

# Design of a Non-Contact Vibration Measurement and Analysis System for Electronic Board Testing

By  
Krissa Elizabeth Arn

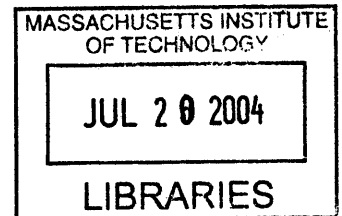
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# **Design of a Non Contact Vibration Measurement and Analysis System for Electronic Board Testing**

by  
Krissa Elizabeth Arn

Submitted to the Department of Mechanical Engineering on  
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Degree of Master of Science in Mechanical Engineering.

## **Abstract**

Traditional vibration measurement methods involve placing accelerometers at discrete locations on a test object. In cases where the test specimen is small in mass, the addition of these measurement transducers can alter its dynamic behavior and lead to erroneous test data. In this thesis a Non-Contact Vibration Measurement and Analysis System has been designed, built, and tested for electronic board testing. Through a product design process, all feasible methods were considered and three optically based concepts were explored: holographic interferometry, area scaling, and displacement sensor grid. Through concept testing and analysis, the displacement sensor grid method was chosen for the design.

The final system incorporates four laser displacement sensors with a vertical scrolling mechanism that attaches to the vibration table's side rails. This manual scanning system provides a quick, low cost method for capturing multiple points on the test object during vibration testing. The MATLAB based software package acquires the raw sensor output and processes it with a five step analysis program. With this software, an 8x4 grid of electronic board displacements were easily transformed into a movie showing the board displacing through its first mode. The system requires the sensors be positioned 1cm away from the test object with the sensors reading up to  $\pm 1$ mm of movement. The sensors have a maximum sample rate of 7.8 kHz and can be used to measure the displacements of any surface type or material. The measurement grid resolution is 0.7 inches horizontally and 0.4 inches vertically. Testing showed that the system captured the natural frequency and peak displacement of the board's first mode within 1.5% accuracy and 0.7% accuracy respectively when compared with previous accelerometer grid testing.

Exceeding its design goals, this non-contact measurement and analysis device provides a highly versatile, accurate, and low cost optical alternative to accelerometers. Also it shows numerous benefits over more complex and costly optical measurement methods. The use of this system eliminates any question of whether mass loading effects are tainting vibration test data. A hardware and software manual are included for reference at the end of this thesis along with a software CD.

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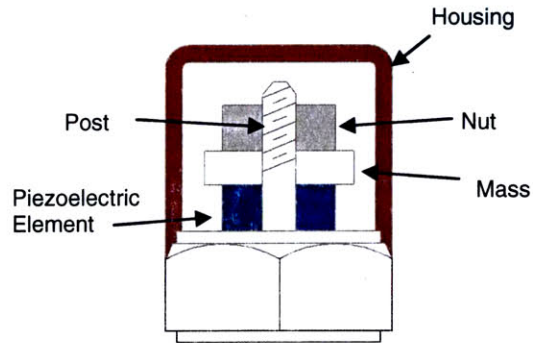
## Chapter 1 Introduction

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Observing the behavior of objects under vibration testing typically involves placing accelerometers at discrete points on the test specimen. When the test object is small in mass, however, the addition of measurement transducers can alter the object's real properties leading to erroneous test data that can go unnoticed. Current methods for capturing the dynamic behavior of light objects under vibration testing without mass loading effects are expensive, have time consuming setups, and may require scaled testing ranges. This thesis will take a product design approach to developing a low cost and versatile vibration analysis system for light object testing. While the system designed will have direct application to electronic board testing, the hardware and software can be applied to most vibration test cases with little or no modification.

The traditional method of measuring vibration response is to attach an accelerometer to the points of interest on the face of the test specimen. Accelerometers come in a variety of different types that operate with a primary sensor composed of a mass spring system

with damper and a secondary sensor converting the acceleration into a signal a computer can read. The most common type incorporates a piezoelectric material that produces an electric charge when the crystal is deformed. Upward and downward motion causes a change in the compression of the crystal resulting in an output signal proportional to the acceleration [1]. See Figure 1-1 below for a drawing of a typical accelerometer.



**Figure 1-1 Basic Piezoelectric Accelerometer [1]**

Accelerometers have a number of benefits; they do not require power to operate, have a high dynamic range and sensitivity, provide a strict directional response, and are relatively small [1]. The weight of accelerometers can range from multiple grams down to less than a gram.<sup>1</sup> Also, they can easily be attached to the surface of the test object with beeswax. Some of the drawbacks are that they are expensive, the lead wires can get in the way, and they can cause mass loading effects that change the object's dynamic response.

The undesirable effect of accelerometers mass loading the test object was discovered during testing at Draper Laboratory when only three accelerometers were available for a set of tests on an electronic board aluminum frame. Because of the limited number of accelerometers, multiple tests had to be run in order to recreate the acceleration map of the entire circuit board. In each test, two accelerometers were moved to various locations on the face of the board; one accelerometer was kept in the center of the board as a control. It was found that moving these two 0.5 gram piezo accelerometers to different locations caused a 10 Hz shift in the natural frequency and a 20-G shift in response amplitude.

---

<sup>1</sup> Endevco® claims to have the smallest accelerometer, the Model 22 PICOMIN weighs about 0.14grams. (documented 24 July 2003)

Accelerometers can make it hard to interpret results especially when the goal of testing is to understand the effects of various components and component mounting interfaces. Also, accelerometers can have a mass equal to or greater than some electronic components.

Mass loading effects can be countered in two ways, the measurement device can be non-contact so it does not touch the test object or modification can be made to the testing conditions so the mass loading effects are removed. Much work has been done to develop techniques to compensate for the accelerometer effects on the dynamics of the test object and the error they have introduced into the measured vibrations. The Society of Automotive Engineers (SAE) recognized mass loading effects when building a test apparatus to measure the vibrations transferred to occupants at the body-to-seat interface. Because the accelerometers changed the motion of soft seats, they had to design a special pad called the SIT-BAR, to incorporate accelerometers and reproduce the same seat conditions [2]. As they found, trying to use accelerometers for vibration measurement made instrumentation more difficult and impractical. For this reason, many vibration tests can benefit from a non-contact vibration system to provide an easier setup, straight forward analysis techniques, and unaltered test conditions.

Currently non-contact methods that exist require very expensive and specialized equipment. Through Real-time holography, displacement fringes of an object under vibration can be viewed on a video screen to locate resonant modes. Then a time-average technique of holographic interferometry can be used to dwell at the identified natural frequencies and record a contour map output of the object's deflections where each contour corresponds to a displacement of one-half the wavelength of the laser used. This technique requires scaled testing so modal displacements are reduced to a level where the displacement fringes can be read. Holographic techniques have the advantage of examining the entire surface of the test specimen where Laser Doppler Vibrometry (LDV) uses a focused laser beam to measure the velocity at a discrete point. The velocity is calculated by using the Doppler shift between the incident light and scattered light returning to the measuring device. The laser beam can be continuously scanned over the vibrating object so mode shapes can be determined. Both of these methods have been



proven successful but require lengthy setup, expensive optics equipment, and much signal processing unless a prepackaged system is acquired.<sup>2</sup>

Simpler non-contact measurement transducers exist. They include: capacitive, inductive, and laser displacement sensors. These sensors are often sold as single sensor probes that have to be integrated into a hardware/software system. For this reason, they are cheaper, more versatile sensors, but they also have limited measurement ranges and target object materials. All of these products will be investigated further during the concept design in the next chapter.

## **1.1 Thesis Objectives**

The goal of this thesis is to develop a non-contact vibration measurement and analysis system for Draper Laboratory that will acquire and analyze the dynamic behavior of an aluminum electronic board frame under vibration testing. This particular board was chosen since much information on the actual dynamic behavior is known and this is the test object that experienced the mass loading problem that prompted investigating non-contact vibration measurement methods. Although this thesis is designing a system specifically for the vibration testing of this electronic board, the system needs to be versatile so it can be used for other light objects being tested. The system must also be low cost, easy to use, simple to configure, and integrated with computer software to quickly process the acquired data. Most importantly, the vibration system must use a non-contact method of acquiring the electronic board's vibration response so mass loading effects do not occur. After understanding the necessary specifications of this test measurement and analysis system, both hardware and software will be designed, built, and tested.

---

<sup>2</sup> Polytec PI offers a single point laser vibrometer system for around \$25k and a scanning system for \$160k

## Chapter 2 Preliminary Design

---

In order to successfully design a non-contact vibration analysis system, it is important to follow a development process to achieve the best product. For this project the design process is focused on using the methods outlined in Product Design and Development by Karl Ulrich and Steven Eppinger. Within this chapter, concept development steps will be taken to identify the customer needs, set the target specifications, and explore options for the required functions of the vibration measurement and analysis system.

### 2.1 Customer Needs

The customer needs below are independent of the device that will ultimately be designed [3]. They capture the uses for the vibration measurement and analysis system,

the like and dislikes of existing products, and any improvements lab employees identify. Table 2-1 below shows the customer needs and their relative importance for the design.

<b>Customer Needs</b>	<b>Importance</b>
Meet required vibration military test specifications	5
Non-contact to eliminate inertial effects	5
Must allow for maximum electronic board deflection	5
Compatible for multiple electronics boards	4
User friendly with an easy setup	3
Adjustable setup for easy calibration	3
Displays full field mode shapes of entire specimen	3
Cost must be kept to a minimum	4
Adequate resolution to determine deflection and modes	5
Test time must be short to enable multiple tests in a day	3
Real-time and continuous output of structure's response	3
Easy Maintenance	3

**Table 2-1 Customer Needs and Their Relative Importance**

Each need is assigned an importance value that will be imperative later in the design process. These importance values are based on how crucial the need is to the function of the product. Now that the needs are identified, each need is quantified into a target specification. These specifications will be used as the goals for each concept and will later be refined based on the limitations of the final product concept selected. In order to develop the specifications, metrics were generated to characterize each of the needs into a measurable attribute of the vibration system. See Needs-Metric table on the following page.

<b>Metric</b>	<b>Imp.</b>	<b>Units</b>
Frequency Range	5	Hz
Deflection of Electronic Board	5	mil
Resolution	5	mil
Cost	4	\$US
Field of View	4	in <sup>2</sup>
Time to Assemble and Disassemble	3	min.
Measurement Area	3	in <sup>2</sup>
Test Time	3	min.
Continuous Real-Time Output	3	Hz
Special Tools for Maintenance	3	List
User Friendly Manual	3	Subjective

**Table 2-2 Needs-Metric Table**

## 2.2 Target Specifications

The target specifications can now be determined from the metrics. The marginal column lists the specifications that would provide adequate performance for the electronics board focused on in this thesis, while the ideal column sets broader specification goals for a more versatile system.

<b>Metric</b>	<b>Imp</b>	<b>Units</b>	<b>Ideal</b>	<b>Marginal</b>
Sample Rate	5	Hz	10k	4k
Deflection of Object	5	mil	4	2
Resolution	5	mil	0.05	0.1
Cost	4	\$US	<25k	<50k
Full Field	4	in <sup>2</sup>	450 (12 in diam)	250 (9 in diam)
Time to Assemble and Disassemble	3	min.	30	90
Measurement Area	3	in <sup>2</sup>	See Full Field	See Full Field
Test Time	3	min.	3	20
Continuous Real-Time Output	3	Hz	2000	30
Special Tools for Maintenance	3	List	Yes	Yes
User Friendly Manual	3	Subjective	Yes	Yes

**Table 2-3 Target Specifications**

**Sample Rate:** Military testing specifications require that a 1G sine sweep from 20-2000 Hz be conducted to qualify electronic equipment. According to the Nyquist Frequency Rules, it is imperative to sample at a minimum of twice that rate to ensure aliasing does not occur. For this reason, the marginal value for Sample Rate is set at 4kHz.

**Deflection of Object:** This specification was set by the maximum displacement the electronics board would have during testing. However, it would be better for the device to be able to be compatible with multiple test structures and they might have a greater deflection.

**Resolution:** The resolution is defined by the smallest measurable distance change that can be detected by the sensor. Since the first mode of the electronic board has a maximum deflection of about 2 mils and the second mode has a deflection of 0.5 mil, the resolution needs to be less than these values so the modes can be captured. It was determined that a 0.1 mil resolution would allow for the second mode to be easily captured.

**Full Field:** Full Field is much like the Measurement Area specification except that it is exclusively relating to dimensions of a full quantitative visual output of the structure during one test. The minimums are based on the largest electronics board.

**Time to Assemble/Disassemble:** This specification was subjectively chosen. Ultimately the system needs to be able to be quickly setup and torn down. It should not take more time than it takes to mount and calibrate the existing vibration table control accelerometers since these setups will be done in parallel.

**Cost:** The cost really is not the concern of this project for comparison. It has to be low cost to gain the support of Draper Labs and be a competitive alternative to traditional methods.

**Measurement Area:** This specification differs from Full Field in that it relates to the amount of test object area that can be measured with the system through multiple tests.

**Test Time:** It takes about 3 minutes to run one vibration pass of 20-2000Hz on the shaker tables since it runs at 2 oct/min. Therefore, the optimal test time is limited by the shaker table. The marginal spec (longest time), is 30 minutes because different

measurement methods are going to require data processing before subsequent test runs can be completed.

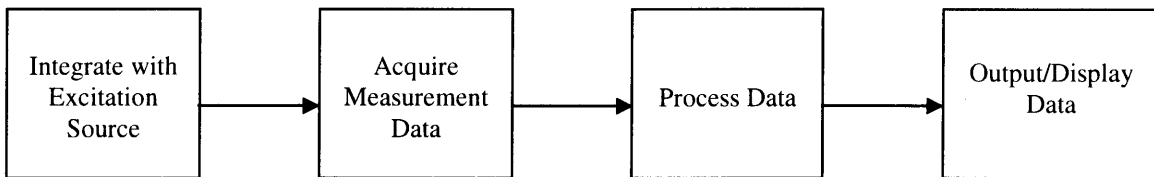
**Continuous Real-time Output:** This specification quantifies the rate at which output can be viewed during a test. The marginal value was set to 30Hz since all high speed cameras send their images to video screen to play at this speed. If video output is not part of the concept, this specification will be equivalent to Sample Rate.

**Special Tools for Maintenance:** This allows for the design to be easily fixed even if it is intricate and has non standard parts. It also acts as a reminder to keep the number of tools required to a minimum.

**User Friendly Manual:** Ensures that the hardware and software can be used by everyone at Draper Labs and it will have an easy learning curve.

### 2.3 Function Diagram

The diagram below outlines the main functions for the non-contact system so different methods can be considered for each function. This allows the design to be formulated with consideration of all viable methods and allows it to be free from bias. For the concept generation, the main functions that are focused on are: how the design will integrate to the excitation source and how it will acquire the measurement data. This decision should not be free from the other functions listed, but it is obvious that a computer will be processing and outputting the data.

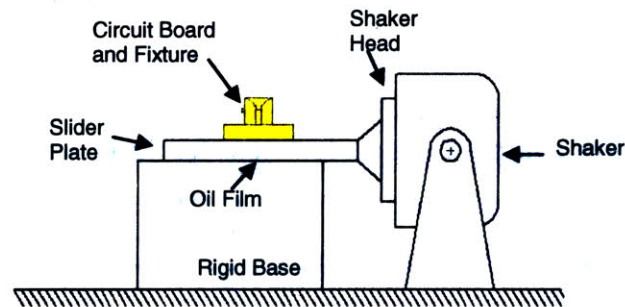


**Figure 2-1 Function Diagram**

Now that the main functions for the non-contact vibration system are identified, different methods can be explored to accomplish each function.

### 2.3.1 Integrate with Excitation Source

A shaker table will provide the outside excitation to the test object to recreate the operational environment of the test specimen. For the testing completed in this thesis, a 2-rail hydrostatic Team Corporation slip table with an auto leveling IMIS base, and four channel control and response will be used. See Figure 2-2 and Figure 2-3 below. This slip table has a large plate where the test object is mounted that slides on a film of oil. These shakers are capable of pure translational motion with very little rotational modes in the horizontal and vertical directions [4]. For testing completed in this thesis, movement will be in the horizontal direction.



**Figure 2-2 Vibration Shaker Table Shown in Horizontal Motion Position**

The actual slip table that will be used for the electronic board testing is shown below in Figure 2-3. However, the shaker will be turned down like the illustration above.



**Figure 2-3 Board Excitation Source: TA 165 Electro Dynamic Slip Table**

The non-contact sensor could attach to the circuit board fixture or slider plate if the sensor can withstand the 1G sine sweep from 20 to 2000Hz. The benefit of mounting directly to the circuit board fixture is that the resonance displacements are all that will be observed. Other options include mounting to the side rails of the vibe table or hanging the hardware from the ceiling. The side rails are on isolation pads and should be free from outside vibration. If the system is measuring test object displacement and is mounted on these side rails, the movement of the vibe table will have to be subtracted off the acquired test data. This is a less desirable option because the vibe table's output is controlled internally and could add an extra source for error.

### **2.3.2 Acquire Measurement Data**

Since the entire system is hinging on the sensor that is selected, the viable sensors need to be identified before the excitation integration is designed. This section will discuss the benefits and limitations of non-contact sensors. These sensors utilize many different measurement principles that allow them to capture the target objects dynamic behavior without physically touching it. Most non-contact sensors will only work with a few types of target surfaces and materials. For the application of measuring electronics equipment, it would be desirable to have a sensor that worked with the multitude of surfaces and materials that make up a populated printed circuit board (PCB).

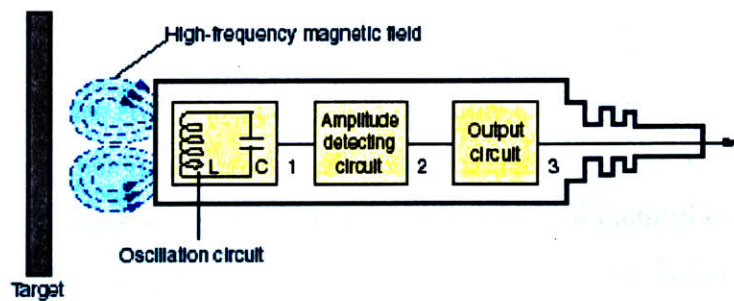
The viable sensor options that do not run on optical principles are inductive proximity (eddy current), and capacitive. Optical sensors allow for a lot more versatility in test measurement but this comes at an increased cost. Although optical methods are becoming more common, a quick survey of sensors listed for vibration testing mention little to nothing about these sensors and their unique capabilities. The optical sensors that could be used in this product are holographic interferometry, laser Doppler velocimetry, laser triangulation, or area scaling. All of these measurement methods are discussed below. This background will then be matched with options from the other functions to form three concepts for the Non-Contact Vibration System.

#### **2.3.2.1 Inductive Proximity (Eddy Current)**

Non-contact displacement sensors using eddy current technology are known as inductive proximity sensors. These sensors make precise static and dynamic



measurements of metal targets and thickness measurements on conductive material backed by metal. These sensors utilize a high-frequency magnetic field which is generated by passing a current through a coil in the sensor head [5]. When a metal target is introduced to this field, electromagnetic induction causes an eddy current to travel on the surface of the target, changing the impedance of the sensor head coil [5]. When a target comes closer to the sensor's head, the oscillation amplitude decreases and the phase difference from the reference waveform increases. The sensor detects the change in amplitude and phase to obtain a value proportional to the distance between the target and the sensor head [5].



**Figure 2-4 Keyence Inductive Proximity Sensors [5]**

The target size is an important consideration when selecting this type of a sensor. If the target is smaller than the sensor head, measurements can be effected by other conductive targets near by. Shielded sensors try to reduce these ill-effects. Proximity sensor's main use is to measure the space between the probes head and a conductive material since non-conductive materials in the gap does not effect measurement. Proximity sensors have a very limited measurement range and have to be placed extremely close (less than a tenth of an inch) to the test specimen requiring mounting methods to be very precise. A benefit over the capacitive sensors that are discussed next is that they are highly insensitive to oil, dirt, dust, moisture, and interference fields [6, 7].

For the application of electronic board's displacement measurement, the conductive material must be present on the surface and not hidden within the layers of the PCB unless calibrated measurement is going to be performed. This could cause problems in

determining places on the board where displacement measurements can be made. Calibration of sensors could make testing tedious and time consuming if each point on a populated board has a different metal consistency. Also, during bare frame electronic board tests, the frames are thinner than the penetration depths of the sensors so a build up of eddy currents on the back of the board could lead to false readings.

