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THESIS

VIBRATION ANALYSIS USING A MEMS ACCELEROMETER

by

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December 2006

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The primary objective of this thesis was to study the feasibility of using a MEMS accelerometer to monitor vibration signatures of a machine to determine if the machine is operating properly. The secondary objective was to investigate the self test features of the accelerometer used in the vibration monitoring.

An Efector Octavis accelerometer sensor was used in this study. It was used to monitor a small air pump and an air conditioning (AC) system. The sensor provided the amplitude for the frequency spectrum of the motor vibration. A reference signal was calculated by taking an average of the spectrum over 30 seconds. Two methods (a ratio of cross-correlation coefficients and a spectral distance) were used to compare the reference to the sensor data. The spectral distance method proved to be the better of the two. Using this method, the system could sense when the pump or the AC unit were malfunctioning. The self test feature involved exciting the Built in Self Test (BIST) pin of the accelerometer with a signal generator. Then the impulse response of the accelerometer was measured from the output pin using an oscilloscope.

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VIBRATION ANALYSIS USING A MEMS ACCELEROMETER

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requirements for the degree of

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from the

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The primary objective of this thesis was to study the feasibility of using a MEMS accelerometer to monitor vibration signatures of a machine to determine if the machine is operating properly. The secondary objective was to investigate the self test features of the accelerometer used in the vibration monitoring.

An Efector Octavis accelerometer sensor was used in this study. It was used to monitor a small air pump and an air conditioning (AC) system. The sensor provided the amplitude for the frequency spectrum of the motor vibration. A reference signal was calculated by taking an average of the spectrum over 30 seconds. Two methods (a ratio of cross-correlation coefficients and a spectral distance) were used to compare the reference to the sensor data. The spectral distance method proved to be the better of the two. Using this method, the system could sense when the pump or the AC unit were malfunctioning. The self test feature involved exciting the Built in Self Test (BIST) pin of the accelerometer with a signal generator. Then the impulse response of the accelerometer was measured from the output pin using an oscilloscope.

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LIST OF ABBREVIATIONS

BIST	Built in Self-test
CBM	Condition Based Maintenance
ICAS	Integrated Condition Assessment System
MEMS	Microelectromechanical Systems

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I would first like to thank God through who all things are possible. I would like to thank my beautiful wife, April, for her love and support.

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EXECUTIVE SUMMARY

This thesis set out to accomplish two main goals. The first was the integration of a vibration sensor and a general purpose computer using Labview. The second goal was to investigate the self test features of the type of accelerometer used in the vibration sensor.

To meet the first goal an Efector Octavis vibration sensor was chosen. It was first used to monitor a motor attached to a small air pump. The sensor provided the amplitude for the frequency spectrum of the motor vibration. A reference signal was calculated by taking an average of the spectrum over 30 seconds. Once the reference was obtained, two methods were used to compare the reference to the sensor data and determine how closely the readings matched the reference. The two methods used were, a ratio of cross-correlation coefficients and a spectral distance. Once the basic setup proved viable, an AC unit was monitored using the same system.

The spectral distance method proved to be the better of the two. Using this method the system could sense when the pump or the AC unit were malfunctioning.

The self test feature involved exciting the Built in Self Test (BIST) pin of the accelerometer with a signal generator. Then the impulse response of the accelerometer was measured from the output pin using an oscilloscope. Several test signals were used but the only one that showed promise was the impulse test. Although there are no conclusive results, it appears that the accelerometer's impulse response is based on its physical structure and if the structure is damaged, the impulse response will change.

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I. INTRODUCTION

A. BACKGROUND

Vibratory motion is a characteristic of all types of machinery, especially rotating machinery. There is great interest in measuring and quantifying this motion because it is indicative of the state and health of the machinery. Measuring vibrations is one part of a so called Condition Based Maintenance system in which repair and maintenance decisions are based not on machine hours or time but on the condition or state of the machinery. The so called “vibration signature” of the device will tell the operator whether the device is operating properly and can offer an early warning if the machinery is beginning to fail.

One method of measuring the vibration of a particular piece of machinery is to mount an accelerometer and measure the accelerations produced by the vibration. There are numerous accelerometers on the market outputting both digital and analog signals that can be captured by a computer. Once the data is in the computer, powerful signal processing tools can be applied to examine and classify the acceleration data. The state of the machinery can be determined through comparing the data with a base-line signal captured when the machinery was in a known good state.

A problem with using accelerometers is the high data rate required to load the data onto a computer. This can be solved by performing some processing onboard the sensor then sending this processed data to the computer. For this thesis an Efector vibration detector was used to measure the vibration of an electric motor and an AC unit. This device sends serial data through an RS-232 cable to the COM port of a computer. Then, using the LABVIEW program, this data is parsed, analyzed and used to determine if the machinery is operating properly.

Another major issue with the use of accelerometers is the difficulty in calibrating and verifying that they are operating properly. With traditional accelerometers, one must remove and test the accelerometer on a bench to determine if it is malfunctioning. A MEMS accelerometer can be tested in place by exciting it with a known electrical signal and observing the output. This signal can be produced on chip resulting in a Built in Self

Test (BIST) or another circuit can be used to produce the signal. The electrical signal excites the same internal components that sense the acceleration, thus any malfunction will result in an altered response to the test signal. In either case, a technician can quickly determine if the sensor is malfunctioning.

B. OBJECTIVES

There were two main objectives for this Thesis. The first task was to monitor a piece of machinery using the Efector Octavis vibration sensor and a CPU running LABVIEW. The second task was to demonstrate the testing and calibration capabilities of a MEMS vibration sensor.

The first objective consisted of writing a Virtual Instrument (VI) script in the LABVIEW program. This included configuring the serial port to communicate with the sensor, parsing the data from the sensor, processing the data and finally analyzing the data.

The second objective consisted of wiring an Analog Devices ADXL105 single-axis accelerometer to a breadboard, exciting it with a signal generator and measuring the response to the self test input using an oscilloscope.

II. OVERVIEW OF VIBRATION SENSORS

A. USAGE OF VIBRATION SENSORS IN MAINTENANCE PROGRAMS

Various industries have implemented Condition Based Monitoring (CBM) programs based on vibration data. Numerous companies have supported research into using condition monitoring to drive repair and replacement schedules. Jardine examined the development of a Condition Based Maintenance program implemented in the food processing industry (Jardine & Banjevic, 1999). In this program vibration data is used to generate a statistical measure of when the bearing is expected to fail and what is the optimal time to replace it.

B. MEMS VIBRATION SENSORS

A MEMS accelerometer senses vibration through the use of micro-fingers in close proximity to anchored electrodes. When the assembly is subjected to vibrations the fingers are deflected and the distance between them and the electrodes changes. This causes a change in the capacitance between the anchor and the electrodes according to the following equation:

$$C = \in_0 \in_\tau \frac{A}{d}$$

Where:

C is the capacitance in farads, F
ϵ_0 is the permittivity of free space, measured in farads per meter
ϵ_τ is the dielectric constant or relative permittivity of the insulator used
A is the area of each plane electrode, measured in square meters
d is the separation between the electrodes, measured in meters

The Analog Devices ADXL103/ADXL203 data sheet explains the method in which this change in capacitance is converted to a change in the output signal. "The fixed plates are driven by 180° out-of-phase square waves. Acceleration deflects the beam and unbalances the differential capacitor, resulting in an output square wave whose amplitude is proportional to acceleration (Analog Devices 2006)."

This can be used to produce an analog signal which will continuously indicate the acceleration of the sensor. If there is no acceleration, that is the sensor is at a constant velocity, the signal will be constant. If, however, the sensor is subjected to continuous but possibly varying accelerations, as it would be when mounted on a vibrating object, the signal will be directly proportional to the actual vibration. Figure 1 is a picture of a MEMS accelerometer showing the fixed electrodes and the deflecting fingers. This only indicates acceleration in a single direction, however, there are MEMS packages that have two or three separate sensors that can measure acceleration in two or three dimensions. The MEMS sensor itself is an inherently analog device so any processing will require at the least an Analog to Digital Converter (ADC).

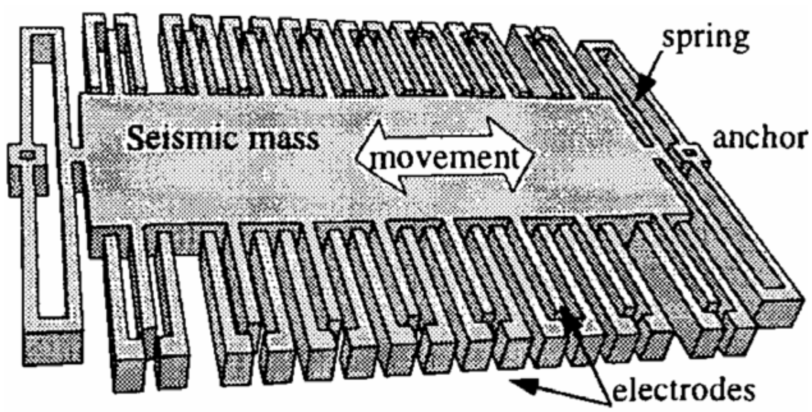

Figure 1. MEMS Vibration Sensor (After Charlot)

C. THE EFECTOR VIBRATION SENSOR

The Efector Octavis vibration monitor consists of a MEMS accelerometer, a 16-bit ADC and a Digital Signal Processing (DSP) chip. The MEMS accelerometer produces an analog time domain vibration signal which is converted to a digital signal by the A/D converter. Then the DSP chip calculates the FFT of the signal which is sent to the RS-232 serial port. There is proprietary software that can then analyze the signal and provide information about the machinery. In this project, LABVIEW was used to capture the data directly from the serial COM port. Appendix One contains the complete product information sheet (IFM Efector, 2006).

D. INSTALLATION OF SENSOR ON OPERATING MACHINERY

The Efector Octavis was installed on an air-conditioner unit in Bullard Hall to demonstrate the vibration monitoring capabilities of the unit. There were two configurations for monitoring the signal, one routed the signal through the NPS intranet the other made use of a small wireless LAN. In both cases, the vibration was remotely monitored from the PC running the LABVIEW software. Once a baseline is established by averaging the vibration signal over several minutes, a tolerance can be established and thresholds set.

