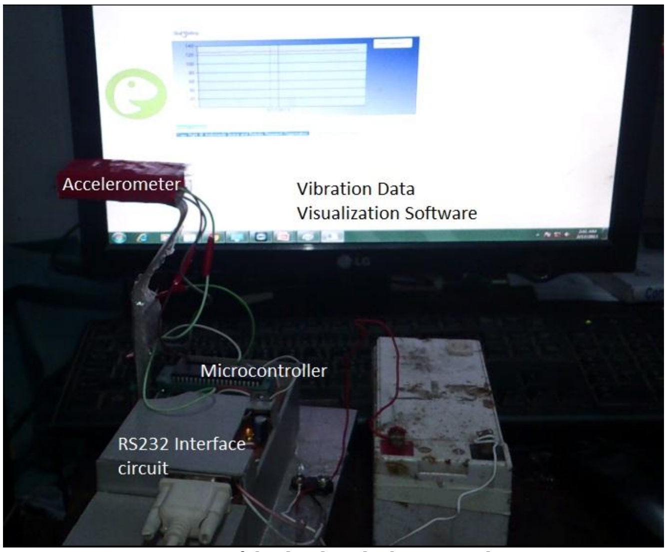

Figure 9: Picture of the developed vibration analysis system

VI. CONCLUSION

There are several approaches for measurement and visualization of vibration signals in different purposes. With the growth of modern technology, new high speed and more precise sensors are being designed, which requires a continuous upgrade in vibration instrumentation systems. This paper focuses on developing a basic way of visual vibration analysis. Though the developed system performed well for general purpose and basic scientific uses, there are still scopes of developing overall performance of the system. Recent works on further development of the system involves adding two new dimensions on vibration sensing for capturing 3 dimensional information, improvement in hardware speed and memory as well as speeding up the graphics performance by use of proper graphics hardware accelerator- which will be discussed in the next publication of this research project.

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