### 2.3.2.2 Capacitive

Non-contact capacitive displacement sensors measure distances, lengths, dimensions, and positions of any electrically-conducting targets (e.g. metals) [6, 7]. This sensor's principle of operations is that a capacitor is formed when two parallel plates are brought near each other and a charge is placed on one of the plates. Current then flows across the gap between the plates and the amount of current is determined by the voltage, area of the plates, and the material that separates the plates [6].

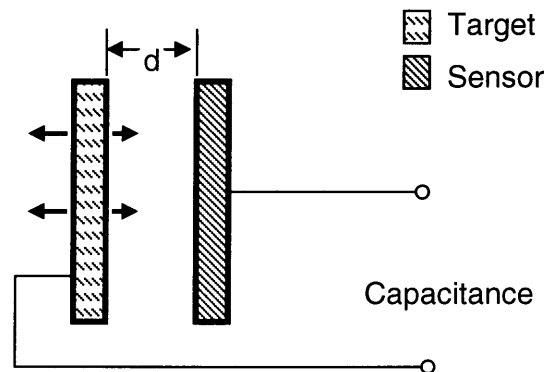


Figure 2-5 Capacitive Sensor [6]

Unlike proximity sensors, the target thickness is not important for capacitive sensors since the charge resides on the surface of the conductor. Also, changes in target material do not affect the sensor's performance as long as it is conductive. With proper calibration, a technique called fringing can be used to measure the displacements of non-conductive materials. Fringing involves inserting the non-conductive target between the sensor and a conductive reference surface [6]. The presence of the non-conductive material's dielectric constant will alter the air medium around the sensor allowing for the

non-conductive target's properties to be measured [6]. A capacitive displacement sensor requires a clean environment. Dirt, dust, or water in the measuring gap can influence the measurement signal [7].

### 2.3.2.3 Holographic Interferometry

Holography uses the coherent light produced by lasers to reconstruct 3D objects. The unique characteristic of holography is that it will record both the phase and the amplitude of the light waves that are reflected off of the object to a photographic surface [8]. The photographic surface responds to the intensity of the light in the form of phase information that can be interpreted when it is compared with the reference beam and converted into variations in intensity [8]. The reference wave and the scattered light waves from the object produce an interference pattern on the photographic film called fringes.

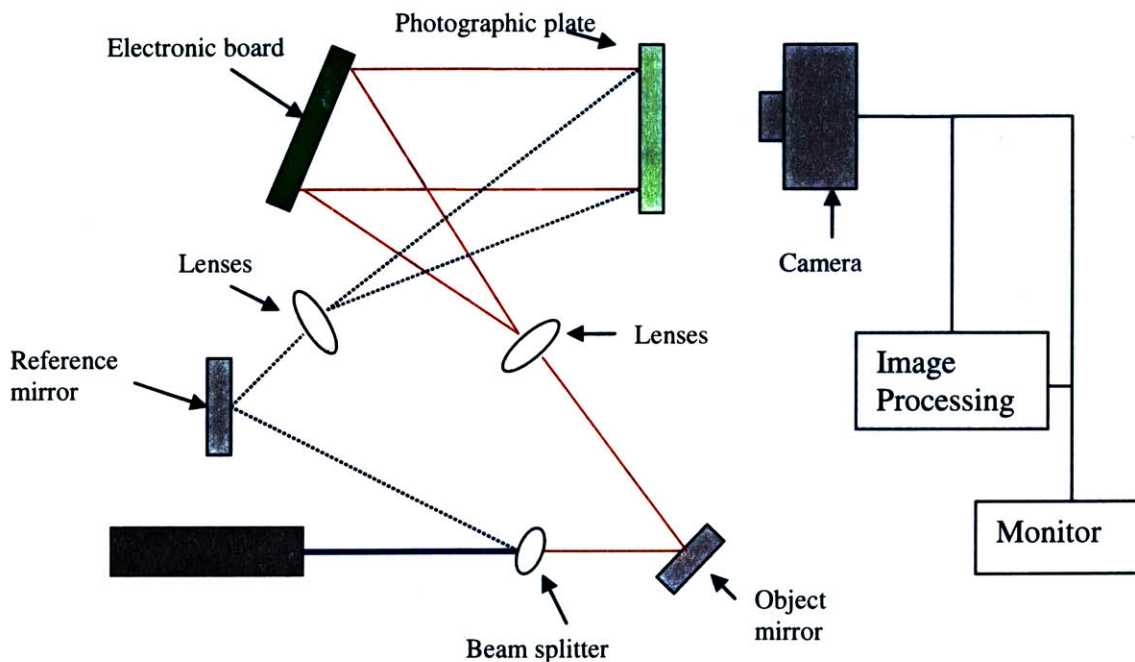


Figure 2-6 Holographic Interferometric Setup

When sequential holograms are compared, small changes in the shape of the test object can be seen and measured through interferometric techniques. Through Real-time holography, displacement fringes of an object under vibration can be viewed on a video screen to locate resonant modes. Then a time-average technique of holographic interferometry can be used to dwell at the identified natural frequencies and record a

quantitative output of the deflections of the object with a resolution of one-half the wavelength of the laser used.

Because this method looks at how the object has changed from the null position captured by a video camera, the imperfections of lenses and mirrors do not effect measurements [8]. The greatest benefit of this technique is that the entire test object can be measured, not just discrete locations like almost every other vibration sensor considered. The resolution of this method is half the wavelength of the laser light used; this is about 10 micro-inches with an argon ion laser [9]. Since the fringes are set by the wavelength of the laser used, scaling the testing conditions is the easiest way to keep fringes readable without doing more complex techniques to acquire data. It is hard to read displacement maps with more than about 20 or 30 fringes (~0.25 mils). With such low displacement levels needed, the excitation source for this method is usually just an acoustic speaker. This test is viable for non-contact testing but if the system does not perform linearly, the excitation scaling will lead to erroneous characterization of dynamic performance.

#### **2.3.2.5 Laser Doppler Vibrometer**

Laser Doppler Vibrometry (LDV) uses a focused laser beam to measure the velocity at a discrete point. The velocity is calculated by using the Doppler shift between the incident light and scattered light returning to the measuring device [10]. The laser beam is continuously scanned over the vibrating object and after demodulation of the data, mode shapes can be determined.

The LDV has some clear advantages over other non-contact measurement methods because there is considerably less data storage and processing required as compared with a full field measuring instruments like real-time and time-average holography [11]. The LDV is completely non-contact and is unaffected by environmental conditions or surface properties. Also, thousands of points can be successively measured, and multi-channel instrumentation is not required [11]. The disadvantages include “speckle drop out” (the speckle noise can distort LDV signal), line of site required from laser head to the target, the time it takes to run the test and then demodulate the data, and the cost of an LDV system [11].

### 2.3.2.5 Laser Triangulation

A laser triangulation sensor is a highly accurate measurement technique using a light emitting element, and a position sensitive detector (PSD). A charge-coupled device, CCD, is also used in the newer displacement sensors instead of the PSD. The triangulation sensor incorporates a semiconductor laser that has its beam focused by a lens as it leaves the sensor head [5]. The beam is then reflected off of the surface of the target and back through a receiving lens. The light beam is focused on the PSD or CCD forming a beam spot and the movement of the beam spot is used to calculate the displacement [5].

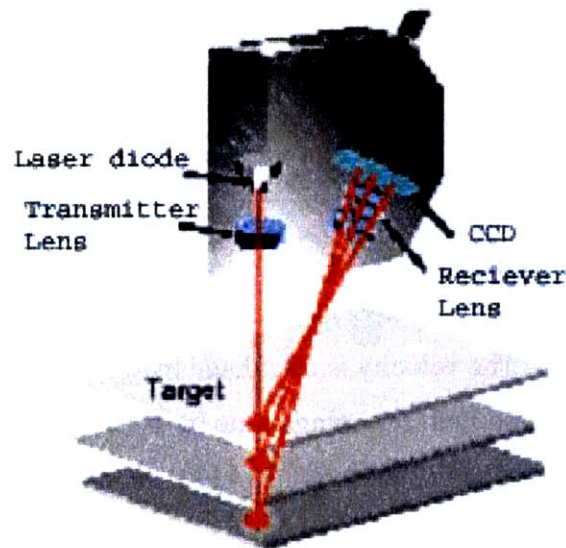


Figure 2-7 Laser Triangulation Sensor [5]

A draw back of most laser triangulation sensors is that they require a highly reflective surface or a highly diffuse surface. This requires painting or sticking something white at the point of measurement which is undesirable. Keyence has a newly released laser triangulation sensor, LK-11, that can measure multiple surface types and colors. This sensor would allow for a more versatile system without mass loading the electronic board with white dots.

### 2.3.2.6 Area Scaling

This measurement option has not been used in vibration testing but the idea seems like a revolutionary method for measuring displacements in a non-contact manner. The area scaling method uses a simple technique of relating the in-plane displacement of an object to its area growth or reduction in the recorded camera images. For example, if one holds an object in front of them and then moves it towards or away from their face, its size grows and shrinks. This technique is much like how we can tell the distance of objects by their relative sizes. The area scaling method looks at the scaling effects of a discrete area on the electronic board due to the planar displacements seen in vibration testing. The discrete area can be an object feature or simply a labeling dot that is just stuck onto the object's surface at the area of interest. The final output of the electronic board's quantitative displacements and mode shapes during vibration testing can be related to how much the discrete area changes. The picture below shows the variables for this technique.

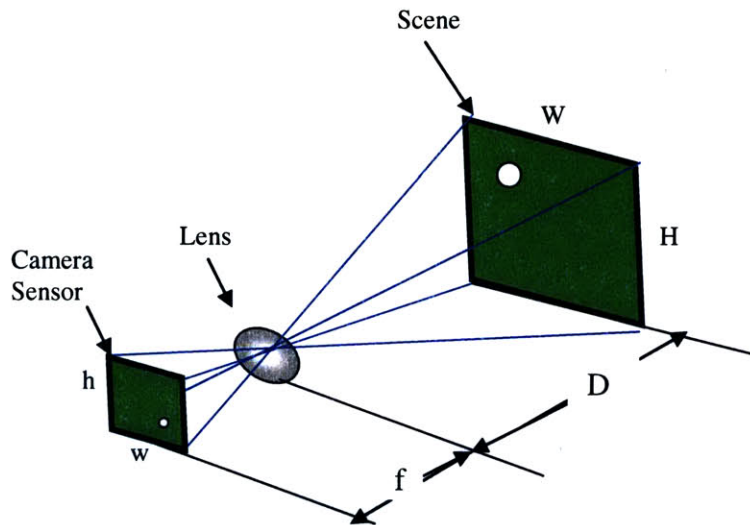


Figure 2-8 Area Scaling Technique Variables

The camera sensor has a height and width that is determined by the size and number of pixels present on the CCD sensor. Pixels average about  $15\ \mu\text{m}$  for a standard digital camera CCD chip. The denser the pixel counts, the larger the sensor area if the pixel dimensions stay constant. The focal length,  $f$ , is the distance from the lens to the sensor. The focal length can be changed by swapping out the lens on the camera. The working distance,  $D$ , is the distance from the lens to the object. Also, the object (scene)

has a given height and width,  $H$  and  $W$ . The scene is scaled to the size of the CCD chip which has its own height and width,  $h$  and  $w$  respectively. The entire electronics board could describe the scene dimensions or just a part of the object could be focused in on for a better displacement resolution. As the scene displaces towards or away from the lens, the working distance shortens or lengthens which equates to a change in the discrete area of the scene.

Since the displacements that are seen in a vibration test of the electronics boards are on the order of a thousandth of an inch, a change in area will not be able to be viewed by the naked eye during testing. Digital processing is required to look at each frame's image pixel by pixel. Edge detection methods could then be used to find the discrete area and subsequent frame by frame comparisons of these images will show the growth and reduction of the known areas of interests. This optically viewed change in area can be then related to the deflection of the object.

## **Chapter 3 Concept Generation**

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### **3.1 Concept 1: Holographic Interferometry**

The first concept involves building a holographic interferometric system to record the displacement fringes of the electronic boards under vibration testing. This method was chosen because it allows for a full field output of the object under testing even though it would involve a complex optics setup. Since military testing specifications require a certain test, it is questionable to scale testing parameters to achieve a lower displacement level. A simple study was completed and reported in Section 3.1.2 to see if image processing could pick out the fringe contours without scaling the excitation levels in the test. The benefits and limitations of this concept are also discussed.



### 3.1.1 Displacement Fringes

During the 20-2000 Hz sine sweep, the fringes of the electronics board's displacements are recorded and sent to a monitor. Because of the amount of data being taken in, displacement maps cannot be recorded for the entire 20-2000 Hz test. Instead, a method called Real-time holography is used to sweep through all the frequencies and the natural frequencies are identified visually on a monitor. Once the natural frequencies are identified, then time average techniques can be used to dwell at the natural frequency of interest and output a displacement map corresponding to the structure's mode. This results in a full field output of displacements but a very long test time. See Figure 3-1 below shows how the test object's deflections are seen as displacement contours.

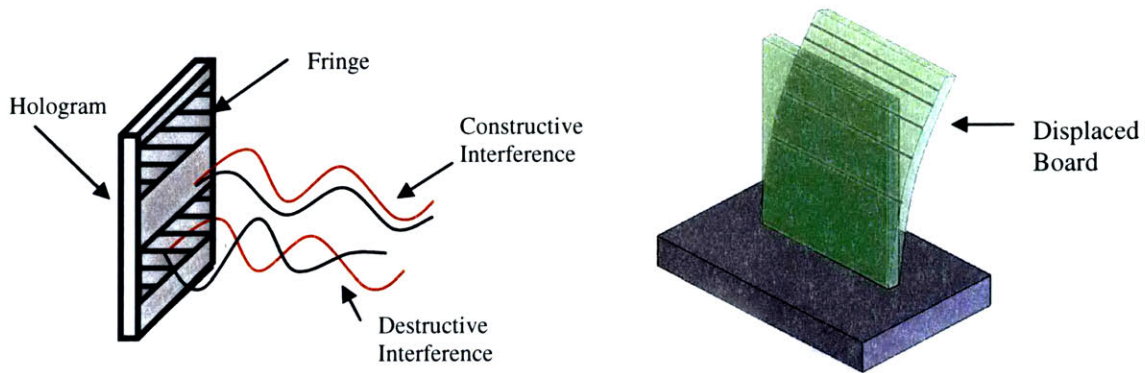


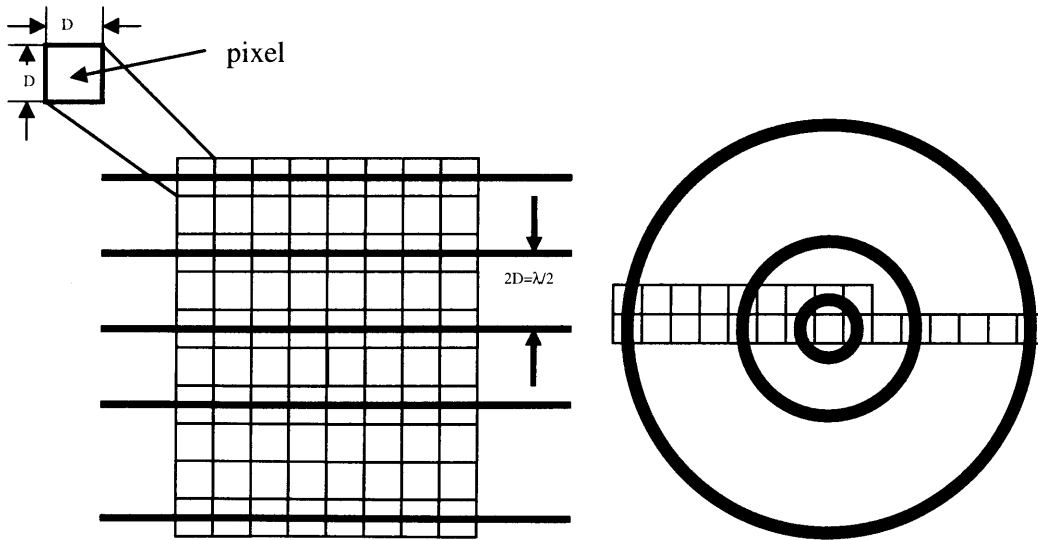
Figure 3-1 Interference Fringe Example [8]

### 3.1.2 Unscaled Testing Study

The goal of this study is to determine if unscaled testing can be used with holographic interferometric techniques. The contour map will have a fringe for every 0.26 microns or 0.001mils<sup>3</sup> of displacement perpendicular to the lens of the camera. See Figure 3-2 for an idealized representation of how the fringes could be discerned pixel by pixel. In actuality, it will take more than one pixel to read a fringe but this will do a decent job of estimating the maximum number of fringes that can be interpreted.

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<sup>3</sup> Argon Lasers are most commonly used and they have a 514nm wavelength.



**Figure 3-2 Fringe Contours on Pixel Grid**

Since the electronics board first mode occurs in the center of the board with a maximum displacement of two thousandths of an inch, the contours will look similar to the image on the right in Figure 3-2. If the 1-G sine sweep is not scaled during vibration testing, there would be approximately 200 displacement fringes. Now assuming the densest fringe scenario where each fringe only takes up one pixel and only one pixel is between fringes, the question is: What is the densest area of fringes that can be discerned with a 0mil to 2mil difference in displacement? The answer is dependent on the resolution of the camera recording the fringe maps. With an 800x600 resolution, the 200 fringes will require 399x399 pixels. If the board area under observation is 3.5x 2.625 inches, then the displacement must occur over a target area greater than 2.33 x 1.75 inches in order for it to be adequately read. Increasing the resolution of the camera sensor to 4k x 4k would allow the 2 mil displacement difference to occur over a minimum area of 0.35 x 0.35 inches.

This quick approximation does not take into account that fringes will occur more than one pixel apart and that fringes may have a width greater than one pixel. Therefore, this estimation could be off by as much as an order of magnitude. However, this study does show that this method would require a reduced G level for the vibration test for cameras with poor resolution. If a camera with greater than 4k x 4k resolution were used,

there is a high possibility that unscaled testing could occur but more in depth testing would need to be performed to see if other variables influence required resolution.

### **3.1.3 Concept 1 Summary**

#### Benefits

- Full Field
- High Resolution
  - 0.26 microns or 0.001 mils
- Real Time Output

#### Limitations

- Intensive Signal Processing
- Hard to decipher large deflections
  - Scaled testing?
- Have to dwell at natural frequency to get quantitative output
- Complex Optics Setup

### **3.2 Concept 2: Area Scaling**

The area scaling idea was chosen for the second concept because it is a revolutionary non-contact sensor method. If a test object's small deflections can be decoded by slight changes in discrete areas present on the object, it could provide a technique for full field measurement with merely a high speed camera and some image processing tools. As discussed in Chapter 2, the area scaling method looks at the size growth and reduction of a discrete area on the electronics board due to the planar displacements seen in vibration testing. The final output of the electronics board's quantitative displacements and mode shapes during vibration testing can be related to how much the discrete area changes. Since the displacements are on the order of a thousandth of an inch, it is questionable whether CCD technology is adequate to capture the slight area change. A test using current lab resources was completed to check the feasibility of this concept and look at the image processing techniques available to capture the area changes in the recorded images. Results of the testing and further analysis are reported in this section.

### 3.2.1 Area Scaling Concept Testing

A high speed digital camera was available for testing so a feasibility test was run to see if the displacements could be captured by the growth and reduction of a predetermined discrete area on the board with the equipment available. Other testing goals included evaluating setup issues and image processing techniques using MATLAB.

The camera being used is a Red Lake CR2000 high speed CCD camera. It can record up to 2000 frames/second at a resolution of 512x192. A better resolution of 512x384 can be acquired if the test is run at 1000 frames/second. Ultimately, a camera that could sample up to 4000Hz would be needed to capture the entire 20-2000Hz sine sweep vibration test but for the purpose of this study, it was not an issue.

For the test, a  $\frac{3}{4}$  inch diameter labeling dot is placed in the center of the electronic board since max displacement occurs there. See Figure 3-3 for the dot location.