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III. USING LABVIEW WITH A VIBRATION SENSOR

This chapter discuses the equipment setup, data acquisition and basic data display. The vibration sensor was setup to monitor a motor attached to an air pump and an air conditioning (AC) unit. The data was sent from the sensor to a computer and parsed for further processing. The frequency amplitudes were plotted on a graph and the machine condition indication parameters were displayed using a gauge indicator

A. EQUIPMENT SETUP

There were two separate pieces of machinery that were monitored for this project. One was a 115 volt single phase electric motor driving an attached air pump. This was chosen for several reasons. It is small enough to sit on the workbench next to the computer so the sensor could be directly linked to the computer's serial port. Also, it has a steel casing with which to magnetically mount the sensor and it was easy to induce a "casualty" condition which would significantly alter the vibration profile (placing an object over the air pump's output). The other was an AC unit installed in the overhead of the Optics Lab of Bullard Hall. This was chosen because it is a "real world", operating piece of machinery. Also, it was close enough to the computer to make setup changes quickly, but far enough away to demonstrate both the wireless and the wired LAN connection capabilities of the system.

The pump motor setup was relatively simple. The power supply and data cable are the only connections made to the sensor and the serial cable is connected directly to the serial port on the back of the computer. Figure 2 is a picture of the pump motor setup. As shown, the senor was mounted directly onto the housing of the motor using a magnetic bracket (the brass colored cylinder). The sensor itself is threaded onto the magnet. In an installed setup, there are holes in the sensor with which to permanently mount it to the machinery.

Figure 2. Pump and Motor Setup

The AC unit setup was significantly more complex because of the use of serial servers to emulate the serial link through an Ethernet connection. The physical setup consisted of magnetically mounting the sensor to the outside of the steel housing as shown in Figure 3. The power connection was identical to the pump and motor setup. For the serial connection two different setups were used. One used a B&B Electronics VLinx serial server to allow the vibration sensor to send its data over the NPS LAN. The VLinx was assigned a static IP address and then acted as a relay for the vibration data. Using the proprietary software, a "virtual comm port" was created on the computer. Then Labview could access the information exactly as if the sensor were physically connected to the computer's comm port. The other setup used a Moxa Nport wireless serial server. This device emulates a serial connection over an 802.11 wireless connection. A Netgear wireless router was setup as a wireless server with the computer and the Nport device as its only clients. Once again the proprietary software allowed Labview to see the sensor as simply another serial connection. Figures 4 and 5 show the serial server setups. As shown, both of them have a power connection and an RS-232 serial connection. While the Nport has an Ethernet adapter cable to link to the serial connection the Vlinx device connected directly to the serial cable itself. The Vlinx connects to an Ethernet drop while the Nport broadcasts its 802.11 signal.

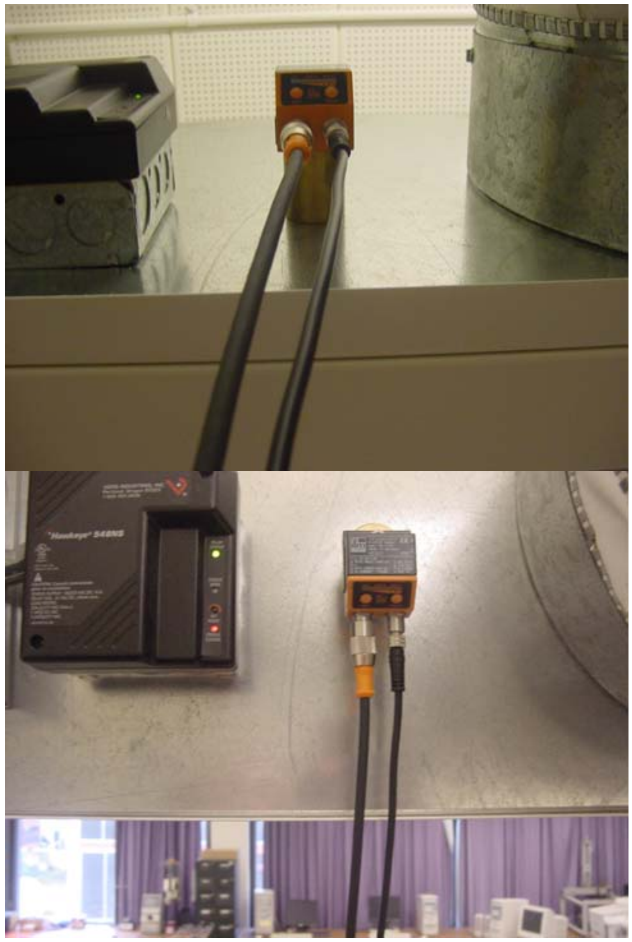

Figure 3.   AC Unit Setup

Figure 4. VLinx Device

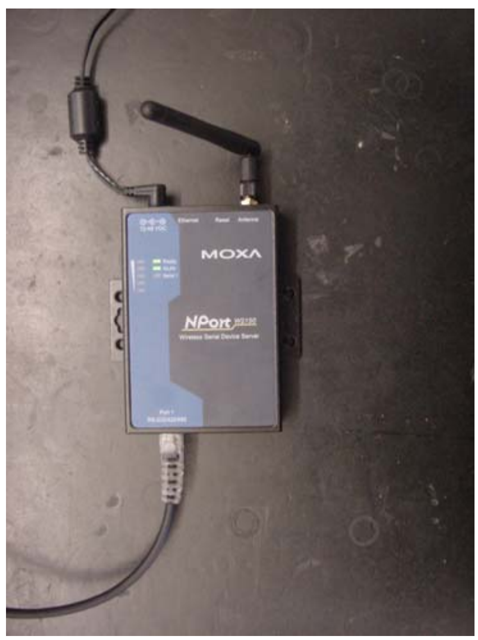

Figure 5. NPort Device

B. DATA ACQUISITION

The Efector Octavis VE1001 uses RS-232 serial cable to send its vibration data. The interface parameters from the company’s data sheet are shown in the following table. For each time instance several operations must occur to transfer the vibration data from the sensor into the Labview program for processing. First, Labview sends an ASCII 3 to the sensor which tells it to send the vibration data. Once the sensor receives the command it sends a string representing the value of the current amplitude for the frequency range it is setup to monitor.

Transmission Rate	57600 baud
Parity	None
Data bits	8
Start bit	1
Stop Bit	1

Table 1. Efector Octavis Interface Parameters

To set up the serial port in Labview the following blocks shown in Figure 6 were used. The parameter outside the box tells Labview which serial port to use. From top to bottom inside the box, 1696 is the size of the buffer in bytes, 57600 is the baud rate 8 is the number of data bits, 1 is the number of stop bits and the zero indicates that there is no parity bits. This command is executed only once at the beginning of the session to setup and initialize the serial port.

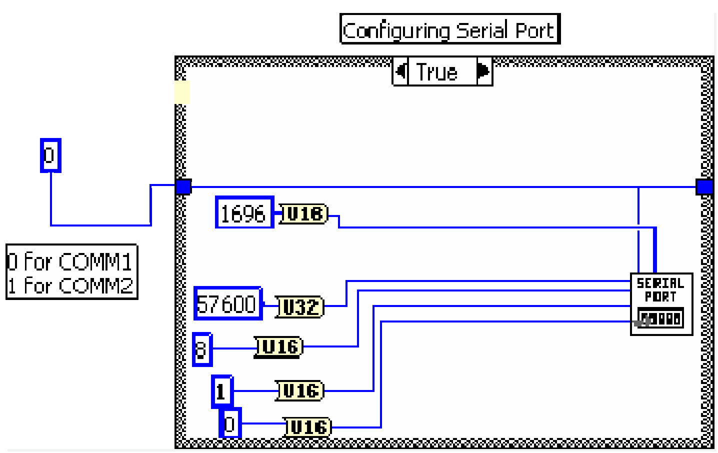

Figure 6. Serial Port Setup

Once the serial port is set up, Labview has two blocks with which to send data to and from the sensor. The Write block is used to send data to the sensor via the serial port and the Read block is used to read data from the sensor via the serial port.

Figure 7 shows the Write (W) block sending the ACSII “3” to the serial port initialized by Labview and the Read (R) block reading 942 bytes from the serial port. 942 bytes will read both the start and stop strings of the sensor and the 896 byte data word. The sensor was set up to look at the spectrum from 0-550Hz. In this mode the data word consists of 448 two byte words. The first eight words represent various parameters of the sensor while the final 440 words represent the amplitude of each frequency at a resolution of 1.25 Hz. The following table is a summary of the data word from the company literature.

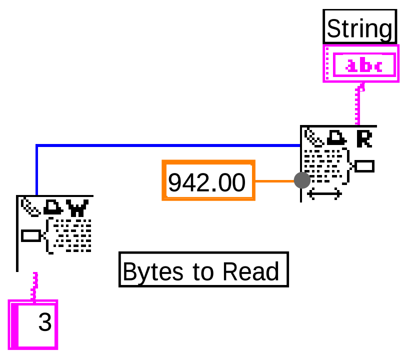

Figure 7. Serial Read and Write

Position	Variable	Determination of
1	N	Rotation speed
2	Px	Peak-Max
3	Pn	Peak-Min
4	Mw	Average value
5	EMw	Average value
6	ShF	Displayed frequency range, amplitude
7	Ex	Amplitude
8	A	Analysis process
9	V1	Amplitude
10	V2	Amplitude
11	V3	Amplitude
12	V4	Amplitude
..	. ...	
848(448)	V848(V440)	amplitude

Table 2. Summary of Data Word

Once the entire data word is in Labview it flows through several steps to parse, convert, display and analyze the data it represents. First, using the block shown in Figure 8, Labview looks for the start word which indicates that the sensor will be sending data. One it finds the start string of "Start_FFTS" Labview reads in the next 896 bytes (448 16-bit words). Now there is a string consisting only of the data sent from the sensor for one instance of time.

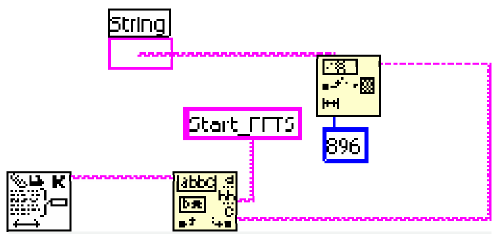

Figure 8. Parsing the Data String

The string then enters a for loop where the string is converted to a number and the actual frequency amplitudes are calculated. The output of the for loop is a 1x440 vector of amplitudes where each element of the vector represents given frequency from 0-550Hz in 1.25Hz increments. Figure 9 shows the basic for loop to convert the raw data string into a vector of numbers. The inputs to the "HZ GEN" block are the parsed data string and the frequency value in Hz to extract from the string. The loop goes from 0-440 and the outputs of the for loop are placed in a vector. Figure 10 shows the inside of the HZ GEN block. The two inputs are "string "and "HZ" and the output is the "Amplitude at Freq". The network implements the following equation for frequency amplitude:

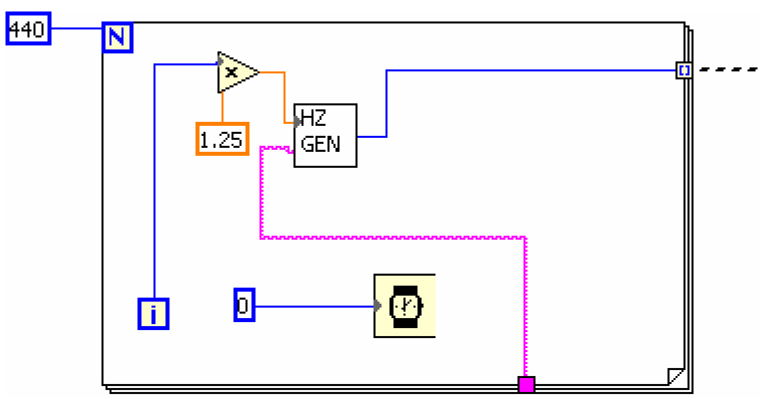

Figure 9. For Loop to Convert Data String

$$A = \left(\frac{(V_n * 2^{Ex})}{275} \right) * 1.990049751$$

Where:

A=Amplitude at the given freq in mg (Milli-g's)
V_n=The Amplitude for the given frequency
Ex=A factor to calculate the value

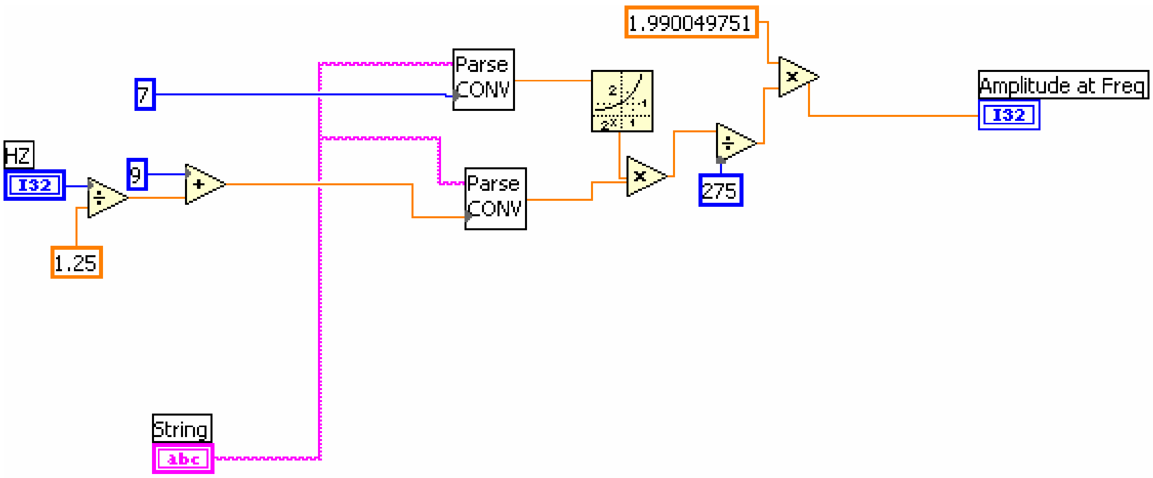

Figure 10. HZ GEN Network

The two "Parse CONV" blocks pick out the "Ex" value and the amplitude of the frequency, convert them both to numbers and output them to the equation network which sends the value back to the HZ Gen command. Figure 11 shows the inside of the "Parse CONV" block. The inputs are the parses data string and the position number of the data word to convert. The middle block takes the entire data string and extracts the two byte word and sends it the "Srt 2Hex" block to convert it from an ASCII string to a HEX string. Finally the right most block converts the HEX string to a HEX number and sends it back to the "Parse CONV" block. Now there is a data vector representing the amplitude of each frequency. The first analysis performed was simply to display the spectrum on a graph in Labview.

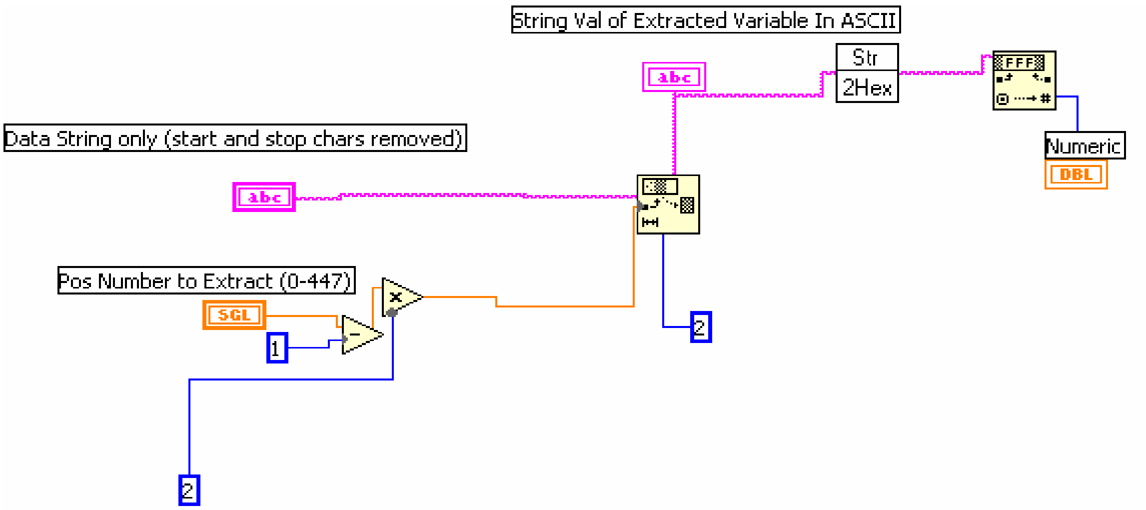

Figure 11. Parse CONV Network

C. SPECTRUM PLOT

A spectrum plot was created using Labview to display the serial data from the Efector sensor. For the configuration used in this project, the magnitude of each component of the range of the spectrum is 0-550 Hz. The resolution of the spectrum plot is 1.25 Hz so there is a total of 440 spectral components. Figure 12 shows a snapshot of the spectrum plot of the pump motor's vibration when it is operating properly.

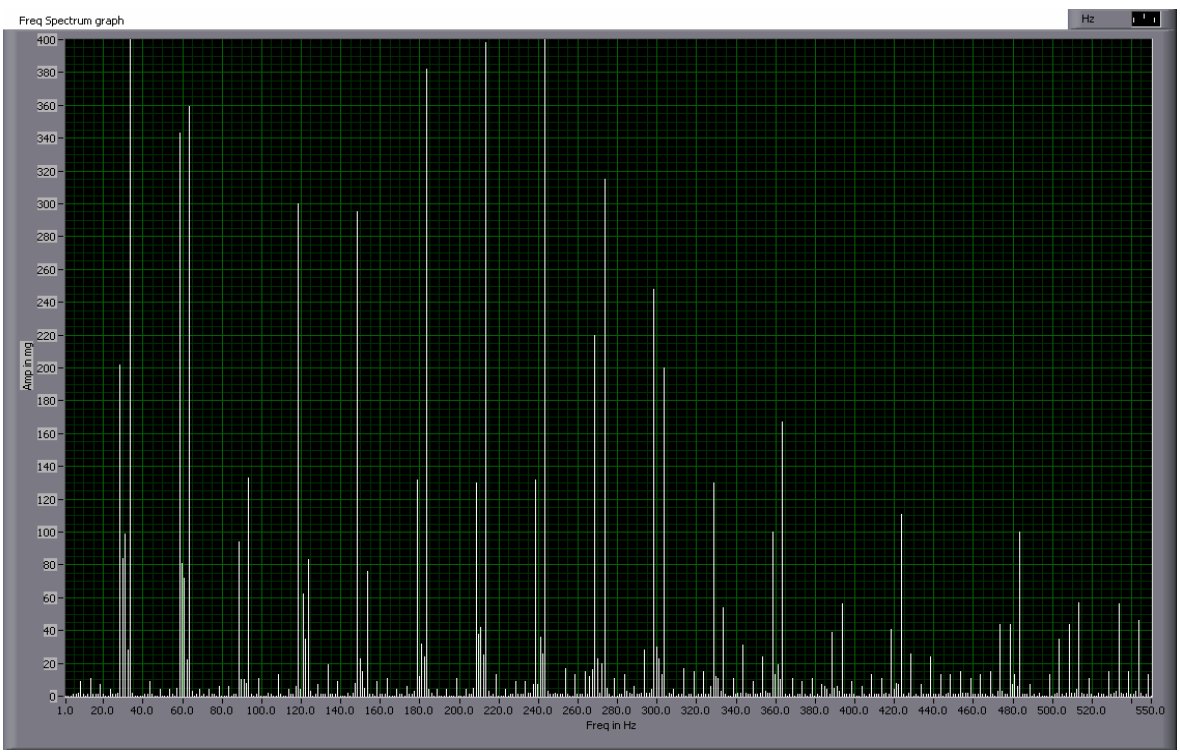

Figure 12. Pump Vibration Spectrum- Normal Condition

A casualty condition was induced by partially blocking the outlet of the air pump and the results are shown in Figure 13. Figures 14 and 15 show similar plots for the AC unit. The only way to “damage” the unit was to turn it off. From these displays it is clear that the spectrum is significantly different based on the operating condition of the equipment. The next task was to some how quantify this difference.