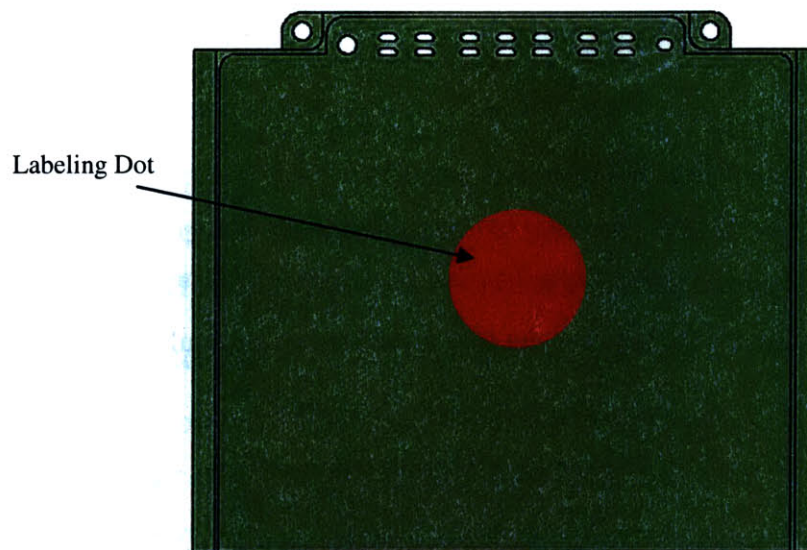
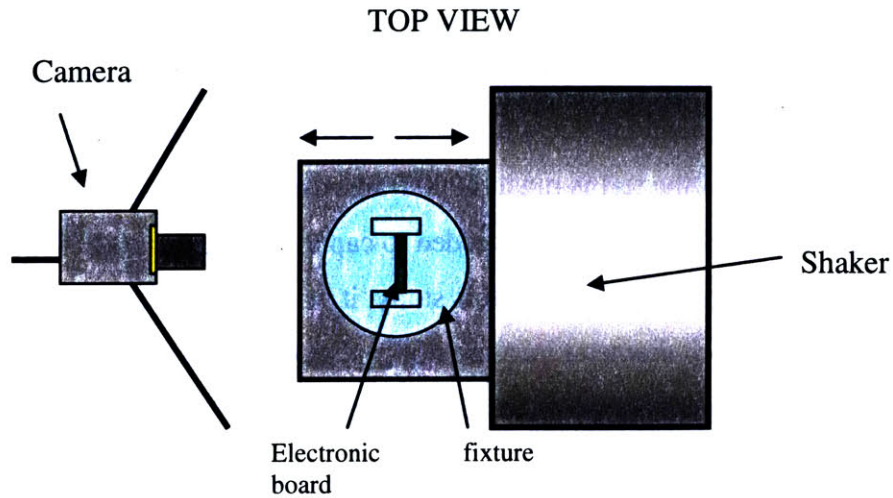


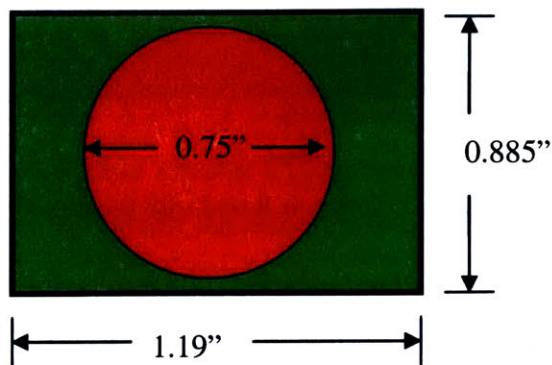
Figure 3-3 Electronic Board with Discrete Area Label

The electronic board is secured in the aluminum test fixture and mounted to the vibe table. Figure 3-4 below shows the test setup.



**Figure 3-4 Top View of Testing Diagram**

When the labeling dot displaces toward the camera, the area of the dot will grow in the field of view (FOV). In order to capture the most area growth, the camera was zoomed in until almost the entire scene was the labeling dot. Enough room was left at the top and bottom of the labeling dot that a change in area could be seen.



**Figure 3-5 Testing Field of View**

Vibration tests were run at frequencies of known displacements and at the first mode. Two sets of tests were completed: one set with a 32 inch working distance and a second with a 15.25 inch working distance. See Figure 3-6 for the exact frequencies the tests were completed at and their corresponding deflections. A still image was taken prior to each test so a null deflection area could be compared with the subsequent test frames.

<b>Frequencies Investigated</b>	
Non Resonating	
-	31Hz (0.010")
-	44Hz (0.005")
-	70Hz (0.002")
-	300Hz (0.0001")
First Mode	
-	666Hz located in center of board
-	Expect deflection of 0.00175"
Known board displacements in parenthesis	
<b>High Speed Camera</b>	
Model: Red Lake CR2000	
Frame Rate: 1000Hz	
Exposure Rate: 983	
CCD Resolution: 512x384	
Record Time: 2 seconds	
Lens: 105mm 1:2.8	

**Figure 3-6 Area Scaling Concept Tests Completed**

### 3.2.2 Image Processing Results

The images were post processed using MATLAB Image Processing Toolbox. The images were imported one by one and then each of the frames intensity images,  $I$ , were read and returned as binary images of the same size. Then edges on the binary images were found using the Sobel method. The Sobel approximation to the derivative will return edges at those points where the gradient of  $I$  is maximum [12]. Then using the MATLAB `BWarea` function, the area of the circle is outputted. Each frame is compared with the subsequent image to reveal the change in area.

Unfortunately, the area scale testing did not show a change in area for any of the tests. Even the test with the greatest deflection, 0.01 inches, was not able to register as a detectable change in area.

### 3.2.3 Area Scaling Analysis

Since the results of the testing proved current equipment could not capture the minute deflections of the electronics board, a second look was taken to determine what sensor resolution is required for this method to work. The concept parameters are seen in Figure 3-7 below.

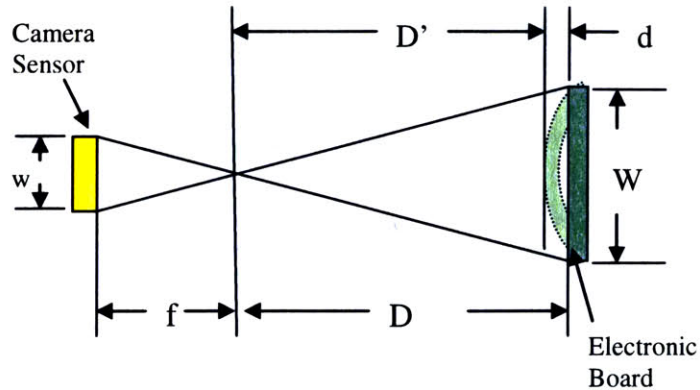


Figure 3-7 Test Parameters

where  $f$  is the focal length,  $D$  is the working distance with the board in the null position,  $D'$  is the working distance in the fully deflected state, and  $d$  is the deflection of the board. The Camera sensor has a width,  $w$  and the electronics board has a width,  $W$ . Since the camera sensor has a larger resolution horizontally, the width of scene and sensor is all that will be used in determining the minimum detectable deflection. The amount the electronics board scene is scaled by in order to be represented on the camera sensor is just a relation between their widths as seen in Equation 3-1.

Equation 3-1

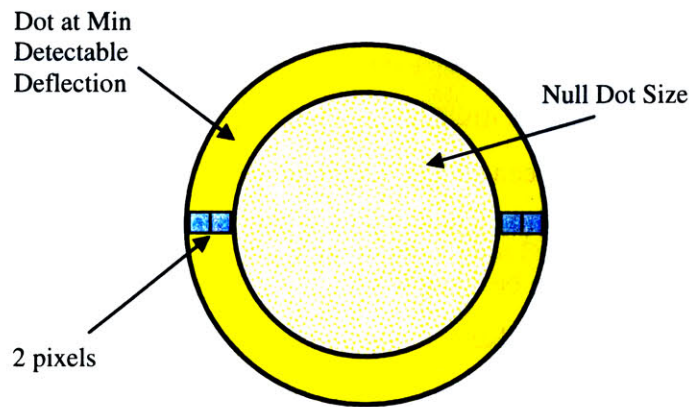
$$Scale = \frac{w}{W} = \frac{0.32256}{1.18} = 0.273$$

The scaled amount can now be used to relate the pixel resolution to the object resolution (smallest viewable feature).

**Equation 3-2** 
$$Scale = \frac{pix\_width}{obj\_res}$$

$$obj\_res = 0.273 * 0.00063 = 0.000172inches$$

To get accurate resolution, two pixels are needed to represent the area edge [13]. See figure below to view assumptions that will be used in calculating the minimum detectable deflection.



**Figure 3-8 Minimum Detectable Dot Growth**

Since two pixels correspond to an object resolution of 0.0044 inches, the 0.75 diameter dot will have to grow by 1.2% or to a diameter of 0.7588 inches to be seen. Now the question is how much does the board have to deflect to achieve this amount of growth? To solve for the growth a simple geometric relationship is used to solve for  $D'$  in Equation 3-3 below.

**Equation 3-3** 
$$\frac{w/2}{f} = \frac{W/2 - (2 * obj\_res)}{D'} \rightarrow \frac{0.32256/2}{4.13386} = \frac{1.19/2 - (2 * .0044)}{D'}$$

$$D' = 15.02 \text{ inches}$$

$$d = D - D' = 0.23 \text{ inches}$$



The minimum deflection that will be able to be seen is 0.23 inches with the current equipment and setup. In order to achieve a displacement resolution equal to the marginal specification of 0.1mil using the same setup, a 34kx34k resolution camera sensor is required.

High speed cameras have just recently been released with over a 1.5kx1k resolution.<sup>4</sup> While, optical techniques could possibly compensate for lower resolution sensors, there is hope with the ever-increasing CCD and CMOS technology that this could be a viable method in the future.

### **3.3 Concept 3: Displacement Sensor Grid**

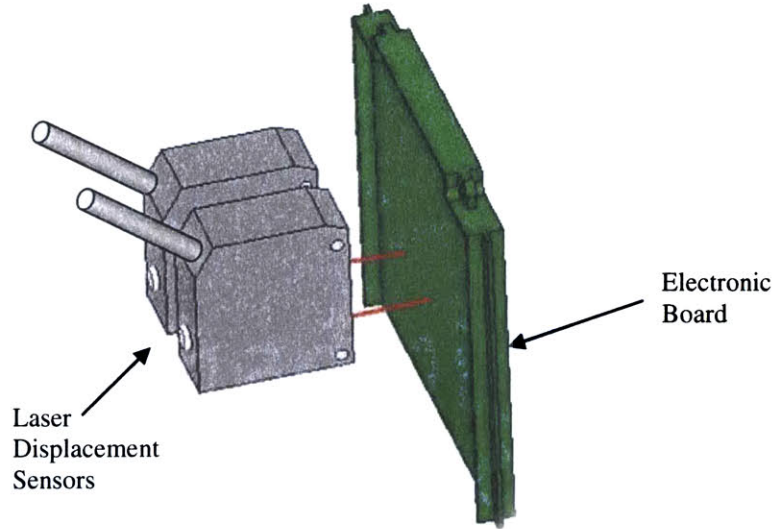
The final concept involves using a grid of displacement sensors that can be scrolled down the face of the electronics board. This option does not require a very complex setup but it will capture discrete locations on the surface of the board. The displacement sensor that has been chosen for the concept is a laser displacement sensor. Two laser sensors exist that could be used in this design. If this concept is chosen, sensor selection testing would have to be completed.

Proximity sensors were also considered but because they require a metal target, it was determined they would be too restrictive on the target objects that could be tested and could make interpretation of test results hard since copper layers exist within the printed circuit boards. Also since the bare frame aluminum electronic(s) board is thinner than the penetration depth of all proximity sensors considered, eddy currents build up on the back of the metal could give false readings.

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<sup>4</sup> Red Lake HG-100K camera has a 1504x1108 resolution and can sample up to 1000 frames/second.

The figure below shows the idea of the sensor probes capturing the board displacements through voltage output during vibration testing.



**Figure 3-9 Displacement Sensor Grid Example**

Since the laser displacement sensors cannot undergo more than 55Hz, they would have to be mounted from the shaker table rails that are on isolation pads. The hardware would not only have to suspend the sensors in front of the board, but it would have to incorporate some sort of a vertical rail so that multiple locations on the board could be captured.

Table 3-1 shows the specifications on the two laser displacement sensors under consideration.

	<b>LK-11 Sensor Head</b>	<b>LC-2440 Sensor Head</b>
Reference Distance	10mm (0.39")	30mm (1.18")
Measuring Range	±1mm (0.04")	± 3mm (0.12")
Resolution	0.2µm (0.008 mil)	0.2µm (0.008mil)
Sample Rate	7812.5 Hz	50,000 Hz
Target Surface	Any	White: Diffuse Reflective

**Table 3-1 Displacement Grid Sensor Comparison**

### 3.3.1 Concept 3 Summary

#### Benefits

- Easy Setup
- Simple Equipment
- Resolution <1 $\mu$ m
- Large Frequency Range

#### Limitations

- Measures Discrete Points
- Limited Measuring Range
- Must Mount to Shaker Table Rails
  - Could introduce error

### 3.4 Concept Comparison

The three concepts have each been assigned ratings based upon how well they meet target specifications. These ratings are then multiplied by the specification's importance to reveal a weighted score. The scores for each product are summed giving a general way to compare the effectiveness of each concept at accomplishing the design goals. The concept comparison matrix is below in Table 3-2.

<i>Selection Criteria</i>	<i>Imp.</i>	<b>Holographic Interferometry</b>		<b>Area Scaling</b>		<b>Grid of Displacement Sensors</b>	
		<i>Rating</i>	<i>Score</i>	<i>Rating</i>	<i>Score</i>	<i>Rating</i>	<i>Score</i>
Sample Rate	5	4	20	2	10	5	25
Deflection of Board	5	3	15	1	5	5	25
Resolution	5	4	20	1	5	5	25
Cost	4	3	12	4	16	3	12
Full-field	4	5	20	3	12	2	8
Time to Assemble/Disassemble	3	2	6	5	15	4	12
Measurement Area	3	5	15	3	9	4	12
Test Time	3	3	9	4	12	5	15
Continuous Real-Time Output	3	5	15	3	9	3	9
Special Tools for Maintenance	3	3	9	5	15	4	12
User Friendly Manual	3	5	15	5	15	5	15
<b>Total Score</b>		<b>156</b>		<b>123</b>		<b>170</b>	
<b>Rank</b>		<b>2</b>		<b>3</b>		<b>1</b>	

**Table 3-2 Concept Comparison Matrix**

The matrix shows that the Displacement Grid Concept will achieve the best result of reaching the target specifications. Second is the Holographic Interferometric method and third is the Area Scaling method. Based on these results and the support of Draper Laboratory, the Grid of Displacement Sensors will be the concept developed. Chapter 4 will cover the prototype hardware and software design, as well as, sensor selection testing.

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## **Chapter 4 Prototype Design and Testing**

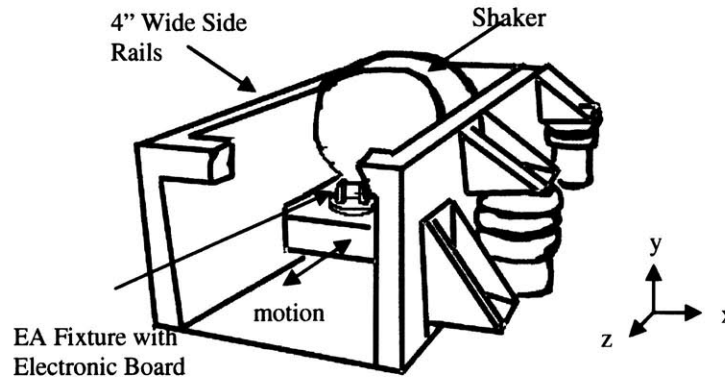
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This chapter will delve into the hardware and software design for the displacement sensor grid system. The goal of this round of design work is to create a prototype system that will test the capabilities of the Keyence LC-2440 and LK-11 displacement sensors. While the hardware will primarily be designed for the sensor selection testing, it must be easily modified for the final multi-sensor system. Sensor selection testing and results will be discussed and by the end of this chapter, a sensor will be chosen for the final design. An evaluation of the prototype hardware will also be presented.

### **4.1 Mechanical Design**

The hardware needs to accomplish the following functions: mount to the slip table side rails, span from rail to rail, provide an interchangeable mount so both the LC-2440 and LK-11 sensors can be secured at their reference distance, and have at least one

unconstrained degree of freedom so sensors can be scanned over the surface of the electronic board. See picture below for shaker table diagram in Figure 4-1.

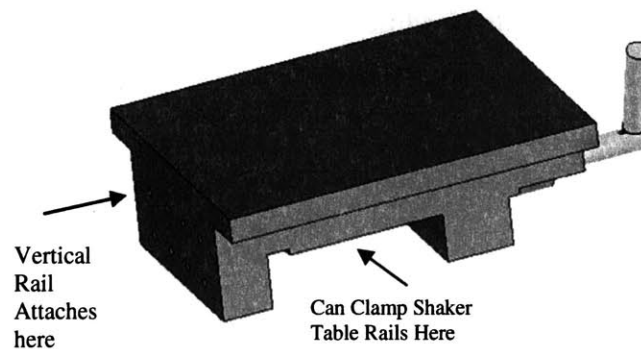


**Figure 4-1 Shaker Table Sketch**

#### **4.1.1 Mounting Options**

The vibration table has two 4-inch wide rails on each side. Since the sensors are going to need to be positioned horizontally (towards or away from the electronic board), the system needs to be easily adjustable in the z-direction. The entire system and sensors will be suspended from these mounting devices so whatever is chosen needs to be sturdy and provide an easy attachment scheme for the sensor cross bar.

Five inch wide drill press vises will be used for the rail mounting function because they fulfill the required functions, they are low cost, and will require little modification.



**Figure 4-2 Shaker Table Mounting Scheme: Drill Press Vise**

Two, quarter inch aluminum sheets will hang perpendicular to the vise's mounting surface by way of an L-Bracket. These aluminum verticals will hang inside the vise table rail walls to provide the mounting surface for the cross bar. The cross bar attachment scheme will have to allow the cross bar to be moved in the vertical, y, direction.

#### 4.1.2 Vertical Movement

The vertical movement of the cross bar can be accomplished in a variety of ways. Holes can be drilled at discrete distances from each other allowing for a precise placement of the cross bar and sensors. This option would ensure that the point on the electronics board being captured by the sensor is known but it would limit the number of locations that could be investigated by the system.

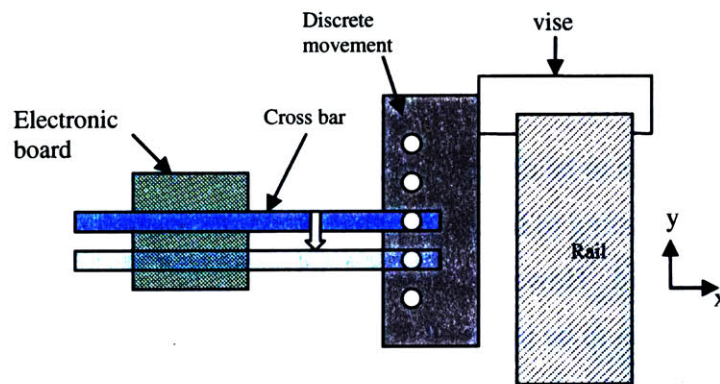
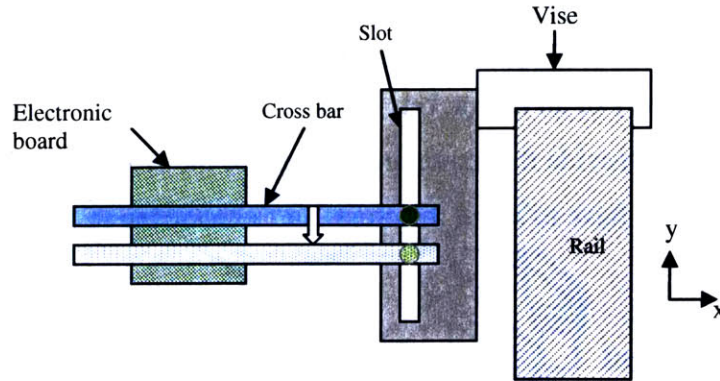


Figure 4-3 Discrete Vertical Movement: Holes

Another option is to incorporate a slot along each rail so infinite points in the vertical direction can be investigated on the board. This would allow for an infinite number of measurement positions.