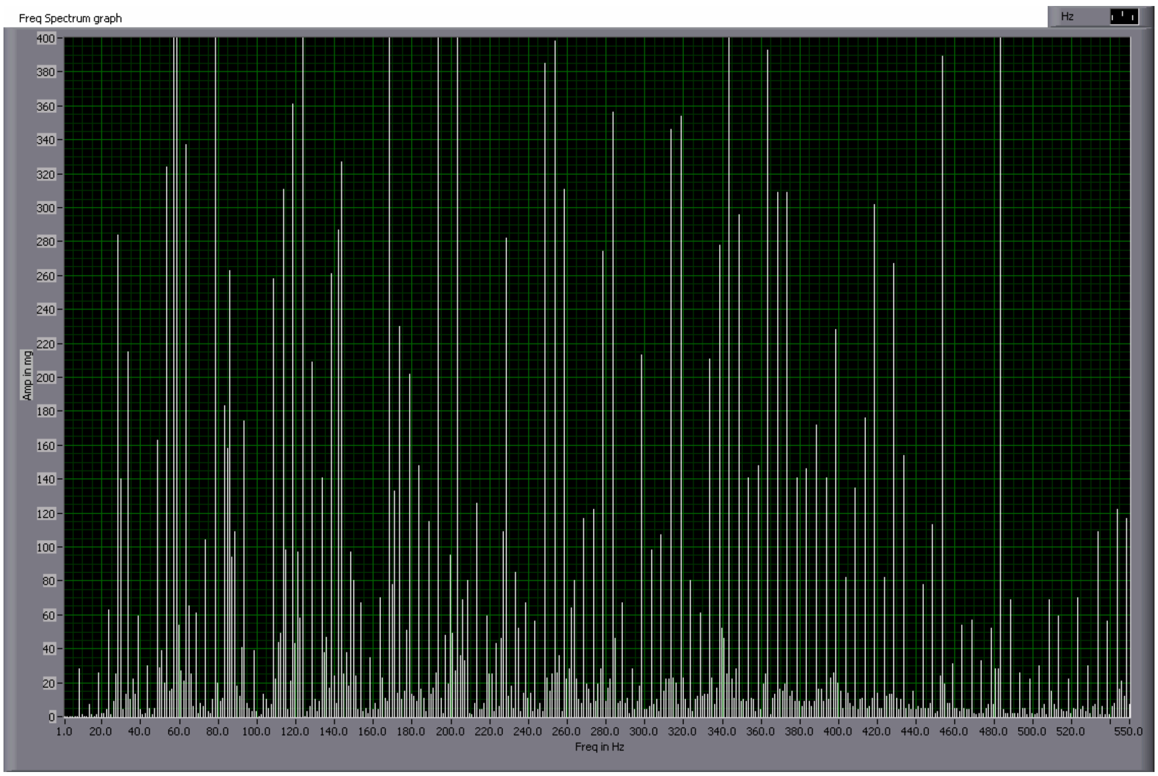

Figure 13. Pump Vibration Spectrum- Damaged Condition (Outlet Blocked)

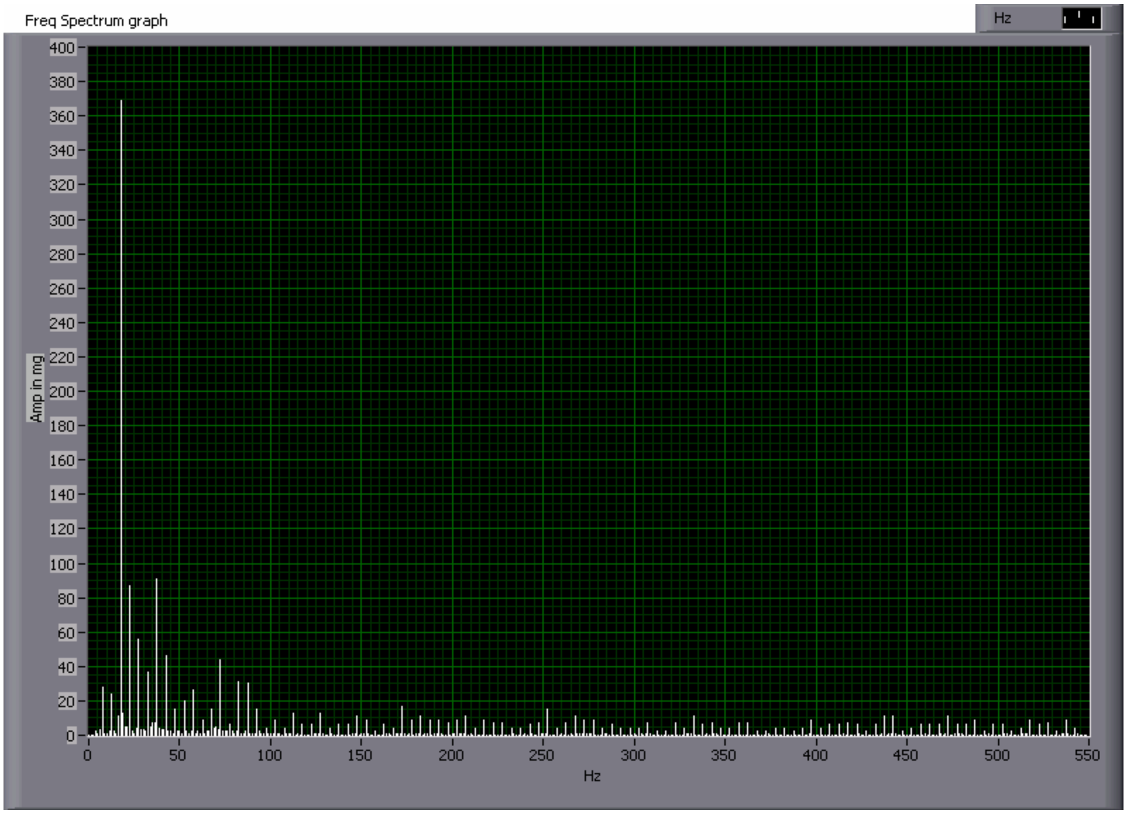

Figure 14. AC unit Vibration Spectrum- Normal Condition

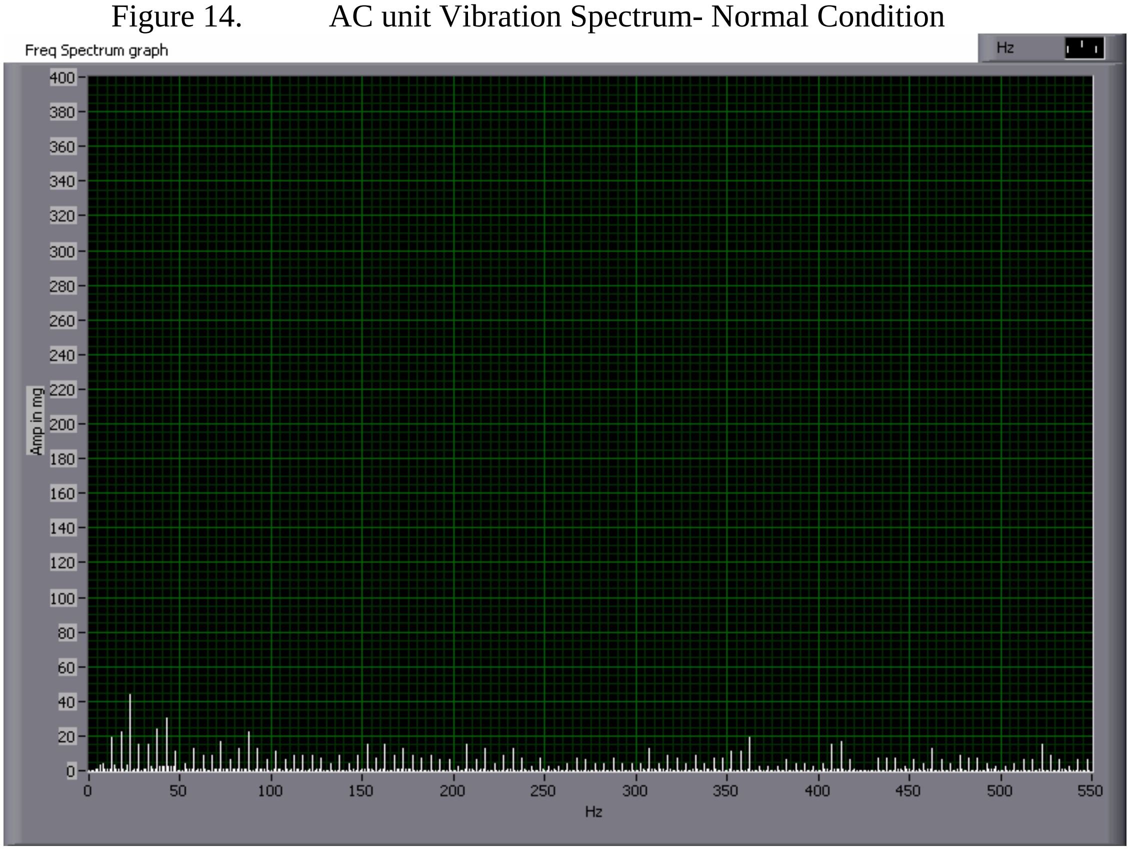

Figure 15. AC unit Vibration Spectrum- Damaged Condition (AC off)

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IV. EVALUATING VIBRATION DATA

This chapter discusses two different methods of evaluating the vibration data produced by the sensor. First, a reference signal is generated from the average amplitude of the vector over several sampling periods. The two methods used to compare the reference signal to an arbitrary signal are Spectral Distance and Cross-correlation.

A. CREATING A REFERENCE SIGNAL

In order to evaluate the vibration data we first need to know what the signal looks like when the machinery is operating normally. To accomplish this we must measure the vibration signal when we know the system is operating properly. Taking the average over several measurements will produce a good baseline signal which can be compared to the measured signal during operation. Figure 16 shows the network to produce the average signal. Only the components directly involved in the averaging process are shown all other were removed from the display. The entire program is running in a while loop so during each iteration, the current data vector is added to the sum of all the previous vectors in an element by element manner. Then the entire vector is divided by the number of loop iterations. Finally the vector sum value is passed forward into the next loop iteration. After the loop runs approximately 20-30 time there is no significant change in the values of the vector. The "AMP Vector" constant is saved and used in the comparison routines.

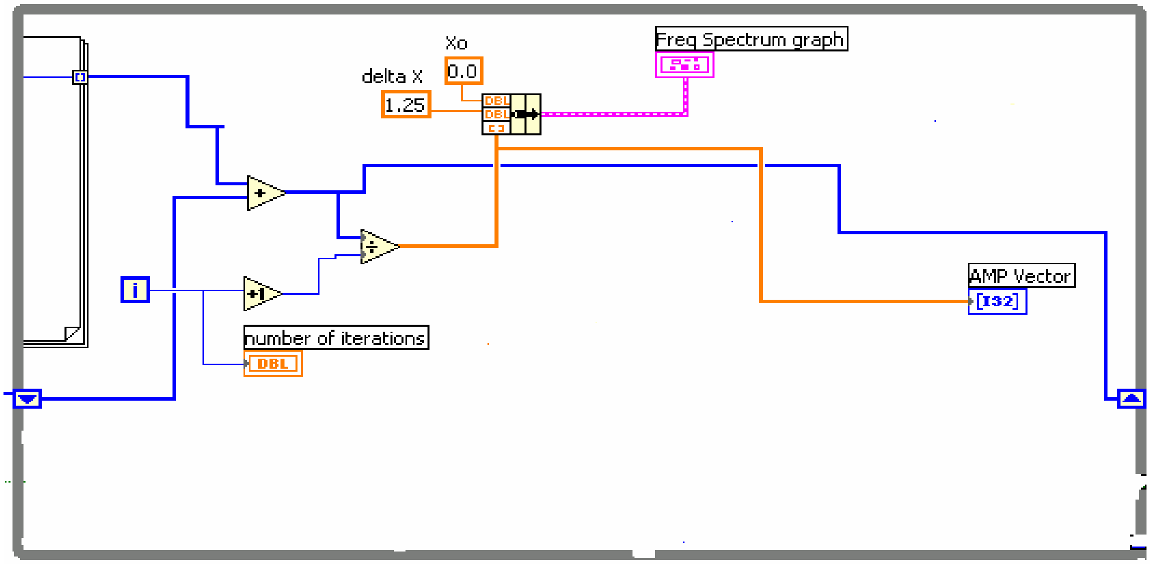

Figure 16. Creating the Average Signal

Figures 17 and 18 show the graphs of the reference signals used to monitor the pump motor and the AC unit. We now need a method of comparing these reference signals to any given signal produced by the sensor. This test method would ideally have the properties of a vector distance namely:

$$D(P_x, P_y)\begin{cases} > 0, \ when \ P_x \neq P_y \\ = 0, \ when \ P_x = P_y \end{cases}$$

$$D(P_x, P_y) = D(P_y, P_x)$$

(after Therrien, 1989)

Where:

D=A scalar measure of the similitary of the two signals
P_x=The sensor data signal
P_y=The reference signal

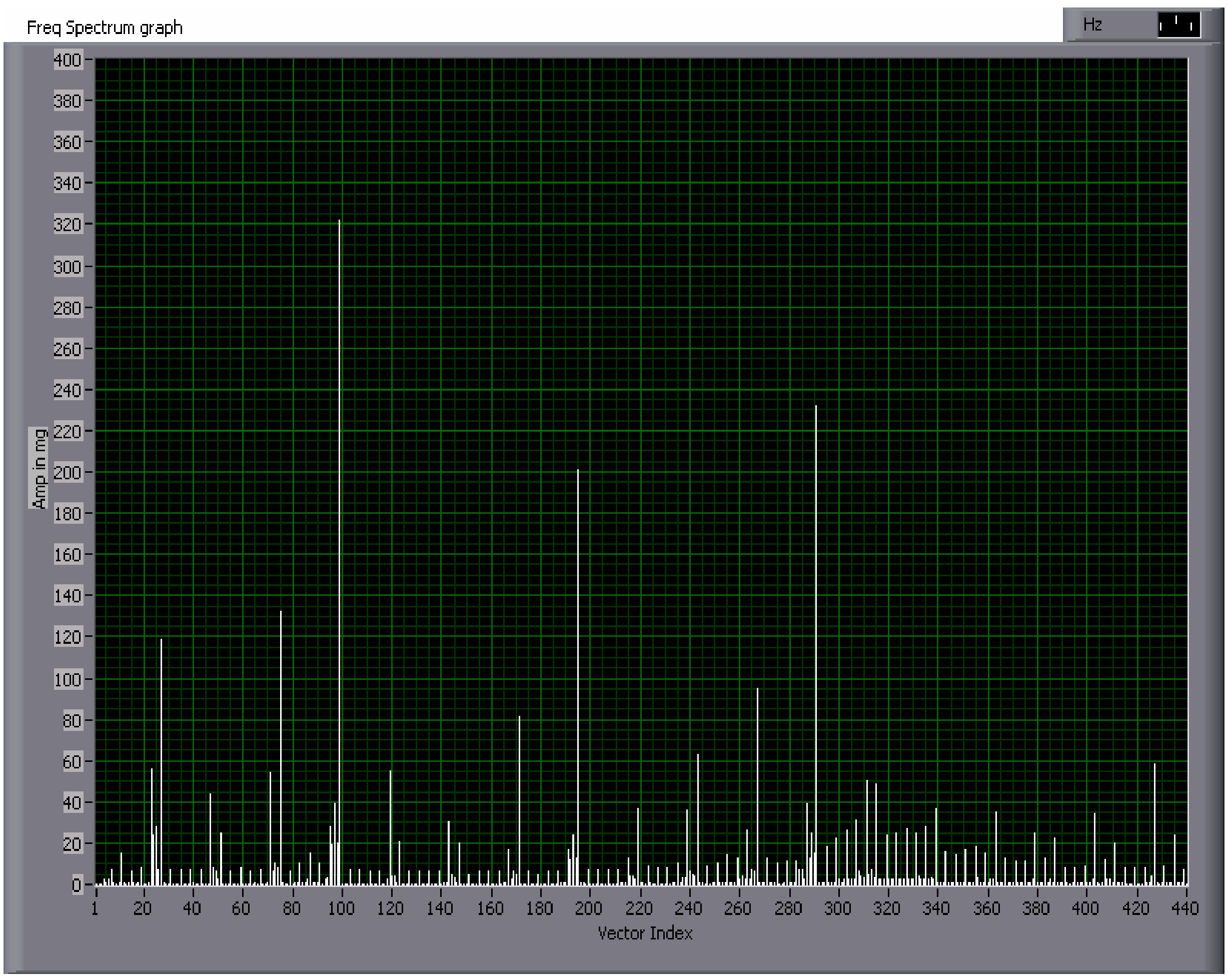

Figure 17. Graph of Pump Motor Reference Signal

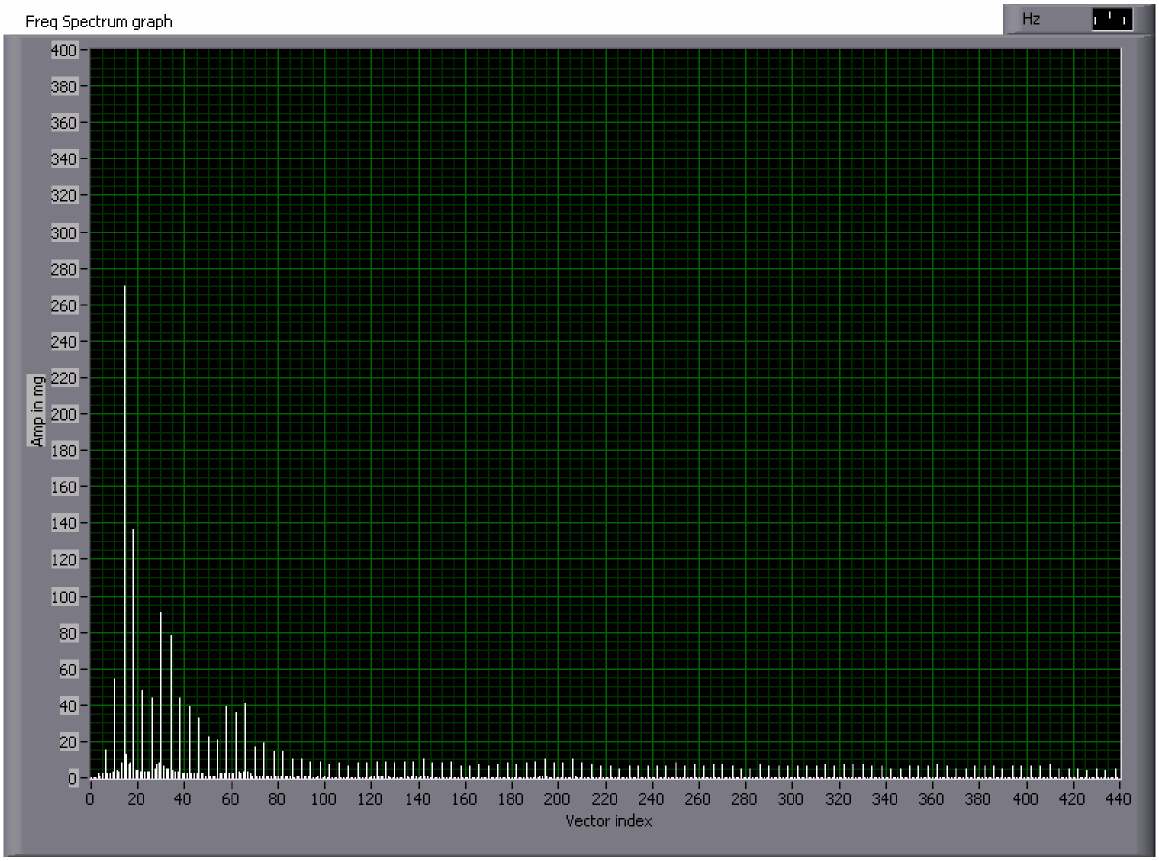

Figure 18. Graph of AC Unit Reference Signal

In addition, it should react quickly and significantly to changes in the machineries' operating condition. There should be an immediate change in D as soon as the spectra deviate and that change must be large enough to be measured.

B. CROSS CORRELATION

Comparison of cross-correlation coefficients was the first method used to compare the reference signal to the sensor signal. When two signals are very similar, the central cross-correlation coefficient is extremely large compared to the coefficients immediately adjacent. When the signals differ significantly, the central coefficient is smaller relative to the other two coefficients. Two D's are then calculated by taking the ratio of the adjacent coefficients to the central coefficient. When the sensor signal is similar to the reference signal, the ratio will be small because the central coefficient will be very large. When the signals differ the ratio will be larger because the central coefficient will be relatively smaller. Labview defines the cross-correlation as:

$$D(t) = \mathrm{P_x}(t) \otimes P_y(t) = \int \mathrm{P_x}^*(\tau) P_y(t+\tau) d\tau$$

This method satisfies all three distance properties listed above. If the two signals are exactly the same, all of the energy will be in the central cross-correlation coefficient making the ration zero. Because correlation coefficients are by definition positive, and this test uses a ratio of correlation coefficients, D can never be less than zero. Finally, one of the basic properties of cross-correlation is cov(x,y)=cov(y,x). Figure 19 shows the Labview implementation of this technique. First the cross-correlation of the reference and sensor signal is computed. The three parse blocks then pick out the central coefficient and the two coefficients immediately above and below. The ratio is then computed and then two maximum value blocks are used to convert the vectors into single numbers. Finally the numbers are displayed on a time history chart and as gauge indicators.