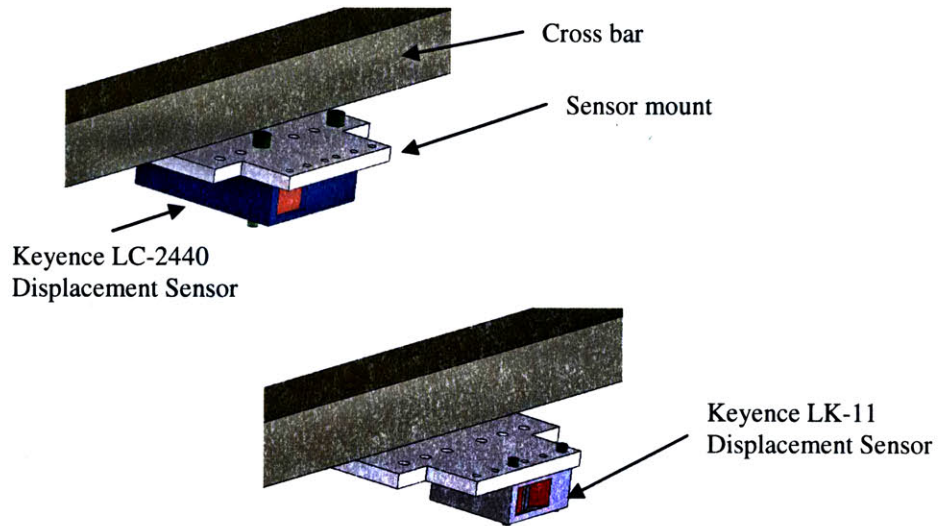


**Figure 4-4 Vertical Movement: Slot**

Since the vertical slot will not limit the vertical position of the cross bar, it will provide the greatest test versatility and was chosen for the system. A nut and bolt will be used to fasten the cross bar in a particular location of the slot and a digital read out (DRO) will be attached to one of the verticals so the exact location of the sensor will be known.

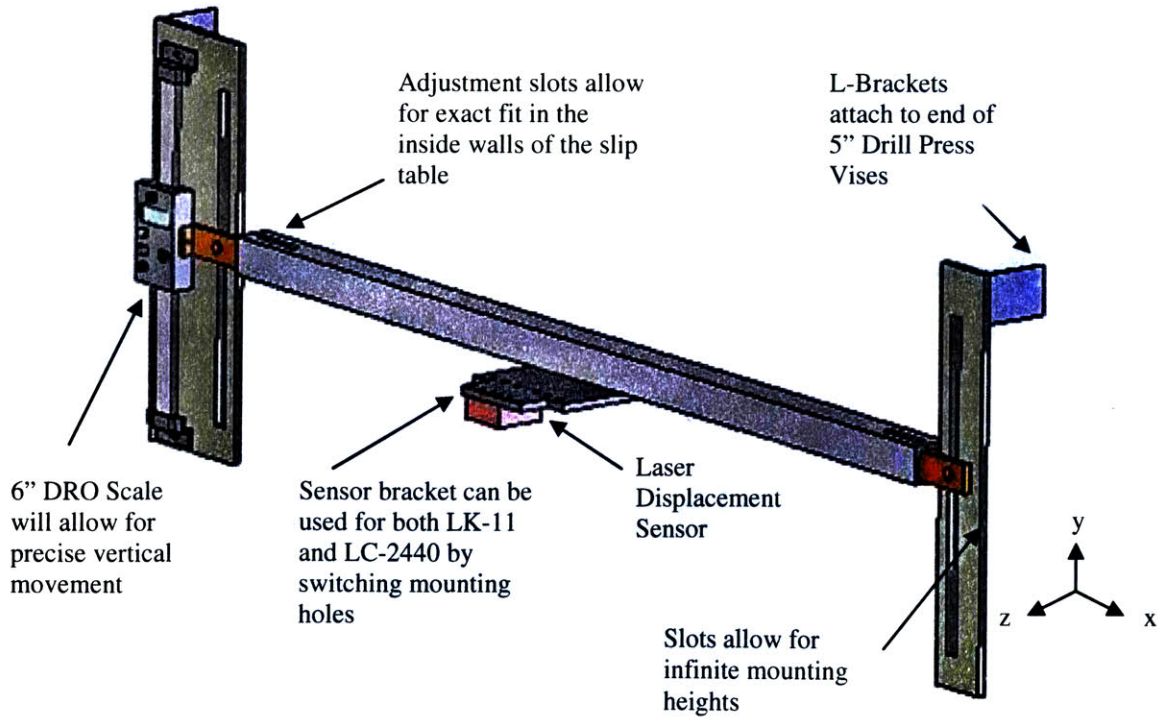
#### **4.1.3 Sensor Mount**

A mount needs to be designed to attach the LK-11 and LC-2440 to the cross bar. Since their output is going to be compared, they should capture the displacements of the same spot on the board. However, they do not have to be mounted at the same time. Since the LC-2440 has to be mounted 30mm from the surface of the board compared to the LK-11's 10mm, a simple bracket mounting the sensors horizontally was designed. See illustrations on the next page.



**Figure 4-5 Sensor Mount in Both Sensor Configurations**

The prototype hardware system that was built for sensor selection testing is below in Figure 4-6.



**Figure 4-6 Sensor Selection Hardware Design**

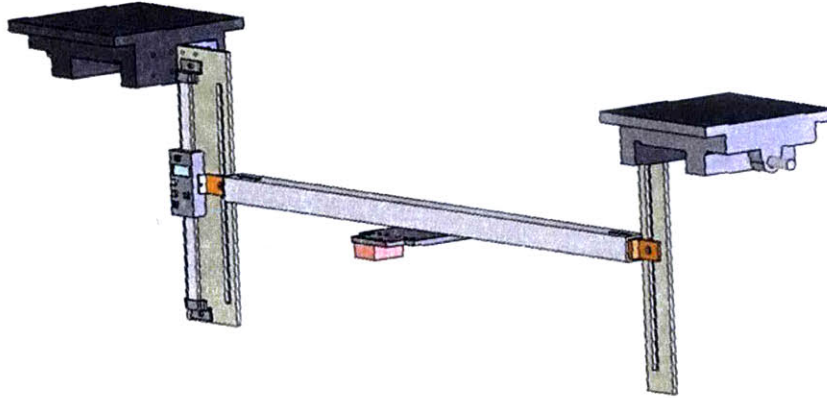


Figure 4-7 Sensor Selection Hardware Design with Vises

## 4.2 Software Design

The final system needs to not only obtain the laser output, but it needs to analyze it as well. For this reason, the most efficient choice is to have both the data acquisition software and analysis software written in the same code. It was decided that MATLAB would be used because a data acquisition and analysis package was available.

A simple program was written to acquire the laser output at a specified sample rate from a National Instruments NI DAQ-1200 card and save it as a “.daq” file for post processing. A picture of the program can be seen in Figure 4-8 below.

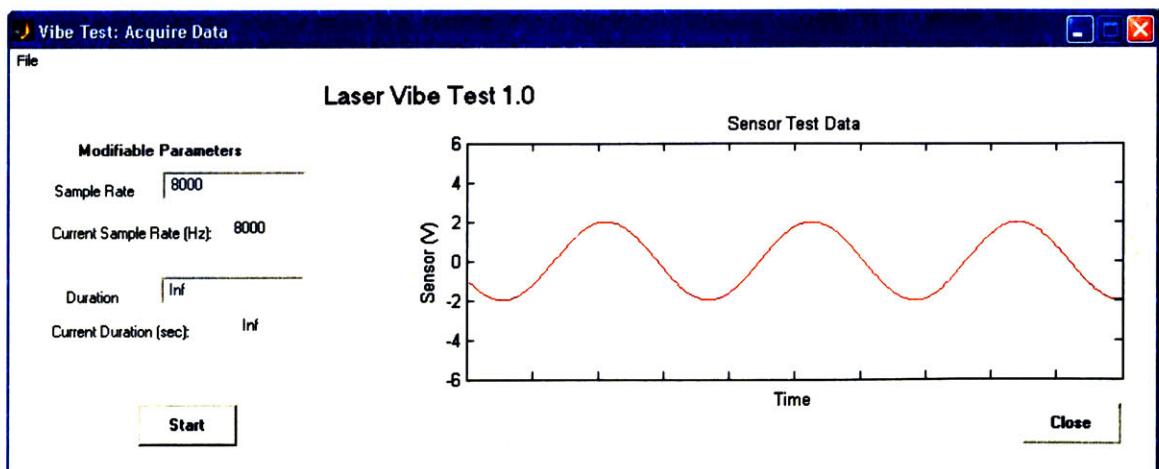


Figure 4-8 Data Acquisition MATLAB Program: Laser Vibe Test 1.0

### 4.3 Sensor Comparison

The Keyence LK-11 sensor head and LK-3101 controller sell for around \$5900 while the LC-2440 Sensor and LC-2400 Controller sell for approximately \$9300. The main advantages of the LK-11 sensor is that it can read the displacement of any surface type while the LC-2440 can only read a specular diffuse (white) target. Since multiple sensors would be incorporated into the final system for shorter test times, the LK-11 sensor would be best suited because it is one-third the size of the LC-2440 allowing four sensors to easily fit the width of the electronic board. The LC-2440 sensor system would be better, however, for a more versatile vibration measurement system because it can sample up to 50kHz while the LK-11 system has a maximum sample rate of 7812.5 Hz. Sensor performance during vibration testing will help determine the best sensor for the final system.

#### 4.3.1 Sensor Selection Test

The purpose of this test was to assess the capabilities of the laser triangulation sensors for electronics board vibration testing, evaluate the hardware and software design, and ultimately compare the results of the LK-11 sensor with the LC-2440 sensor to determine which would be used in the final vibration measurement and analysis system.

##### 4.3.1.1 Test Setup

The electronic board bare frame was mounted in an aluminum fixture that bolts down to the vibration table. See Figure 4-9 below.

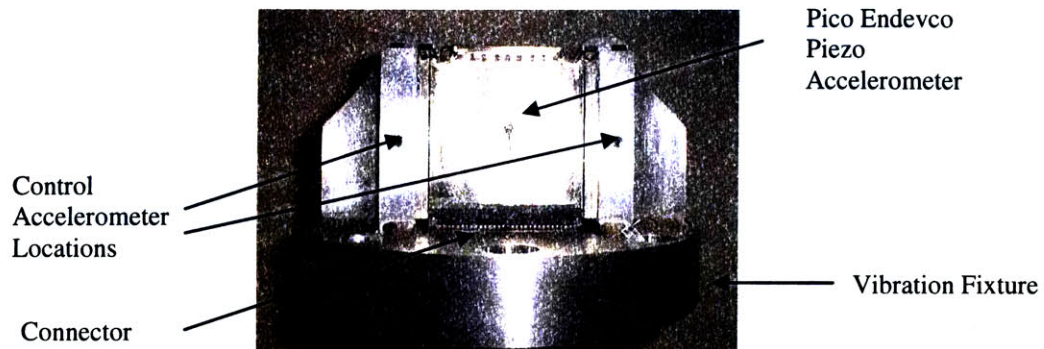
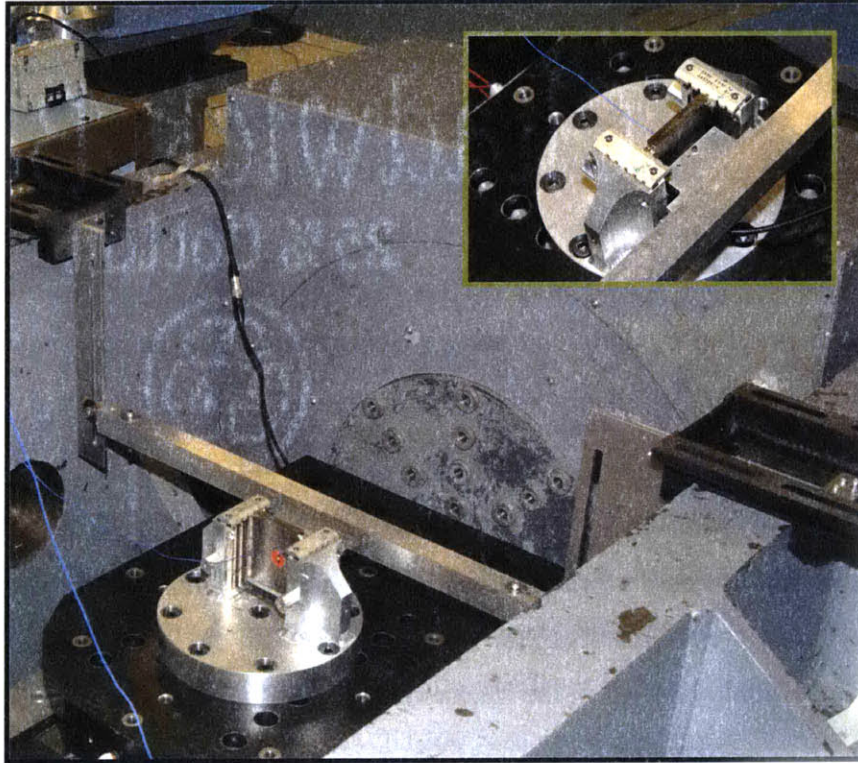


Figure 4-9 Electronic Board Test Setup

The control accelerometers are averaged and used by the table to ensure the board is held under a constant 1-G acceleration during the sine sweep. The center mounted

accelerometer verifies that each test produces the same electronic board response and since the accelerometer is capturing the same point as the laser sensor, it can be used later to validate the laser displacement output. See Figure 4-10 below for complete hardware setup.



**Figure 4-10 Hardware Test Setup**

#### **4.3.1.2 Sensor Setup**

The Keyence LK-11 displacement sensor with the LK-3101 controller requires 24V DC input and will output a voltage of  $\pm 10V$ . The National Instruments DAQ 1200 board has an input voltage limit of  $\pm 5V$  so a voltage divider circuit was built to cut the laser output voltage in half. A wiring diagram for the LK-11 test can be seen in Figure 4-11.

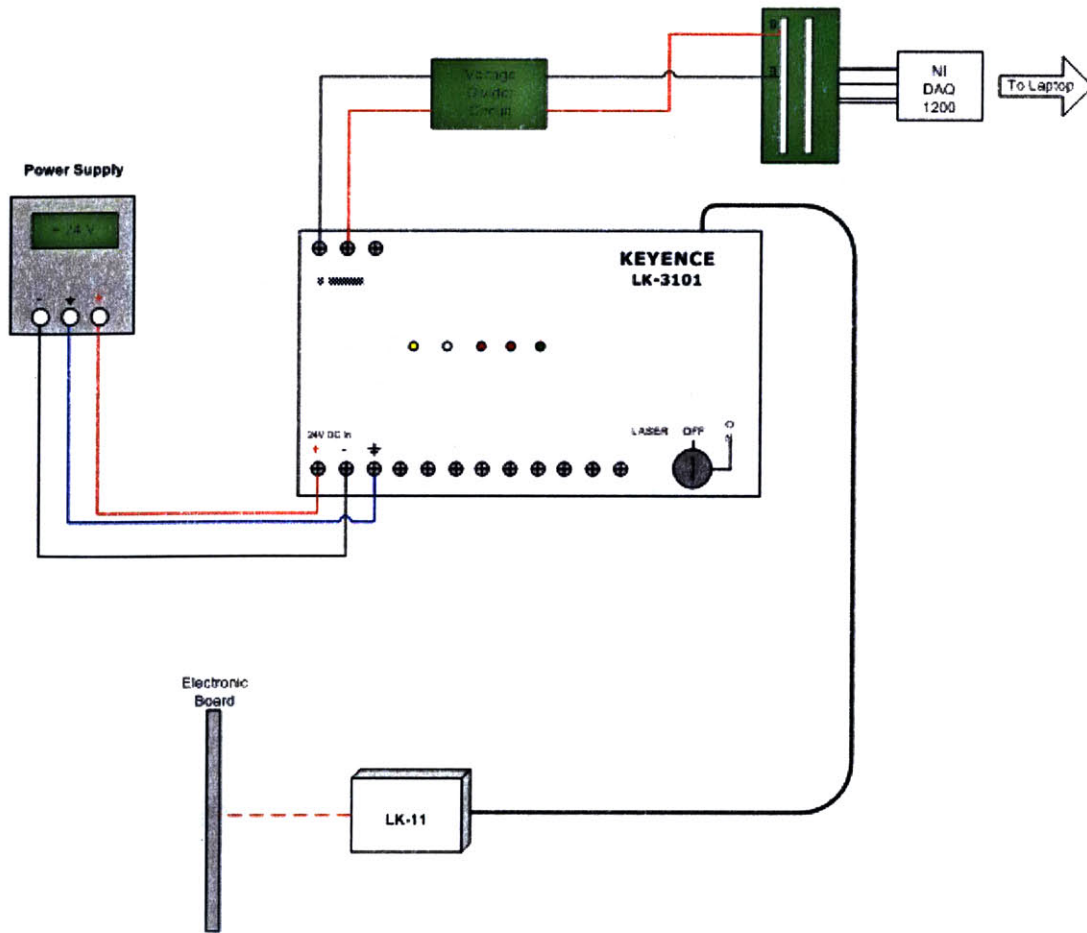
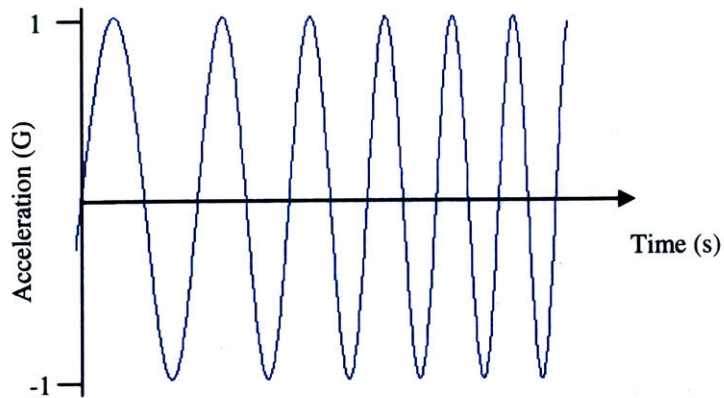


Figure 4-11 Displacement Sensor Setup Diagram

The LC-2440 displacement sensor setup is simpler; its controller, the Keyence LC-2400, plugs directly into the wall outlet. Like the LK-11 setup, a voltage divider circuit is used in the LC-2440 setup to cut the output voltage in half before it is run into the NI-DAQ-1200 card and recorded by the MATLAB program.

#### 4.3.1.3 Sine Sweep

A sine sweep is obtained by continuously varying the frequency of a sine wave. A 1-G sine sweep is used to excite the electronics board. The vibration table runs the sine sweep at 2 oct/min so it takes just over 3 minutes for the test to be completed.



**Figure 4-12 Vibe Table Sine Sweep Representation**

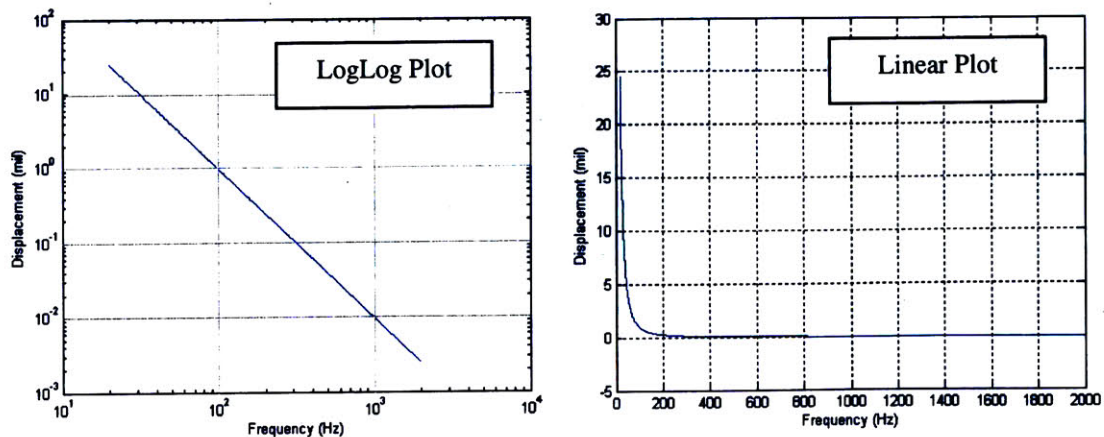
The displacement of the vibration table during the sine sweep will be seen as a downward sloping line on a loglog plot following Equation 4-1 below.

**Equation 4-1**

$$Y_o \cong \frac{9.8 * a}{f^2}$$

where  $Y_o$  is the single amplitude displacement in inches,  $a$  is the acceleration in G's and  $f$  is the forcing frequency in hertz.

The slip table displacement will have to be subtracted off of the laser displacement output to get the electronic board's modal displacement. See Figure 4-13 below for the vibe table displacement during the 1G sine sweep from 20-2000Hz. Please note that Figure 4-13 depicts the single amplitude displacement or the maximum positive amplitude of the sinusoidal motion. See figure below.



**Figure 4-13 Vibration Table Sine Sweep Displacement vs. Frequency**

### 4.3.2 Electronic Board Accelerometer Output

The maximum displacement of the first natural frequency of the electronic board occurs at the center of the board so the center mounted accelerometer will pick up the board's max dynamic response around 660 Hz and 80 G's (1.8 mil). The typical accelerometer output for the 1G sine sweep of the electronic board under investigation can be seen below.