Figure 20 shows the time plot of the two ratios over one minute of operation for the pump motor. At approximately the 10 second point on the graph, the pump's air outlet was obstructed. This corresponds to the very high spike on the lower graph. The outlet was obstructed for 20 seconds and then the pump was allowed to run normally for about 20 seconds. During the final 10 seconds of the graph, the motor was off. There is very little recognizable difference in the graph during the different operating conditions. The only indication of a problem while the pump outlet was blocked is the large spike in the lower graph. In the final portion of the experiment, the plot quickly returns to within 25% of the normal operating condition despite the pump being off. When the pump is turned off, the lower graph does indicate a problem with a value approximately twice that of the normal value. Overall, this was a poor indicator of the condition of the pump. This method was even worse at determining the condition of the AC unit. Figure 21 shows the plot of the cross correlation ratios over one minute of operation in which the AC unit was turned off at approximately 20 seconds and back on at approximately 40 seconds. There is no discernable difference in the signal during any change in condition. The relatively fewer dominant frequencies in the AC unit's spectrum make it harder to detect a change in operating condition. The bandwidth of the spectrum is only 50 Hz while the pump motor's spectrum has relatively large components for the entire bandwidth to 550 Hz. This results in more components that differ from one another so there is a stronger indication when there is a change in operating condition.

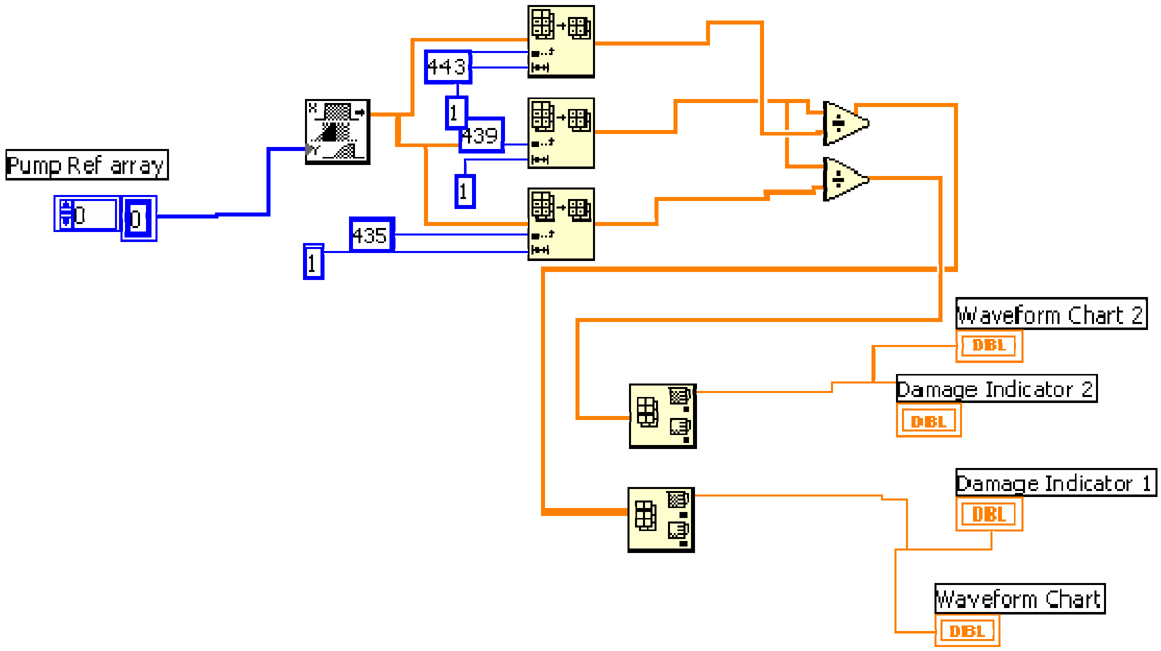

Figure 19.   LabView Cross-correlation network

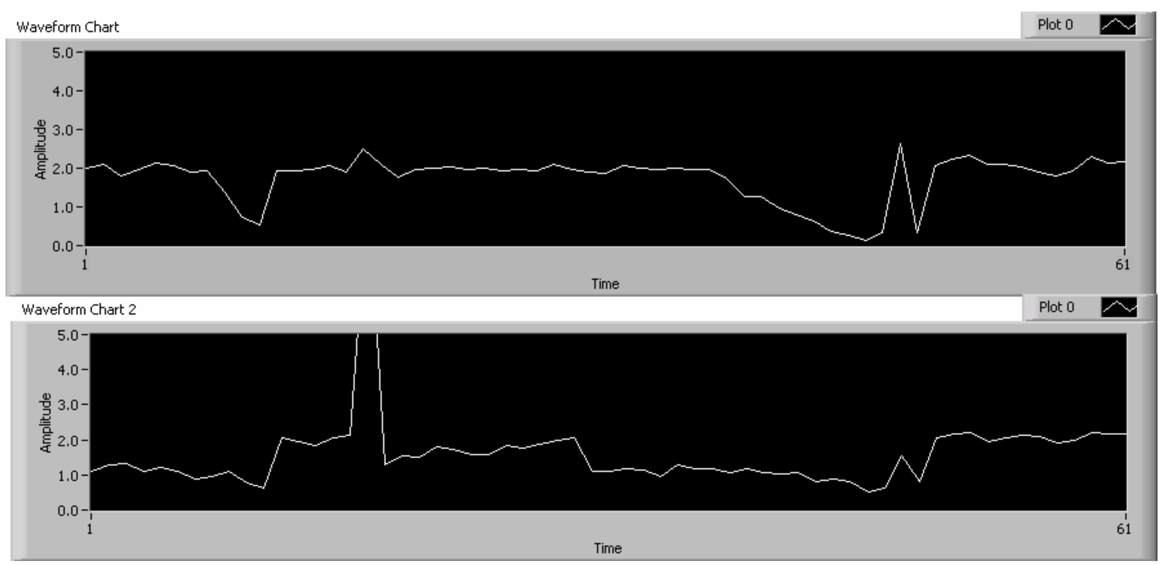

Figure 20.   Pump Motor Cross Correlation Plots

This characteristic will show up in the next comparison method also. The cross-correlation test was inadequate for the needs of this project. Although it met the properties of a distance, it did not react properly to changes in the sensor data.

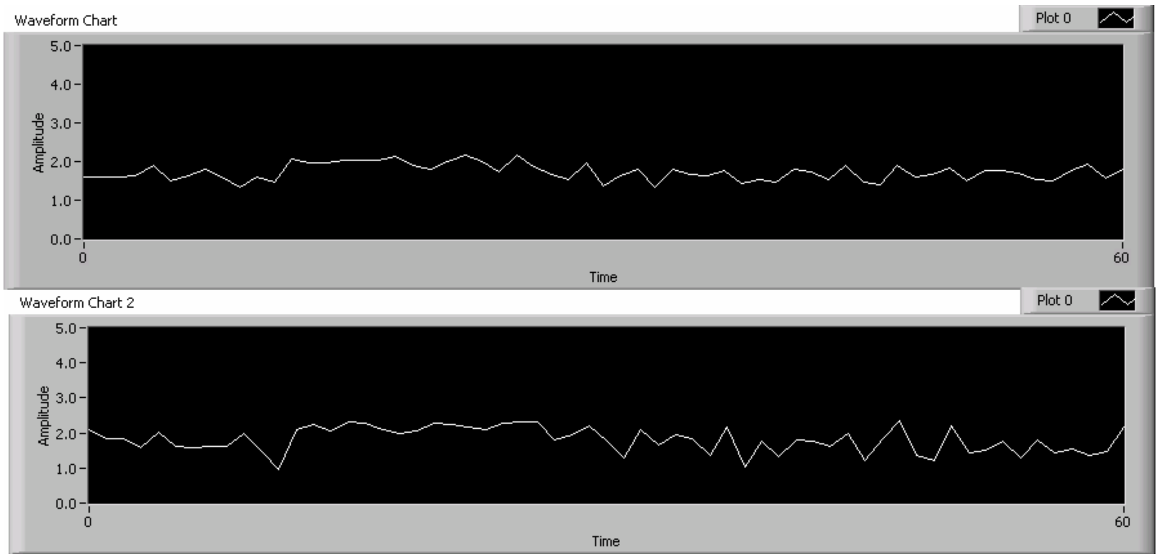

Figure 21. AC Unit Correlation Plots

C. SPECTRAL DISTANCE

The next method used to compare the two spectra is the divergence test. This test should have several properties to ensure it will be effective for this application. This test was originally created to compare probability density functions. Given the two signals P_x and P_y, we first change them into Probability Density Function (PDF) "like" signals by normalizing them to unit power. Then we use the following equation to calculate the "distance" between the two signals. (Fargues, Cristi, & Vanderkamp, 1993)

$$D_{XY} = \sum_{k=1}^{N} \left(\frac{\ln(P_x(2\pi k/N))}{P_y(2\pi k/N)} \right) P_x(2\pi k/N) - \sum_{k=1}^{N} \left(\frac{\ln(P_x(2\pi k/N))}{P_y(2\pi k/N)} \right) P_y(2\pi k/N)$$

where

N=440

P_x=Reference Spectrum normalized to unit power

$P_{y=}$Unknown Spectrum normalized to unit power

This equation satisfies only one of the three distance properties. It is clear from inspection that when the signals are identical each element of each of the sums will be zero. The equation is not always greater than zero but can in fact produce large negative numbers. Finally, it is not clear that swapping P_x and P_y in the equation will result in the same value for D. Figure 22 shows the Labview for loop to calculate D for over all values of k. The "+1" blocks were needed because some of the elements of both the reference and sensor vectors were zero which would cause the equation to go to infinity. Each time this loop ran it sent the value to a vector outside the for loop. The first value of the vector from the for loop is always infinite so the vector is parsed to exclude the first value. Once the full vector is calculated for one time instance, it is then summed and the absolute value taken before it is output to a gauge indicator, numerical indicator and time plot graph.

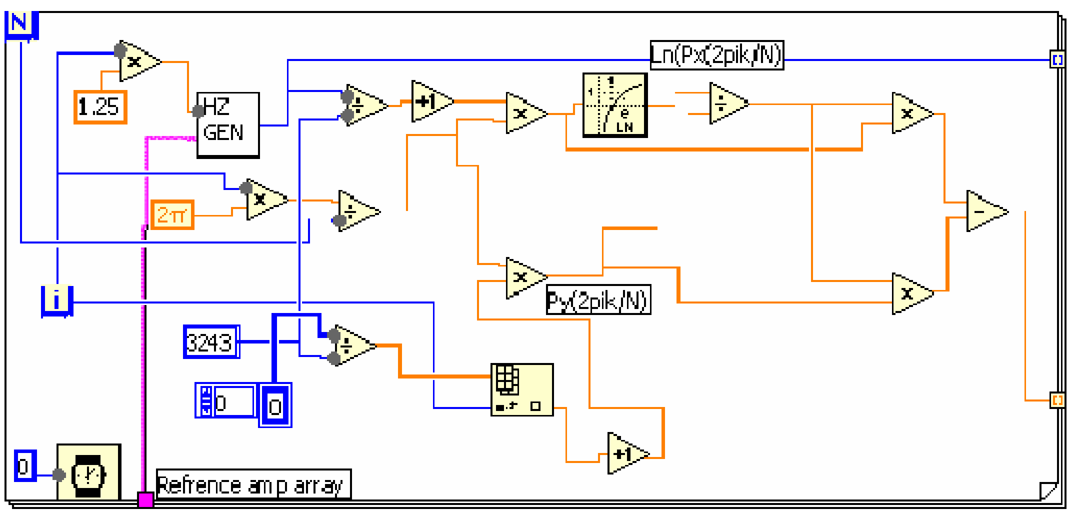

Figure 22. LabView Spectral Distance Network

This equation is a modification of the Mutual Information equation:

$$I_{x;y}(a_k;b_j) = \log \frac{P_{X|Y}(a_k \mid b_j)}{P_X(a_k)}$$

This equation is used to measure how much an occurrence of an particular value in a probability Y tells us about the possibility of another value occurring in X. Its definition is "the information provided about the even $x=a_k$ by the occurrence of the event $y=b_j$." Therefore, if the information contained in P_x tells us very little about P_y, I will be a small number and will indicate that the two signals are close together. The expression for D, in an intuitive sense, is measuring the amount of new information provided by the sensor about the reference signal. (Gallager, 1968)

This test proved to be a much better indicator of the state of the motor. Figure 23 shows the spectral distance plot for the pump motor. The same operating conditions were used for this test as with the above cross-correlation test. It is clear from the large values from the 10 to 30 seconds that the pumps air outlet was blocked. The values are approximately 20-25 times greater than the normal operating value.

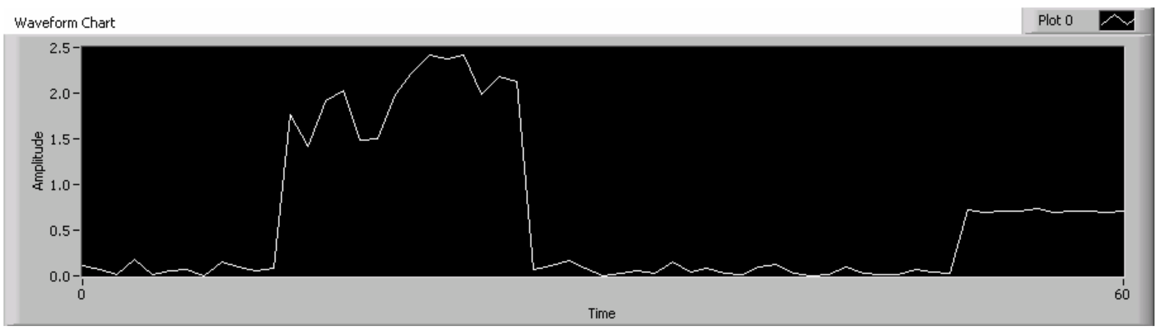

Figure 23. Spectral Distance Plot Pump motor

For the final 10 seconds of the test while the pump was off, the value was about 8 times the normal operating value. This clearly shows how the spectral distance can accurately indicated the state of the pump. Figure 24 shows the plot for the AC unit. At approximately 20 seconds the unit was switched off. There is a clear jump from close to zero up to approximately 0.25. As mentioned above, the AC unit did not have as many relevant spectral components for comparison so D does not change as much as with the pump motor.

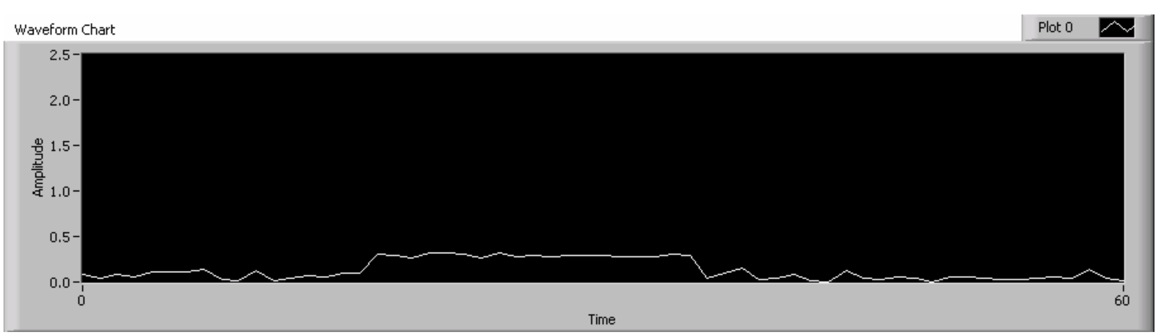

Figure 24. Spectral Distance Plot AC unit

V. TESTING OF MEMS ACCELEROMETERS

MEMS accelerometers can develop flaws due to stress, over acceleration or fabrication errors. Fortunately there is an efficient and reliable way to determine whether a MEMS accelerometer is operating properly. This is an advantage over other types of accelerometers that must be tested by physically inducing the test signal by shaking the device on a test bench.

A. USING THE BUILT IN SELF-TEST FEATURE

The ADXL105 is a single axis accelerometer produced by Analog Devices. Like most MEMS accelerometers, it has a Built in Self-Test (BIST) pin. The BIST pin excites the same components that are used to detect accelerations. When a step input is applied to the pin, the fingers of the accelerometer are deflected and start to vibrate. These vibrations decay exponentially in a manner characteristic to the particular accelerometer. Figure 25 shows the ADXL105 attached to an evaluation board. The evaluation board is used to test different setups and makes it easy to use the ADXL105 with the protoboard. Figure 26 shows the complete setup with the signal generator and oscilloscope.

A signal generator was used to excite the ADXL105's self-test pin. Using an oscilloscope both the test signal and the output from the sensor were displayed. Figure 27 shows the oscilloscope output for the accelerometer when it is excited by a 5 volt square wave. The signal decays in a characteristic manner and the only way this decay can be altered is through a change in the physical structure of the device. This would indicate that the device must be replaced because the measurements from the device could no longer be trusted.