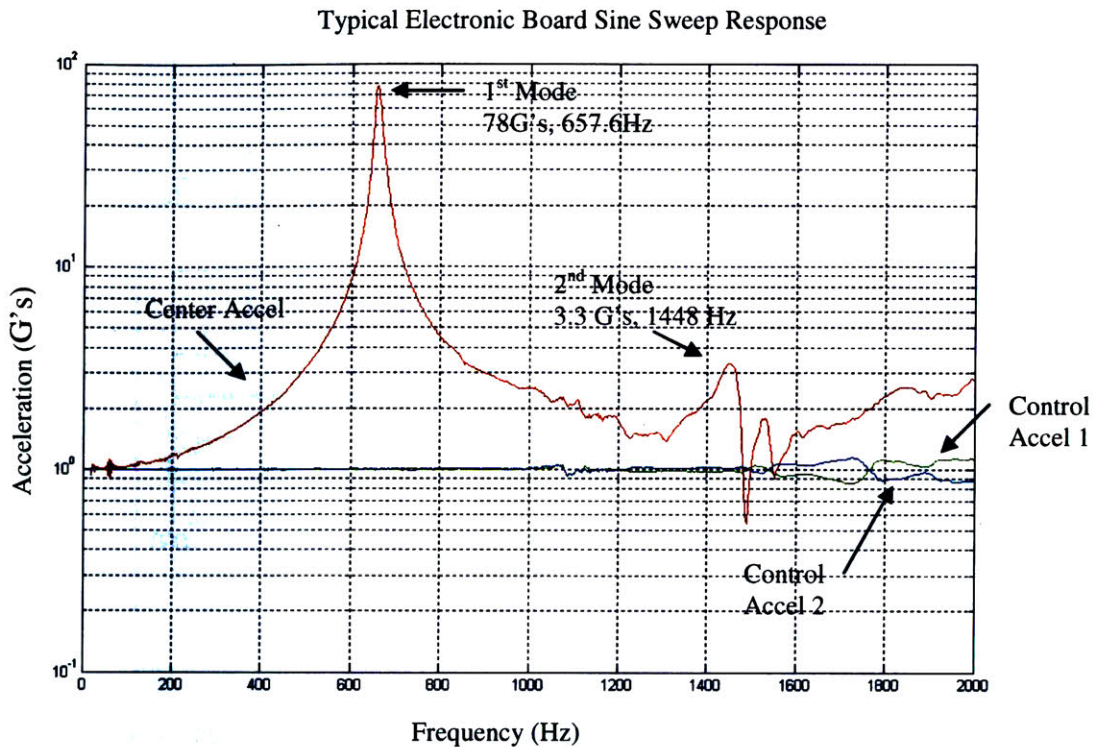


Figure 4-14 Typical Accelerometer Output for Electronic Board

### 4.3.3 Laser Displacement Output

The laser output is voltage vs. test time. This data can be easily converted to displacement versus time with a conversion factor. However, only a rough estimate of displacement versus frequency can be shown at this point using the test time and the 2oct/min vibrate table sweep speed. A more accurate way of determining frequency of the data, will be shown later in Chapter 5, where an algorithm will actually step through the laser output and read the frequency content directly from the sine wave zero crossing times.



### 4.3.3.1 Keyence LK-11 Sensor Performance

The LK-11 sensor captured the electronic board's response at a sample rate of 7812.5Hz in the sensor's "normal" mode, and highest response speed. Multiple tests were run and each produced the same response. See figure below.

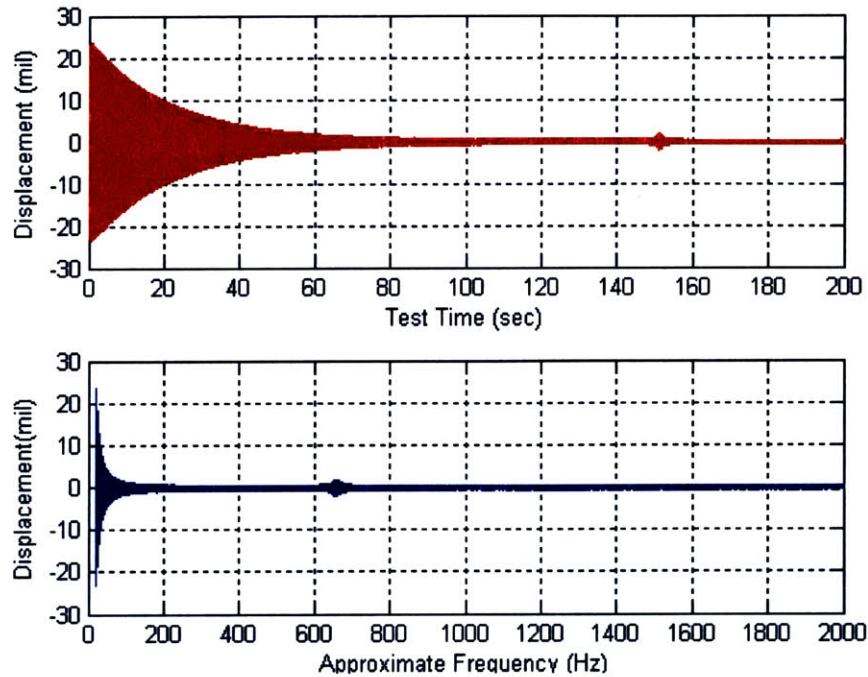


Figure 4-15 Center of the Board LK-11 Sensor Output

A close up of the LK-11 test data at low frequencies show that the structure is acting as a rigid body and that the board is displacing with the vibration table. The plot below shows the center of the board displacement and the peak vibration table displacement.

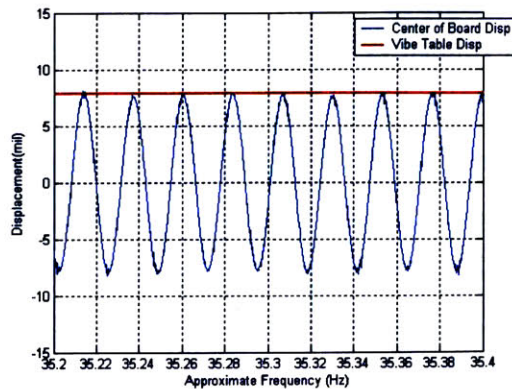
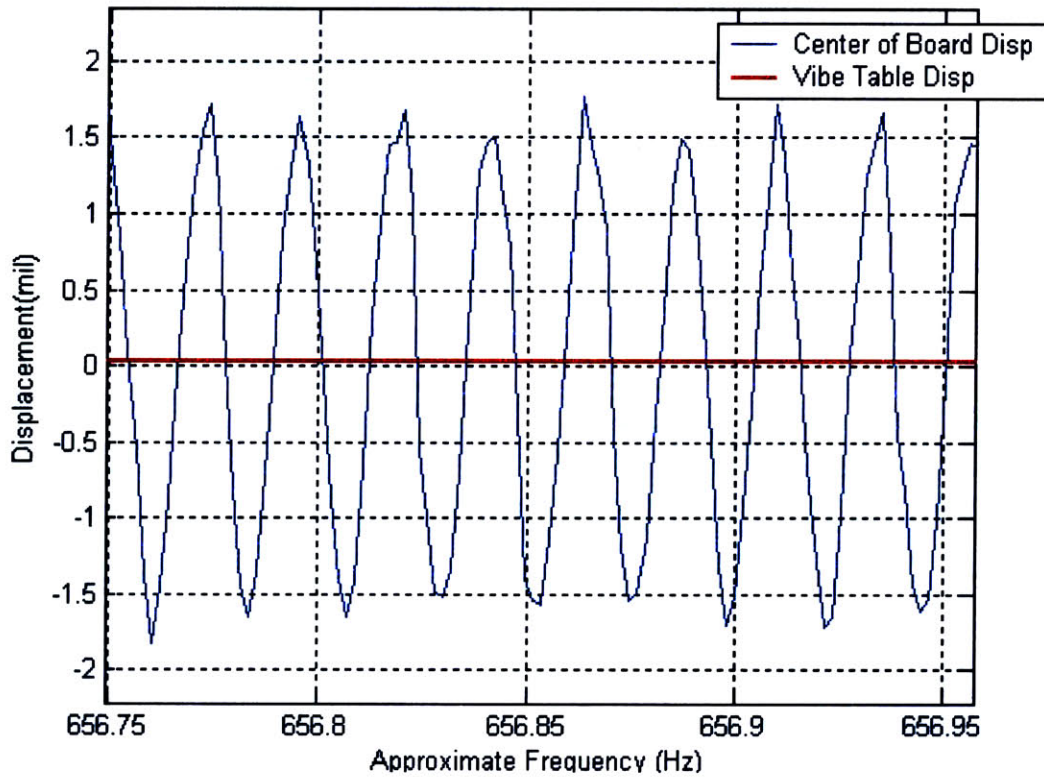


Figure 4-16 Low Frequency LK-11 Test Data Comparison with Vibration Table Displacement

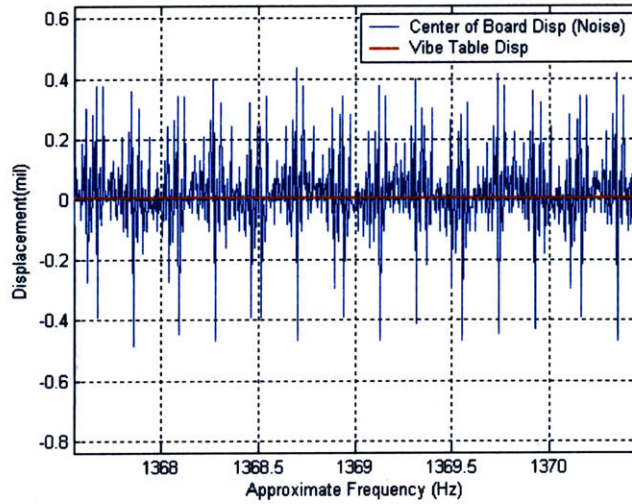
The board should hit its first resonant mode around 660 Hz with a displacement just below two mils. The bump in Figure 4-15 in this frequency region is evidence that the LK-11 sensor picked up the board's first mode. A close up of this region of the test data with a comparison to the vibration table displacement is below in Figure 4-17.<sup>5</sup>



**Figure 4-17 Comparison of Vibration Table and Board Displacement in the First Mode Region**

The LK-11 sensor captured the first mode displacements of the electronic board quite well. The only area that is of concern is the noise in the LK-11 output that masks the second mode and could limit the resolution of the final vibration system if this sensor is chosen. See Figure 4-18 for a plot of the sensor noise.

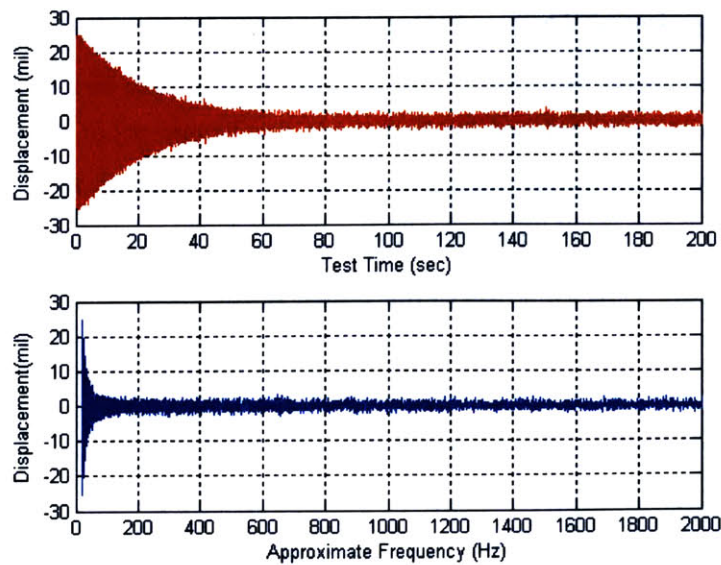
<sup>5</sup> The center of the board displacement as captured by the lasers refers to the displacement of the board and the vibration table. The actual board displacement can be found by subtracting the peak vibration table displacement from the peak board displacement.



**Figure 4-18 LK-11 Sensor Test Noise**

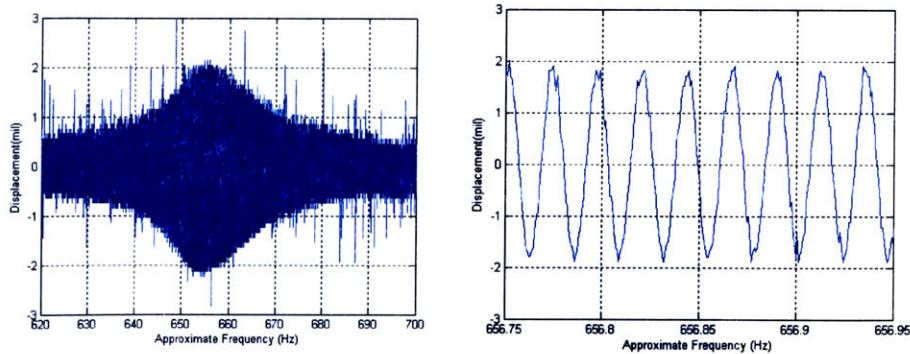
#### 4.3.3.2 LC-2440 Sensor Performance

The LC-2440 is a larger and much more sensitive sensor but it has to have a diffuse reflective target (white). During testing it was set to a sample rate of 20kHz and the laser beam was focused on a white labeling dot in the center of the electronic board (the same point on the board that was captured by the LK-11 above). Figure 4-19 shows the LC-2440 test data. It can easily be noticed that more noise exists in the LC-2440 sensor data compared to the LK-11 data presented in Figure 4-15.



**Figure 4-19 Center of the Board LC-2440 Sensor Output**

Unlike the LK-11 sensor, it is not apparent at this viewing resolution that any of electronic board's resonant modes were captured by the sensor. An up close look at the first mode region does in fact reveal that the sensor's mode was captured.



**Figure 4-20 LC-2440 Sensor Output: First Mode Region**

#### **4.4 Sensor Selection**

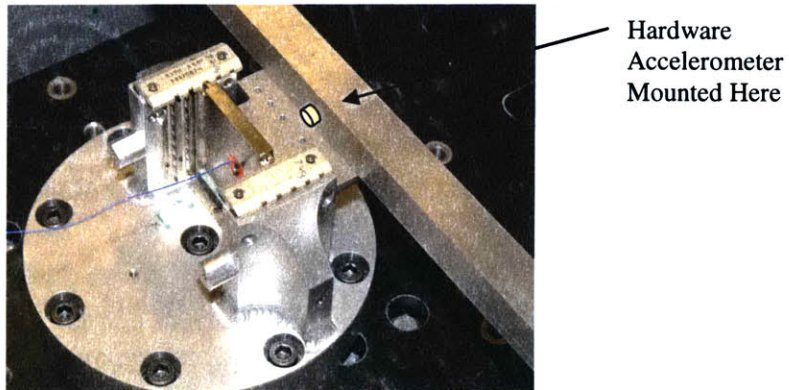
The LK-11 sensor was chosen for the final system. Based on test data, the sensor provides less output noise and has the distinct advantage over all other displacement sensors in that it can read all target materials. It is a huge drawback that the LC-2440 system requires a white dot to be stuck on the test specimen, especially since the purpose of this thesis is to develop a measurement system that does not mass load the structure during testing. The LK-11 is more compact and will allow up to four sensors to be stacked side by side to measure the electronic board's displacements. In comparison, the LC-2440 would only fit two sensors, requiring twice as many tests at around the same cost as the four LK-11 sensors. Both sensors provide promising results of the first resonant mode of the electronic board but because of noise, the second mode is not distinguishable. Work will be done in the next chapter to try and reduce the noise level of the LK-11.

#### **4.5 Hardware Evaluation**

The hardware worked quite well for the sensor selection test. The small slot adjustments on the crossbar and the vertical movement slots on the vertical rails allowed for exact placement of the laser beam in both the horizontal and vertical directions. During testing, since only one sensor was used, the levelness of the crossbar was

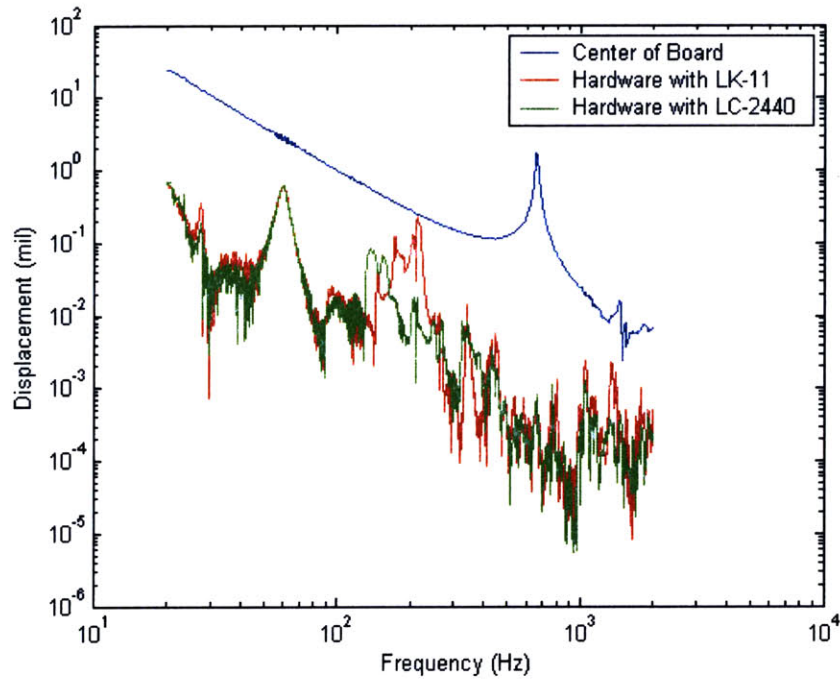
neglected. However, when more sensor heads exist, there will be a need to ensure the cross bar is level.

The hardware setup had a natural frequency of 16 Hz with the LK-11 (80 gram) sensor attached and 15.5Hz with the heavier LC-2440 (250g) sensor. In order to test how much vibration the sensors saw during the sine sweep and to ensure the vibration table rails were isolated from vibration during the test, an accelerometer was placed near the laser sensors to capture the vibration in the horizontal direction.



**Figure 4-21 Hardware Accelerometer Location**

If these sensors were not properly isolated and the sine sweep provoked the system's natural frequency, false displacement readings might have been recorded when in actuality, it is the sensor head itself displacing. Figure 4-22 shows the accelerometer output for the hardware with the LK-11, the hardware with the LC-2440, and the center of the electronic board response during the sine sweep.



**Figure 4-22 Comparison of Sensor Head Displacement with Center of the Board Displacement**

The sensor's displacement stays about an order of magnitude below the electronics board displacement. The additive/subtractive sensor displacements are negligible in comparison to the board displacements the sensors will measure in the board's first mode region. However, it is evident that the heavier LC-2440 hardware configuration pushed the sensor head horizontal vibration amplitudes down. Since the LK-11 sensors will be used in the final system, actions should be taken to ensure the system is weighted enough so false displacement readings do not occur and a better system resolution can be obtained.

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## **Chapter 5 Final Design and Testing**

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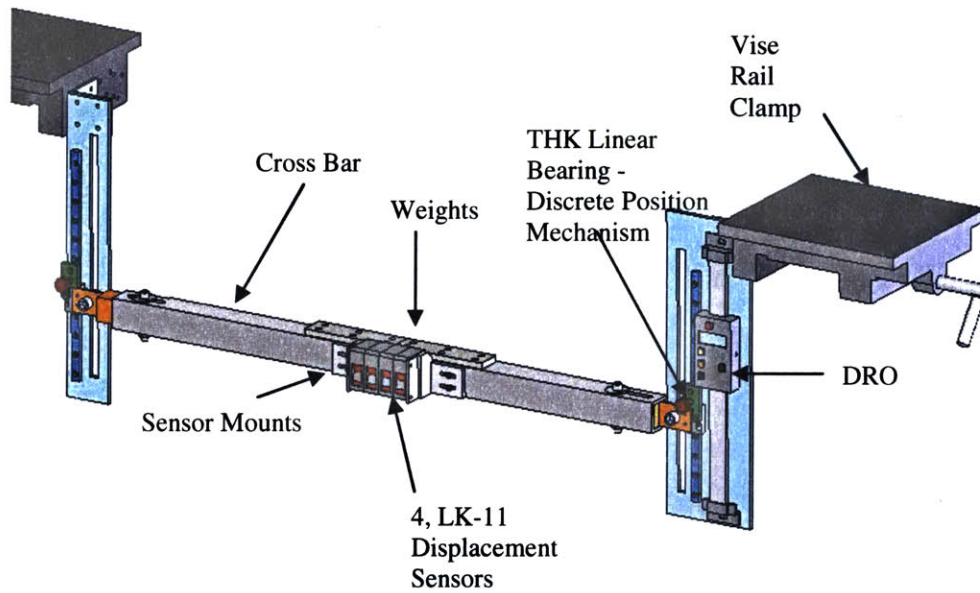
The four sensor hardware design was built and a MATLAB software package was written to acquire and fully analyze the electronics board displacement data during vibration testing. In order to evaluate the Non-Contact Laser Vibration Measurement and Analysis System's performance, two rounds of vibration tests were completed. Each test captured an 8x4 grid of electronics board displacements during a 20-2000Hz sine sweep at 1-G on the shaker table. The final hardware design, test procedures, and test results are presented in this chapter. The analysis software package was written to quickly process the raw voltage output from the displacement sensors and create a movie file displaying the electronics board's modal displacements. The five step analysis program will be explained as the data analysis methods are discussed.