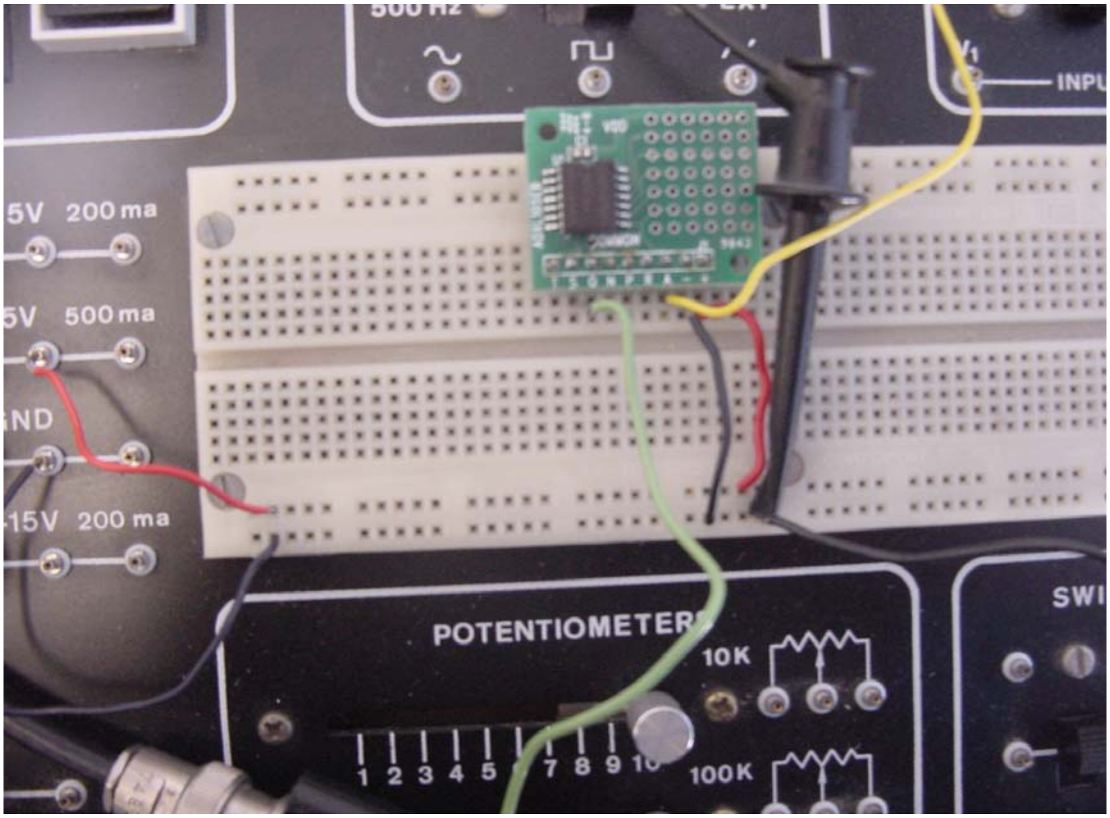

Figure 25. Accelerometer Test Setup Protoboard Only

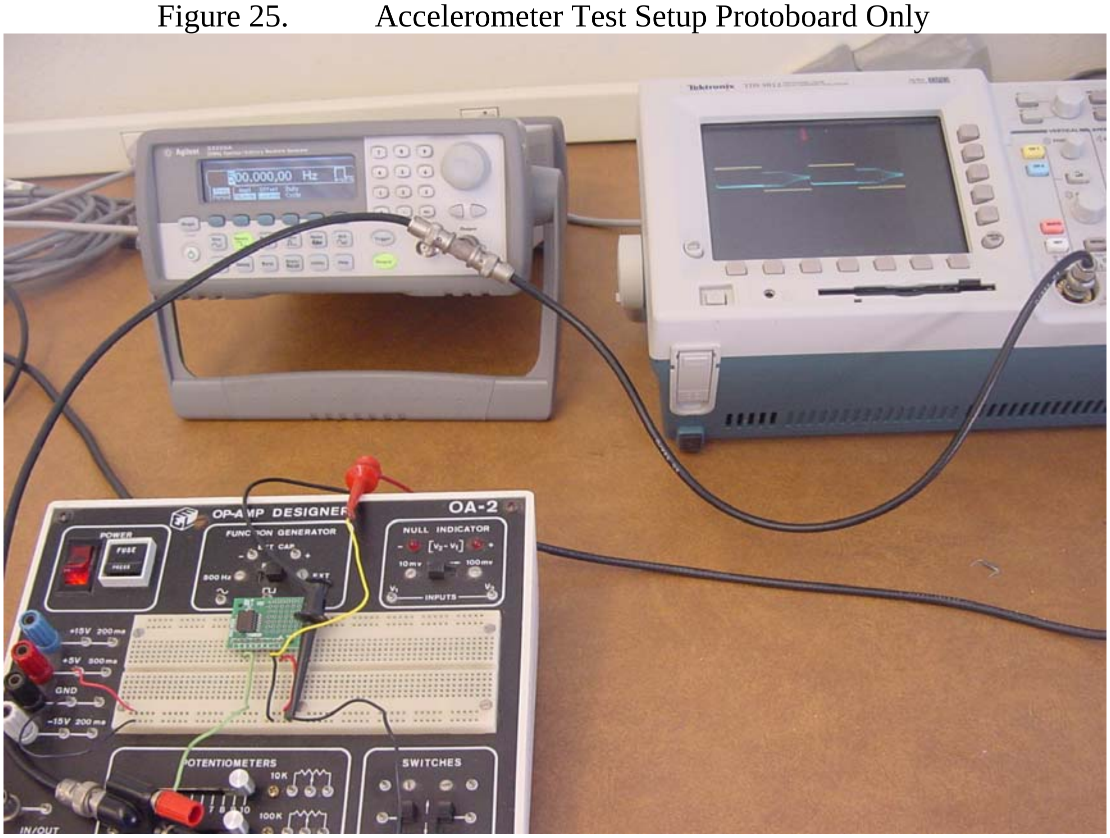

Figure 26. Complete Accelerometer Test Setup

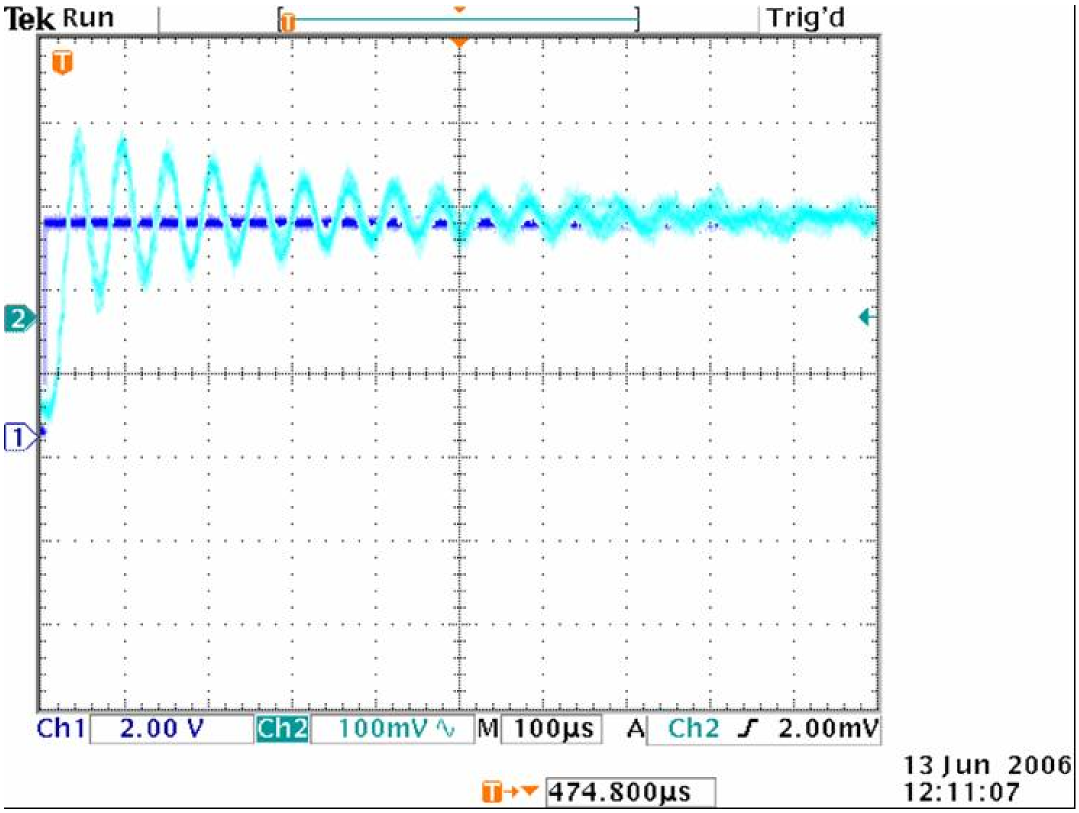

Figure 27. Oscilloscope Display

B. FEASIBILITY OF TESTING USING THIS METHOD

The previous method of testing an accelerometer consisted of removing it from the machinery, taking it to a testing lab, shaking it at a specific frequency and amplitude and observing the results. With the BIST it is conceivable that the sensor could be tested in place. With the machinery off, the test signal could be applied to the BIST pin and the result observed using standard electronic test equipment (oscilloscope and signal generator).

C. OTHER POSSIBLE TESTS

The step response was the only test investigated for this project, but there are other possible test signals that could be used to determine if the accelerometer is operating properly. Several sinusoidal signal of a differing frequency and amplitude could be used to create several different test points for the accelerometer.

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VI. CONCLUSIONS

There were two goals for this thesis. The first goal was to monitor machinery vibrations using a MEMS accelerometer. The second was to investigate the BIST feature of a MEMS accelerometer. The first goal was accomplished through integrating a COTS vibration sensor with a desktop computer using the Labview program. The sensor monitored both a pump motor operating on a bench top and an installed AC unit. The sensor system was able to detect malfunctions in both pieces of machinery. The MEMS BIST is an easy way to determine whether the MEMS sensor is operating properly. Currently, the test amounts to a "go/no-go" reading, there is no calibration possible and there is no way to determine what is causing the accelerometer to malfunction.

This thesis has application in shipboard and shore based machinery monitoring. It is feasible from a cost and complexity standpoint to install and maintain vibration monitoring equipment onboard Navy and Coast Guard ships. The sensor used for this project retails for $750, with associated cabling and other items costs could be kept under $1000. This setup would be ideal for monitoring high value equipment such as reduction gears or generators or vital pieces of equipment such as AC units for sensor and weapons equipment.

Both of the research goals set for this thesis were met. There are several areas in which to extend these goals.

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VII. RECOMMENDATIONS

The Efector sensor is ideal for monitoring high value bearings and machinery such as reduction gears and main propulsion motors. Coupled with the Zigbee wireless technology researched by Chimi Zacot, the sensor could be integrated into the ICAS network onboard ship for real time monitoring of equipment.

The onboard testing is not currently available on the Efector sensor but would potentially be offered on future products. This would provide a quick way to check whether the vibration sensor is operating properly.

Further work should be done on exactly how the accelerometer test parameters change with different kinds of damage. The sensors should be subjected to temperatures outside their operating range and accelerations above their maximum to determine what if any effect these tests have on the BIST response signal.

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APPENDIX

A. EFECTOR OCTAVIS VE1001 DATA SHEET

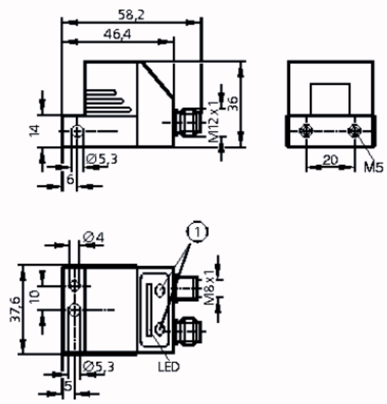
efector800

Diagnostic systems

VE1001

Vibration diagnostic unit
Connection via M12 x 1 and M8 x 1 connectors

Spectral analysis / FFT
Envelope-curve FFT
Trend analysis



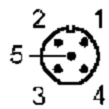
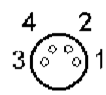
1: Programming buttons

Application	Up to 20 frequencies in the spectrum, freely selectable, diagnostic level adjustable
Electrical design	DC PNP
Operating voltage [V]	10...32 DC
Current consumption [mA]	100 (24V DC) *
Measuring range [g]	± 25 **)
Sensing principle	micromechanical accelerometer / capacitive measuring principle / one measurement axis
Overload protection [g]	100
Minimum measuring time [s]	0.8
Frequency range [Hz]	3...6000
Spectral resolution [Hz]	1.25
Monitoring range [rpm]	120...12000 (the actual rotational speed range depends on the type of the rolling element bearing and can therefore differ)

ifm efector, inc. 782 Springdale Drive, Exton, PA 19341

We reserve the right to make technical alterations without prior notice. — US - VE1001 - 1/2 — 21.06.2006

VE1001

Operating temperature [°C]	-30...60
Protection	IP 67, III
EMC	IEC 1000-4-2/3/4/6
Housing material	housing: diecast zinc nickel-plated; keypad: polyester
Wiring	 M12 connector (electrical connection) Pin 1: supply + Pin 2: red function; switching output 2 / 100 mA / NO/NC programmable Pin 3: supply - Pin 4: yellow function; switching output 1 / 100 mA / NO/NC programmable Pin 5: rotational speed, 0...20 mA or pulse input
Wiring M8 connector (RS-232 communication)	Pin 1: - Pin 2: TxD Pin 3: GND Pin 4: RxD 
Remarks	history memory: 2580 data sets as ring buffer *) plus optional external pulse pick-up **) nominal ± 20 Pin 2 (switching output 2) and pin 4 (switching output 1) can only be programmed in pairs

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