### **5.1 Final Hardware Design**

The final hardware design was based on the prototype evaluations and the required modifications to incorporate the four LK-11 sensors. Since the original

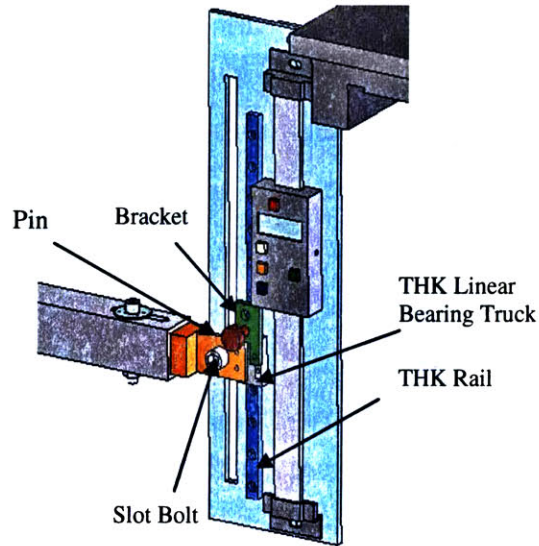


electronics board vibration fixture was going to be used, the four sensor mounting scheme had to be carefully designed. The final design can be seen below.



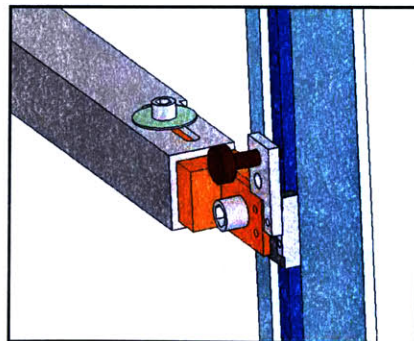
**Figure 5-1 Final Hardware Setup**

THK Linear Bearings were added for smoother vertical movement and discrete positioning. The system uses a unique setup to horizontally position the cross bar in 1cm increments. The THK Rails came with  $\frac{1}{4}$  inch diameter bores every 2 centimeters of the rail that were used in connection with a two-hole Bracket attached the linear bearing trucks. The holes on the bracket are spaced one centimeter apart giving the system 1cm vertical movement resolution. See Figure 5-2.

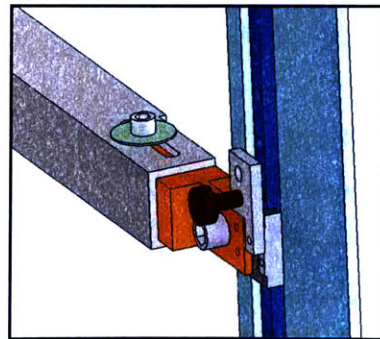


**Figure 5-2 Discrete Vertical Movement Mechanism**

To move the sensors/cross bar in the vertical direction loosen the bolt in the vertical slot on both sides and the pin on one side. Hold the cross bar stable, remove the pin on the other side and switch the hole it is in on the bracket. Then move the sensors/crossbar down until pin slips into the next bore on THK rail.



Pin in top Bracket hole



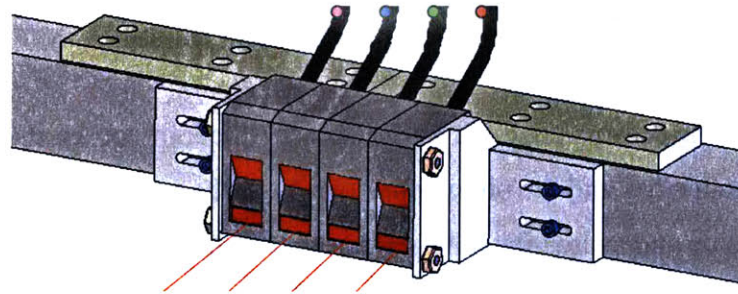
Pin in bottom Bracket hole and lower bore on the Rail. Sensors are now positioned 1cm lower

**Figure 5-3 One Centimeter Vertical Movement Resolution Diagram**

The digital read out, DRO, is located on the right vertical and acts as a height gage for the sensors. The DRO will provide a method to null the position of the sensors with respect to the electronics board before testing; the sensors can be positioned at any location and the DRO can be used as a height gage by sliding it down until it stops on top

of the Bracket attached to the THK Linear Bearing Truck. The DRO is zeroed at this known location. The first discrete point from that location can then be measured with the DRO so that the point being measured by the laser sensors are always known. Please see the Hardware Users Manual for more information.

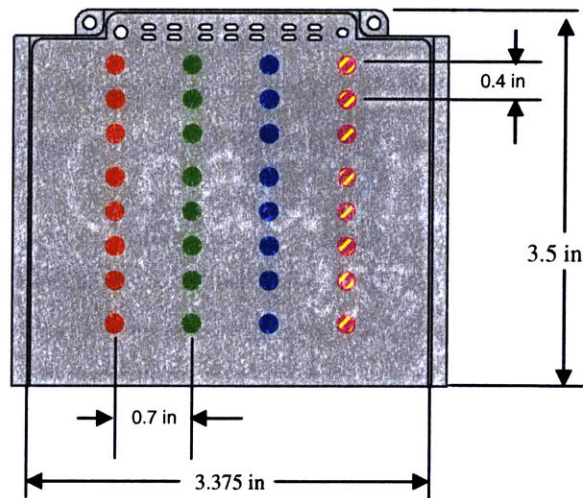
The sensor mount bracket aligns the sensors and provides slot mounting for exact horizontal positioning. Careful planning went into the mount's design so that sensor cords did not interfere with the crossbar and could easily be routed to the controllers. Also, the sensors had to be turned with the lasers on the bottom so that the lowest part of the board could be captured without fixture modification. See Figure 5-4 for mount design.



**Figure 5-4 Sensor Mount**

## **5.2 Electronic Board Vibration Tests**

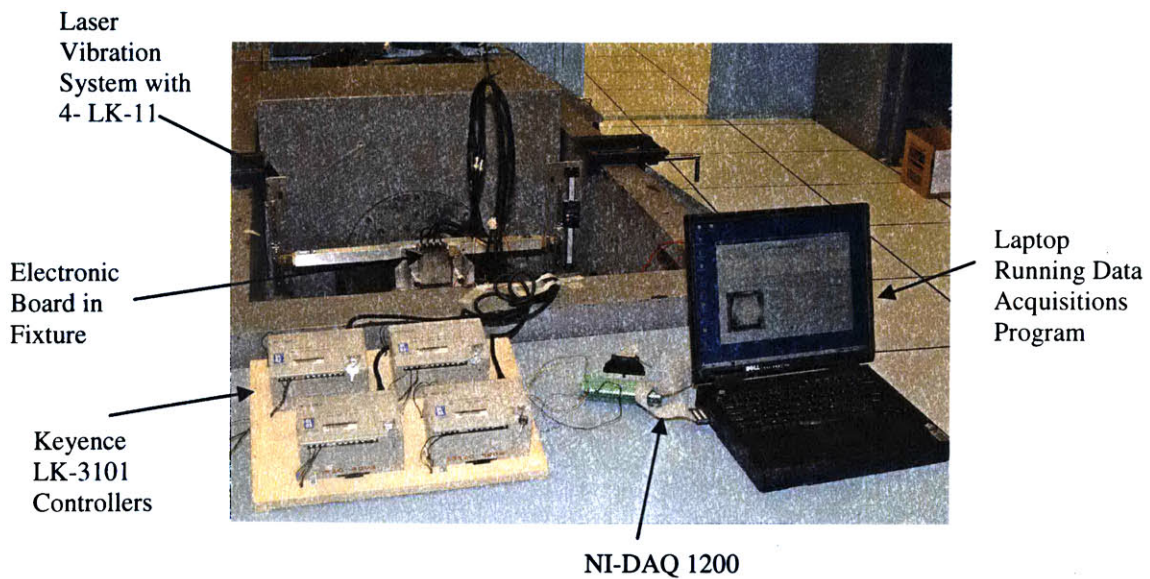
Two tests were performed to evaluate the performance of the vibration analysis and measurement system by capturing an 8x4 grid of bare frame electronics board displacements during a 20Hz to 2000Hz sine sweep at 1-G. The grid points captured will be used in generating mode maps that can be compared with accelerometer test data to prove the system's performance. The points captured on the board can be seen in Figure 5-5. The four laser displacement sensors in a side by side mounting scheme provide 0.7in horizontal resolution and the laser vibrate system provides 0.4in or 1cm vertical resolution. The color coding will be used through out this thesis to refer to the specific sensors. Red is the sensor capturing the left or first column of displacement, green is the sensor capturing the second column, blue is the next, and magenta/yellow is the far right column.



**Figure 5-5 Electronic Board Displacement Grid Diagram**

### 5.2.1 Test Setup

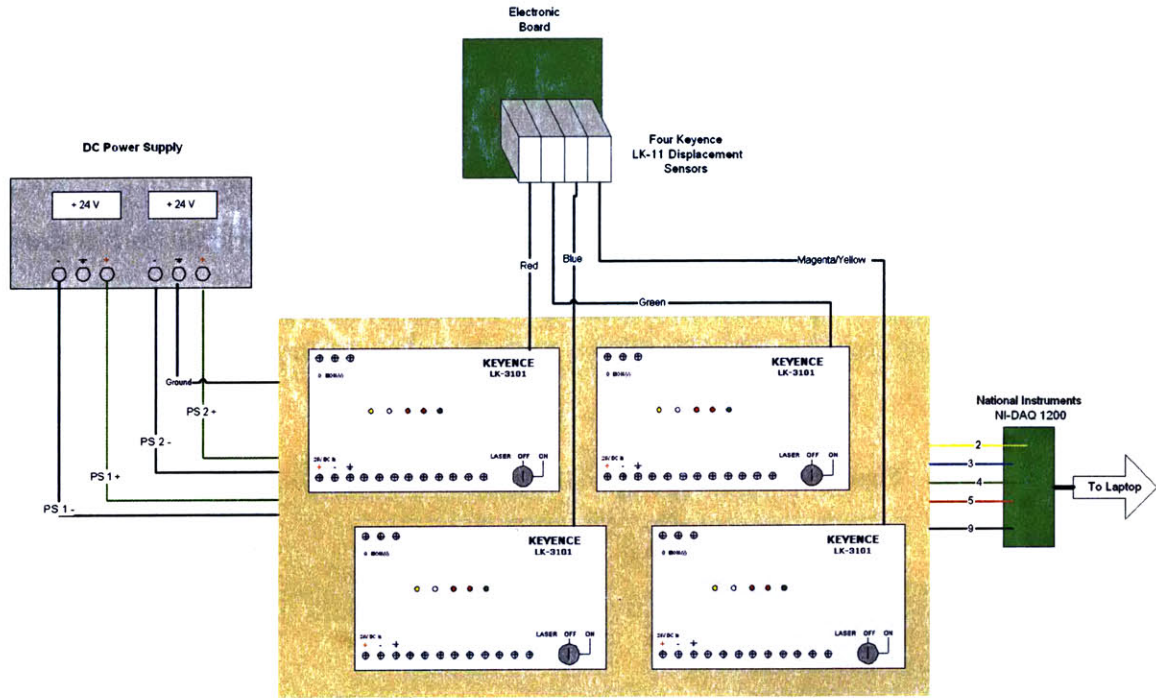
The test setup uses the new hardware design and integrates the four displacement sensors into a simple and compact setup.



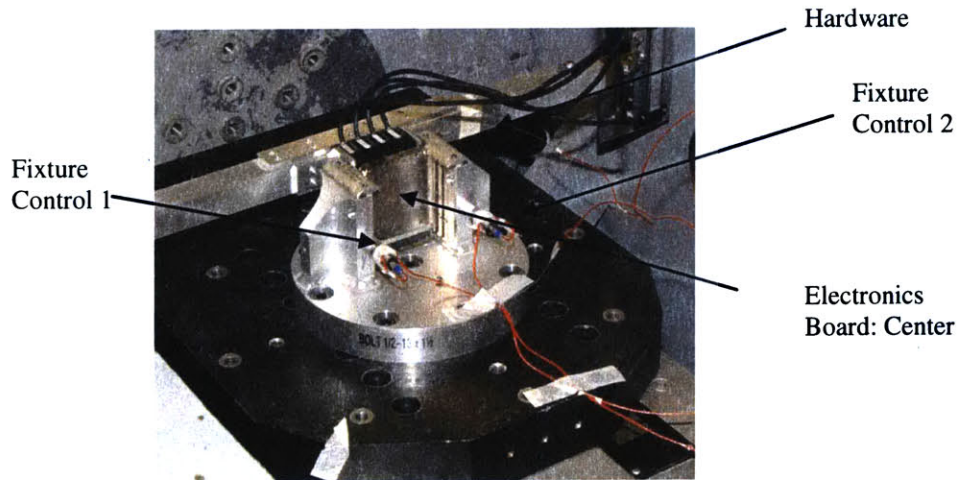
**Figure 5-6 Test Setup**

The wiring diagram can be seen on the next page. A bread board (not pictured in the diagram) is located under the sensor controller’s mounting table to route the 24VDC to each LK-3101 controller box and route the output from the sensors through a voltage

divider circuit and into the National Instruments card (NI-DAQ 1200) for recording by the MATLAB GUI, *Acquiredata*, on the laptop.



**Figure 5-7 Sensor Wiring Diagram**



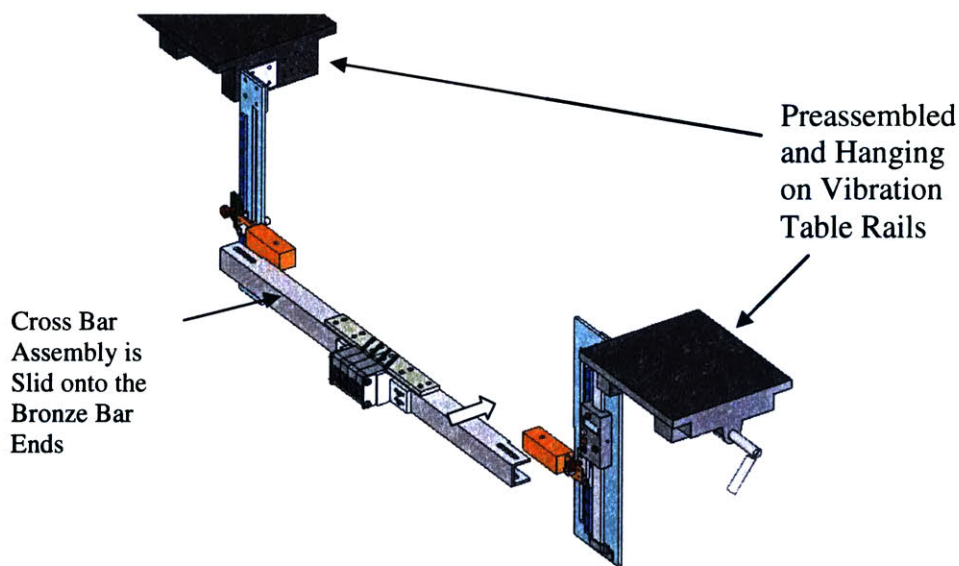
**Figure 5-8 Accelerometer Locations on Test Setup**

The two accelerometers on the fixture towers are averaged and used by the vibration table to ensure the electronic board is held under a constant 1G acceleration during the sine sweep. The hardware mounted accelerometer will provide a basis to

judge if the sensors are adequately isolated from vibration because any movement in the laser displacement sensors could lead to erroneous electronic board displacement readings. The accelerometer mounted in the center of the board is used to ensure the same dynamic response is being captured from test to test.

### 5.2.2 Test Procedures

Each vise clamp is preassembled with the vertical movement mechanism and bronze bar ends prior to clamping to the vibration table rails. After the preassembled vises are mounted on the table, the sensors can be mounted to the cross bar and inserted onto the bronze bar ends. See Figure 5-9 for assembly illustration. Mounting of the electronics board in the vibration fixture can occur before or after the Laser Vibration System is mounted.



**Figure 5-9 Assembly of Laser Vibration System on Vibration Table**

With the electronic board and fixture mounted and the laser vibration system in place, the sensors can be horizontally positioned with respect to the electronic board by adjusting the cross bar on the bronze bar ends. Be sure that the mounts will not hit the fixture when the table starts moving. There is a very small clearance on each side. Tighten the  $\frac{1}{4}$  inch slot bolts securing the bronze bar ends to the cross bar. Refer to the Hardware Manual in the appendix for further step by step details.

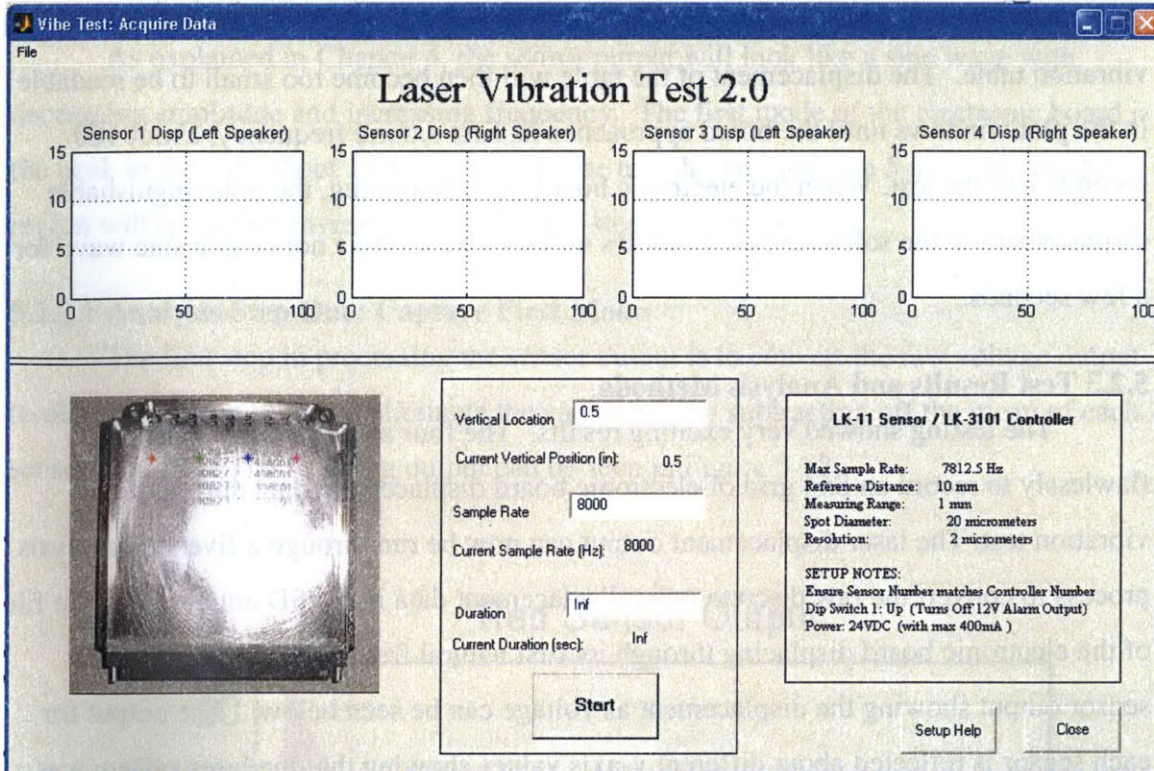
After the hardware is setup, the sensors can be configured. Connect all of the wires as shown in Figure 5-7. Ensure the keys in the LK-3101 controller are turned to the OFF position and that the sensor extension cables connect the LK-3101 boxes to the corresponding sensor head before the power supply is turned on; failure to do so can ruin the sensor heads. After the power is on, the lasers can be configured for the vibration test by setting the sample rate to 7812.5 Hz for a 128 $\mu$ s sampling cycle. Ensure the mode is set to NORMAL and the DIP switches are set to the following: *Alarm* is on HOLD, *Key Protect* is on FREE, *Response* is on HIGH. Now the laser sensors can be activated by turning the key to the ON position. Hold down the *Zero/Reset* button for about 5 seconds to ensure the sensor output is not being zeroed.<sup>6</sup> Step by step directions for testing can be found in the Hardware manual.

With the lasers on, the laser measuring point locations can be found using the DRO. Position the sensors so the lasers are pointing to the top of the electronic board and then move the DRO down flush with the bracket. If the DRO is zeroed at a known point, when the discrete positioning is set to the first test position, the DRO will measure how far the sensors are vertically from the top of the electronics board.

Position the sensor 1cm from the face of the electronic board by adjusting the vise clamping locations. The lights on the back of the sensors should be a solid green or orange in color. If they are flashing orange, they are either out of range or stuck between the green and orange range which causes the sensors measurements to provide false readings. On the laptop, open MATLAB and type *AcquireData* in the prompt to open *Laser Vibration Test 2.0*. The Sample Rate should be set to 7692.3077 Hz and the Duration should be set to *inf*. See Figure 5-10 for software snapshot.

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<sup>6</sup> Zeroing the sensors, drastically reduces sensor's measurement resolution.



**Figure 5-10 Laser Vibration Test 2.0: AcquireData.m**

When the *Start* button is pressed the sensor output will be displayed as Volts in the plot windows at the top of the program screen. Ensure the sensors are centered about 0 Volts as best as possible. Exact centering of output is unnecessary because the signal bias will be removed during data processing steps taken later in the analysis section. Each test acquisition run must be saved before subsequent tests are recorded.

### 5.2.2.1 Vibration Table Configuration

For both tests that were run, the vibration table performed a 20-2000Hz sine sweep profile at a constant 1-G at a speed of 2 oct/min. The abort G limit on the table was set to 100-G's allowing the board to pass through its first natural frequency without tripping the abort. The accelerometer data was saved after each run for comparison with the Laser Vibration System output.

### 5.2.2.2 Expected Software Output

When the test starts, the program plot windows will show evidence of the vibration table's sinusoidal movement, starting with large amplitude and then gradually



decreasing. At low frequencies the board is acting as a rigid body and displacing with the vibration table. The displacement of the table will then become too small to be readable in the plot windows until the board approaches its first natural frequency, about 160 seconds into the test. When the electronic board starts humming, the indistinguishable displacement in the software plot windows will turn back into a noticeable sine wave for a few seconds.

### 5.2.3 Test Results and Analysis Methods

The testing showed very exciting results. The four sensor system worked flawlessly to record an 8x4 grid of electronic board displacement data during the vibration test. The laser displacement output can now be run through a five step analysis process to convert the raw discrete point displacement data into a 3D animated movie file of the electronic board displacing through its first natural frequency. The typical raw sensor output showing the displacement as voltage can be seen below. The output for each sensor is reflected about different y-axis values showing that the laser system was not exactly planar with the electronic board. This is not an issue since the bias can be easily subtracted out.

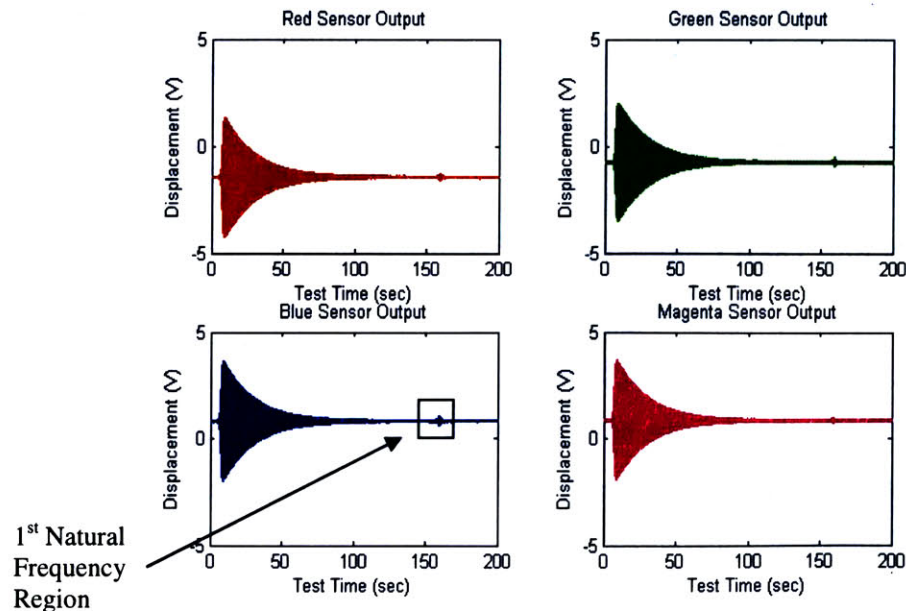


Figure 5-11 Typical Vibration Sensor Output

As explained in Chapter 4, the sensor output will look like a sine wave with decreasing amplitude and increasing frequency. The first mode of the electronic board is the peak in the data about 160 seconds into the test shown in Figure 5-11. This modal region will be further investigated in the five step analysis process.

### 5.2.3.1 Analysis Step One: Capture First Mode

The first step in processing the sensor output is to convert the raw voltage output to displacement in mils and eliminate the signal bias by subtracting off the mean of each sensor's output. The resulting output can be seen in Figure 5-12.

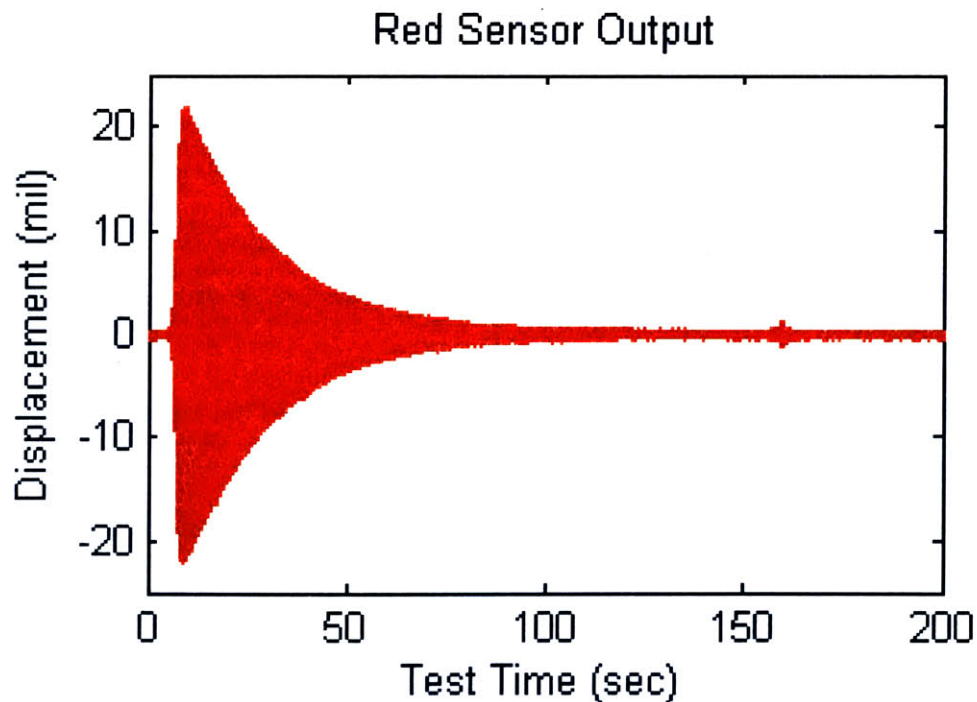
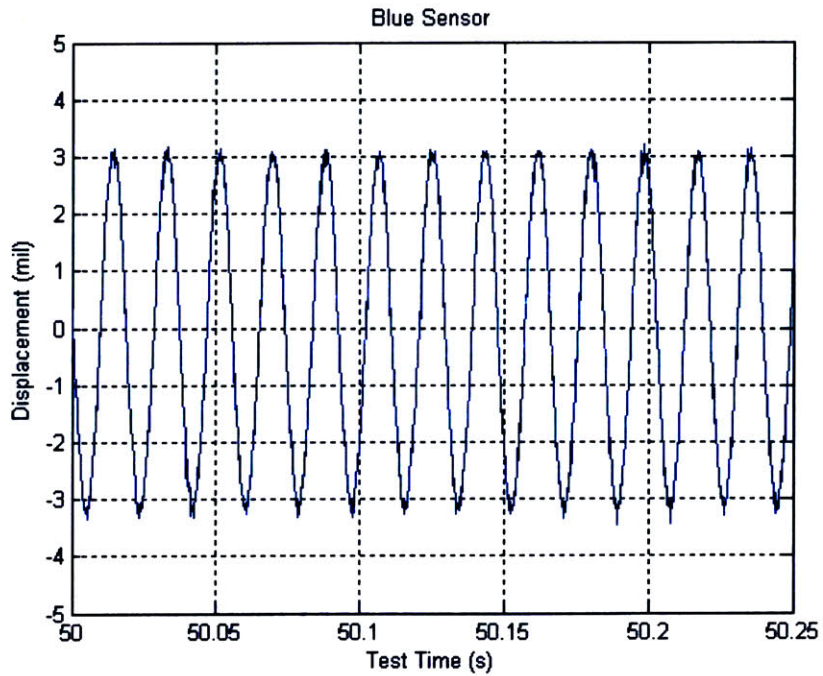
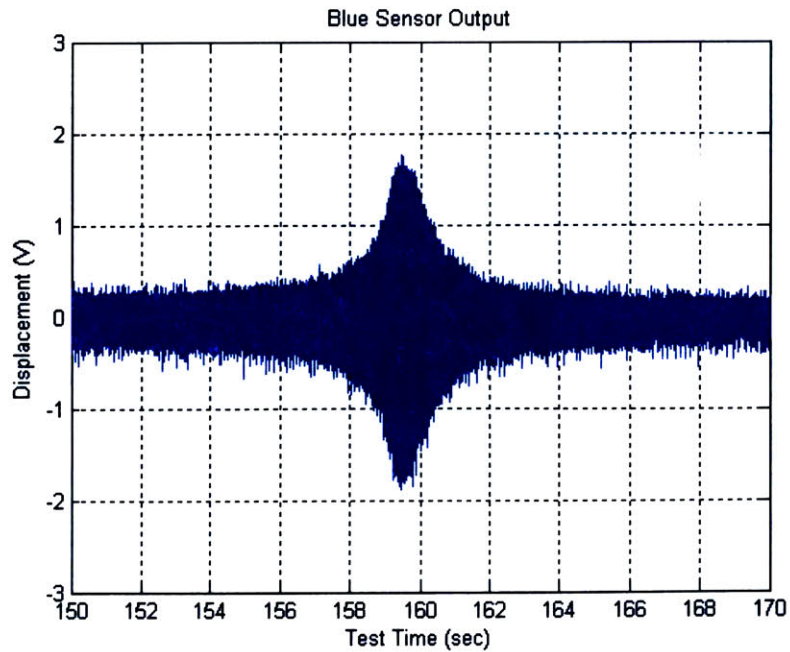


Figure 5-12 Typical Unbiased Displacement vs Time Sensor Output



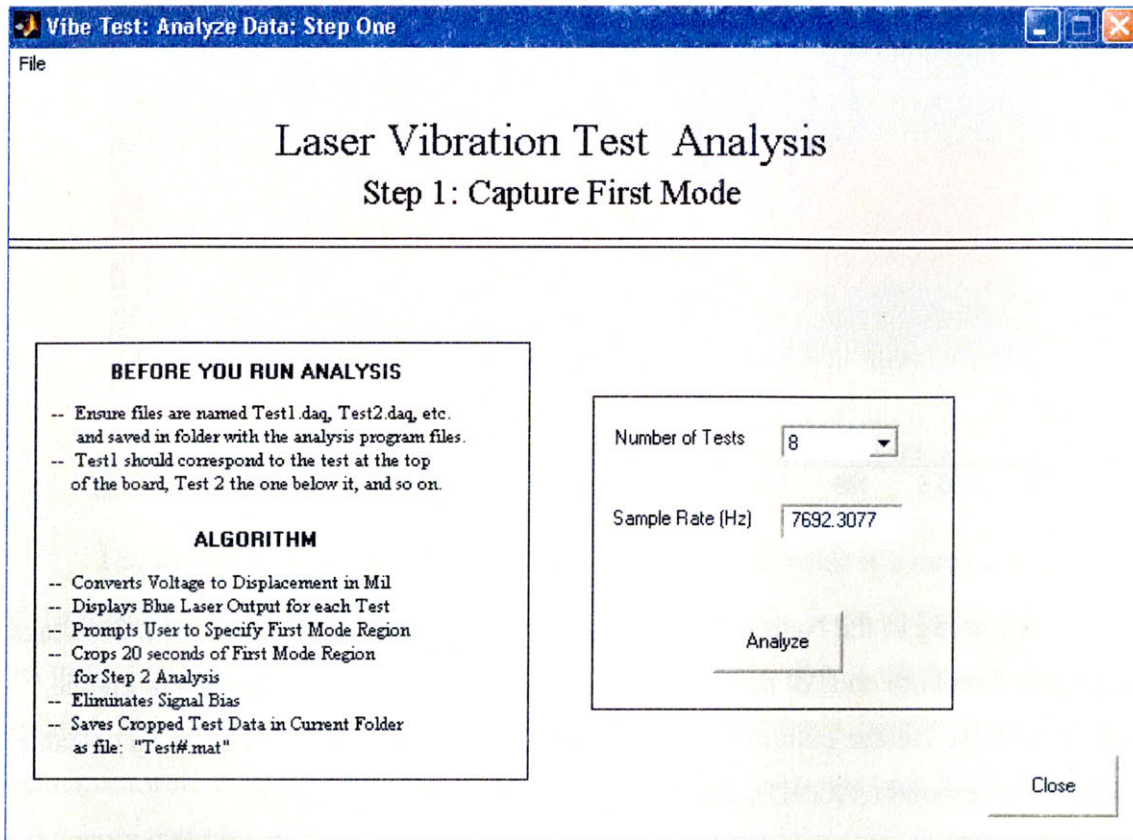
**Figure 5-13 Typical Sensor Output Zoomed In**

Now the first mode region can be cropped. The peak occurs over a 10 second period so a 20 second region is captured to ensure all important information is retained.



**Figure 5-14 First Mode Region**

The previous analysis steps are all accomplished with the *AnalyzeData1.m* MATLAB GUI. To see more specific instructions or to walk through the analysis software with actual vibration test files, see the Software Manual and the Vibration Test CD in the appendix.

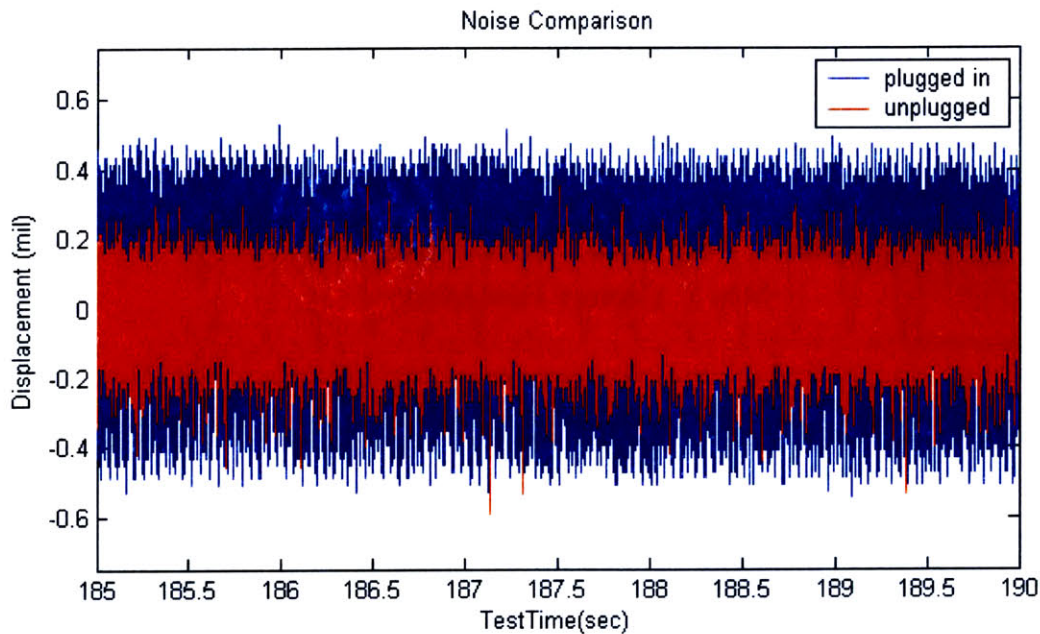


**Figure 5-15 Step One Analysis GUI: Capture First Mode**

### 5.2.3.2 Analysis Step Two: De-noise Data

Noise has been an issue for these displacement sensors in the vibration test environment. During testing different grounding methods were tried and the sensors were even run off of a car battery and generator trying to eliminate noise. While these methods failed to produce noticeable results, the noise was cut in half by simply unplugging the laptop during testing. The laptop power supply cord plugs in right next to the National Instrument DAQ-1200 card and doubles the sensor noise. The comparison

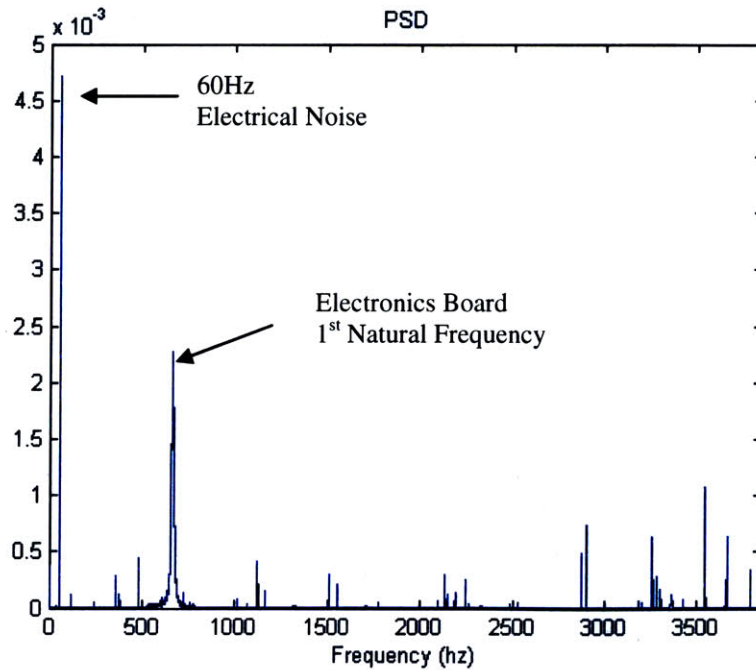
of noise bands for the laptop plugged in versus running it off its battery can be seen below. The noise band is cut from  $\pm 0.4$  mil to  $\pm 0.2$  mil.



According to the National Instruments online support page, when the DC voltage is compared on both ends of the laptop power supply with respect to a solid reference, there is a 60 Hz voltage pattern with a high peak-to-peak voltage that causes an unstable analog input ground (AIGND), and therefore produces a noisy signal.

The LK-11 sensor specifications report that the sensor should have an output resolution of 0.007 mil. It can be seen that even the noise band with the laptop running off of its battery is greatly reducing the measuring resolution lower boundary. Displacements below 0.2 mils are lost in the noise band and cannot be seen.

The noise is masking the first mode region so before the frequency content of the data can be found; a de-noising technique had to be devised. An FFT was run on the 20 second first mode region to quickly identify the frequency components within the data so filtering methods could be developed.

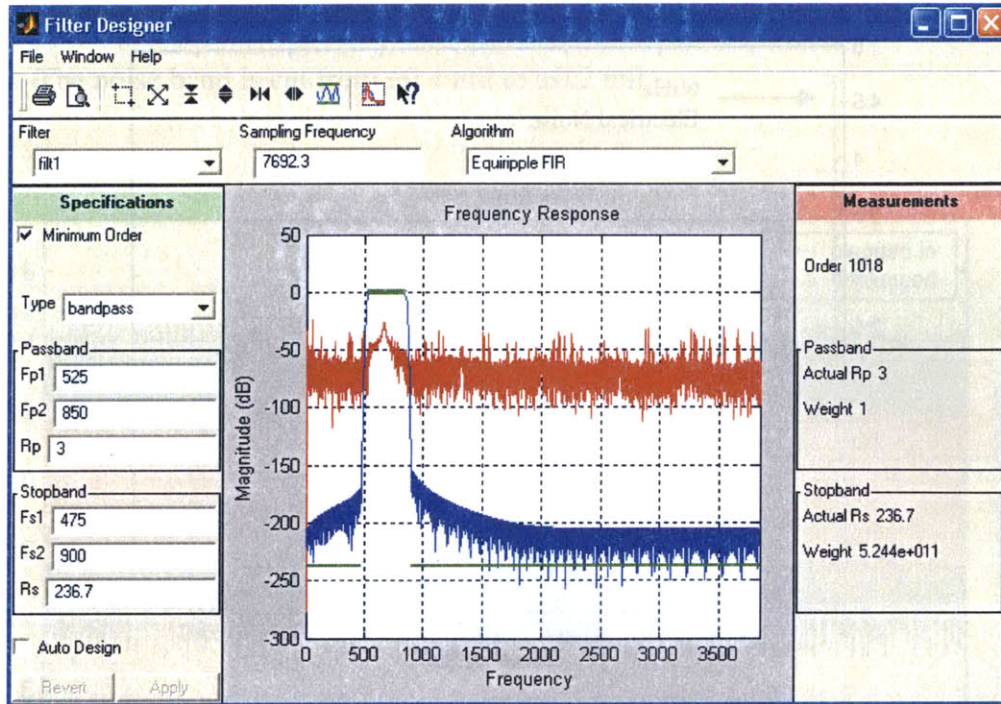


**Figure 5-16 First Mode Region Power Spectral Density Plot: FFT**

The largest peak occurs at 60 Hz indicating electrical noise is a large component of the overall signal noise. The second highest peak is a wider band showing the electronics board passing through its first natural frequency – this is what needs to be isolated. The other substantial peaks occur in the higher frequency ranges. Two techniques were used to isolate the first natural frequency peak: a simple band pass filter and a more complex wavelet de-noising method.

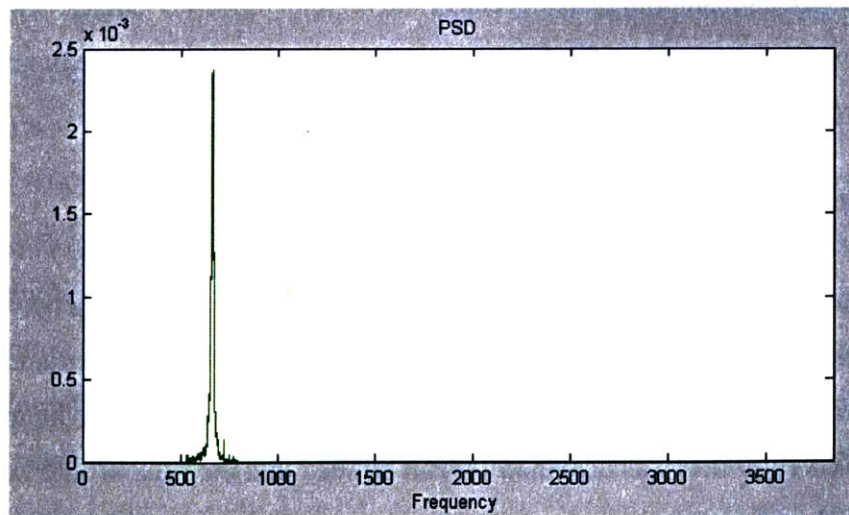
#### **5.2.3.1.1 Band Pass Filter**

A band pass filter was designed to capture the first mode frequency components and discard the noise components. A band pass filter keeping everything between 525Hz and 850 Hz was built. See figure on next page for filter algorithm and parameters. The red shows the FFT of the 20 seconds of first mode data captured by a sensor and the blue is the band pass filter that was designed. It can be seen that the filter would keep only the first mode peak and hopefully discard the noise.



**Figure 5-17 Bandpass Filter Design**

An FFT of the filtered data shows that only the first mode peak was kept; the filter was successful.



**Figure 5-18 PSD of Filtered Sensor Data**

The original data compared with the filtered time data shows that the filter caused a slight delay and ripple effects in the data.

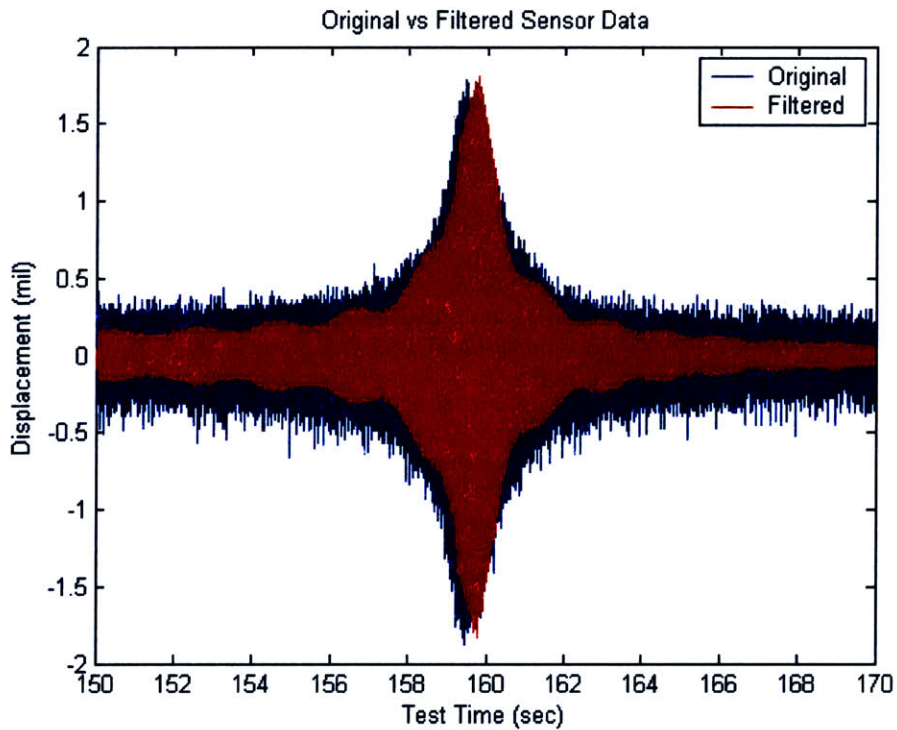
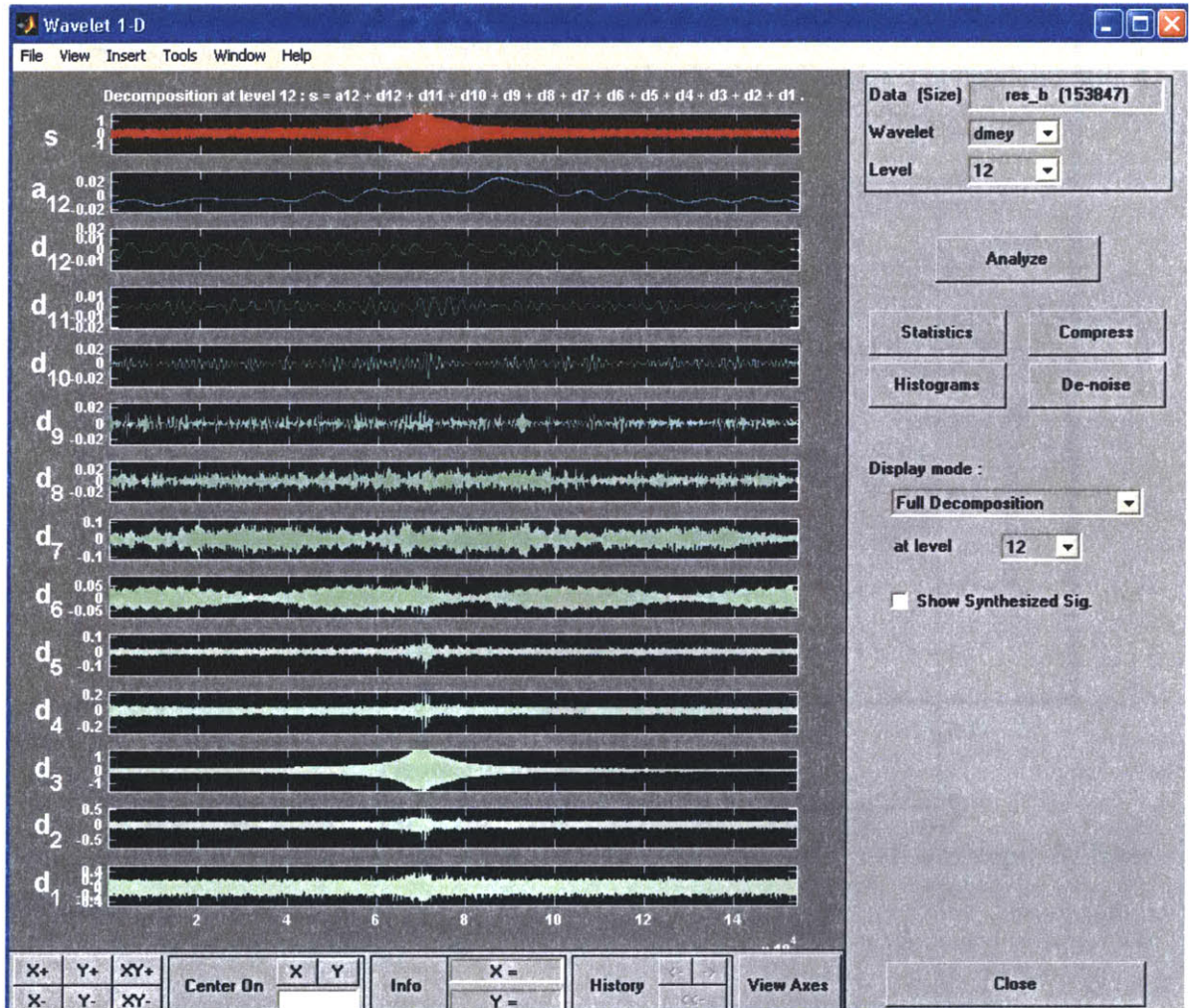


Figure 5-19 Original vs Filtered Sensor Data

### 5.2.3.1.2 Wavelet De-Noising

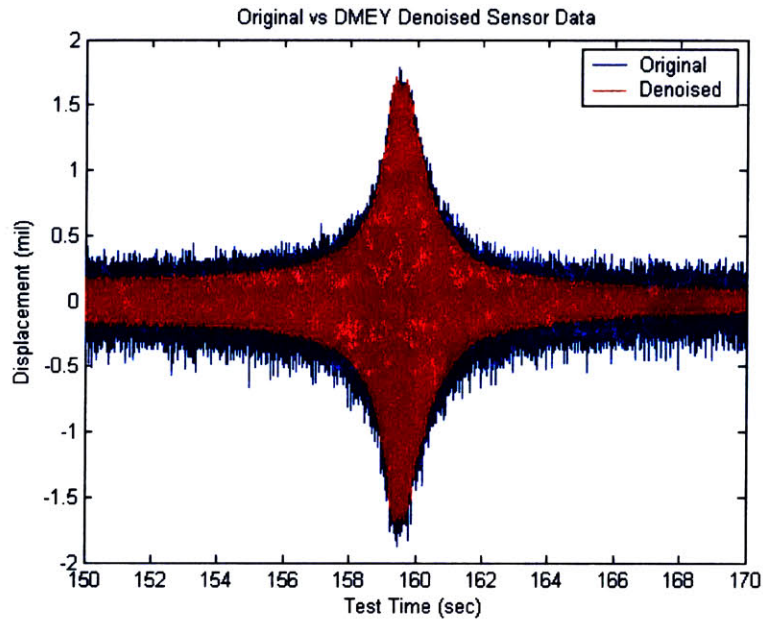
The second method for de-noising involves splitting the displacement signal into levels using a wavelet and removing those levels that contain noise components in them. The Wavelet 1-D GUI in MATLAB was used to graphically explore how the different wavelets broke up the displacement data into levels. The *dmey* was the only wavelet that captured the first mode sinusoidal displacement in one level and the noise components in the other levels. The *dmey* wavelet is a discrete approximation of a Meyer wavelet. Because this wavelet separated the noise components from the sinusoidal displacements of the resonating board, the *dmey* wavelet was chosen. To view a typical *dmey* wavelet decomposition of the first mode region, see Figure 5-20.





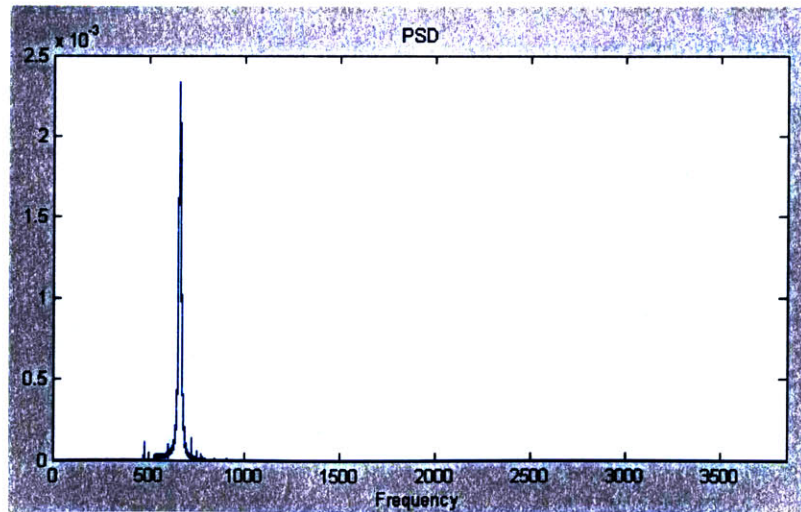
**Figure 5-20 DMEY Wavelet Decomposition of Modal Region**

All of the details coefficients for the 12 levels were discarded except for  $d_3$  since this level captured the true modal displacements. The signal was then reconstructed with level 3 detail coefficients to output the de-noised data.



**Figure 5-21 Original vs De-Noised Sensor Data**

The dmeY wavelet de-noising techniques look like they have de-noised the first mode region quite well. There is no delay or rippling effects like the filtered data. To ensure that all of the noise components of the PSD were eliminated and that the modal region was kept, a FFT was run on the de-noised data. See figure below.



**Figure 5-22 PSD of De-Noised Data**

The FFT shows that the wavelet de-noising method was also successful in eliminating the noise components and retaining the first mode.

### 5.2.3.1.3 Method Comparison: Filtering vs. Wavelet De-Noising

The plot below shows the original sensor output, filtered results, and de-noised results.

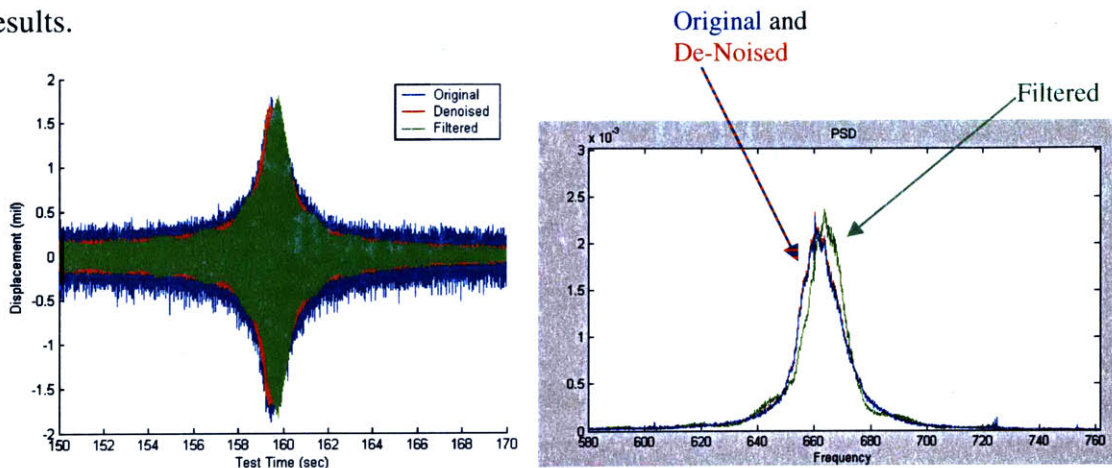


Figure 5-23 Original, Filtered, and De-Noised Comparison

The wavelet de-noising results used a more complex method to eliminate noise and proved to produce better results. Since the method was chosen by visually inspecting different wavelets and choosing the one that captured the mode the best without real knowledge of wavelet techniques, it is interesting to see that the de-noising method provided a smoother and more accurate representation of the original modal displacements peak. The DMEY wavelet de-noising method was chosen for the process used in step two of the analysis software.

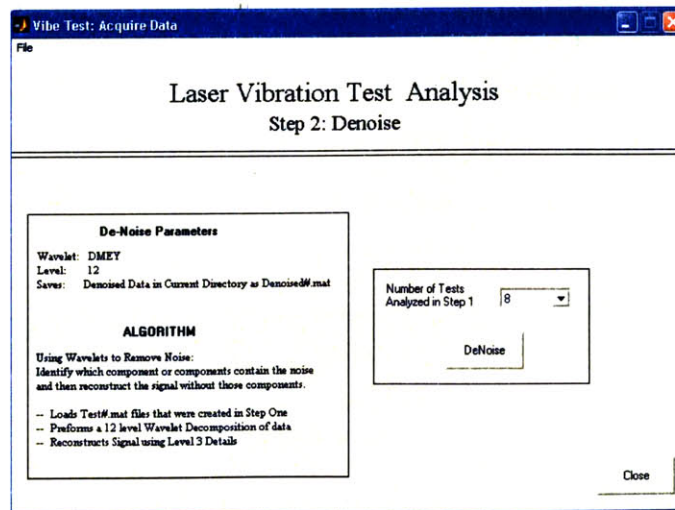


Figure 5-24 Step Two Analysis GUI: De-noise

### 5.2.3.3 Analysis Step Three: Find Frequencies

To accurately represent the displacement of the electronics board during its first mode, it is necessary to pick the amplitude and frequency content out of the time data instead of relying on the vibration table sweep rate of 2 oct/min. To accomplish this, an algorithm was written that determined the zero crossings of the sinusoidal displacement data, and averaged the frequency output over a specified number of periods to smooth the data and found the max positive displacement within each set of averaged cycles.

#### 5.2.3.3.1 Zero Crossing Algorithm

The zero crossing algorithm uses a simple relationship to quickly process the data and identify the zero crossings (ZC's).

##### MATLAB Code:

```
y=denoised_data;  
ZC_indice=find((([0 y] < 0) & ([y 0] > 0) | ([0 y] > 0) & ([y 0] < 0)));
```

The above code finds where there is a sign change between the current displacement value and the subsequent displacement value. The results of this algorithm on the sensor output can be viewed in Figure 5-25.

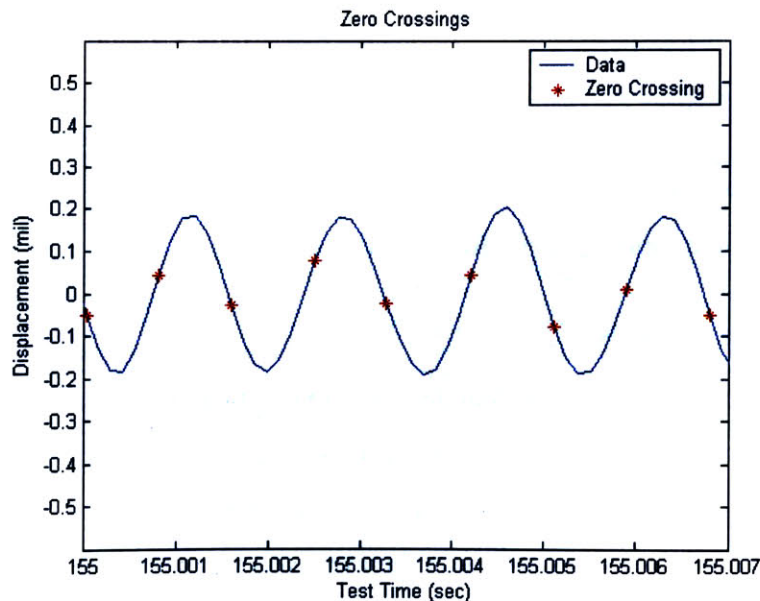


Figure 5-25 Zero Crossing Algorithm Results

### 5.2.3.3.2 Interpolation and Averaging

The *zero crossing* algorithm can detect points closer to the zero axis if the data is interpolated. Since the time between zero crossings will be used to indicate half-cycle time for the frequency calculation, it is important that they are as accurate as possible. For example, interpolating the data with a scale of two would double the data's sample rate and thus double the number of data points describing the output. The more times, the data is interpolated, the better the results from the *zero crossing* algorithm. The algorithm results after linearly interpolating the data with a sampling rate 15 times smaller than the original data's sample rate, can be viewed in Figure 5-26.

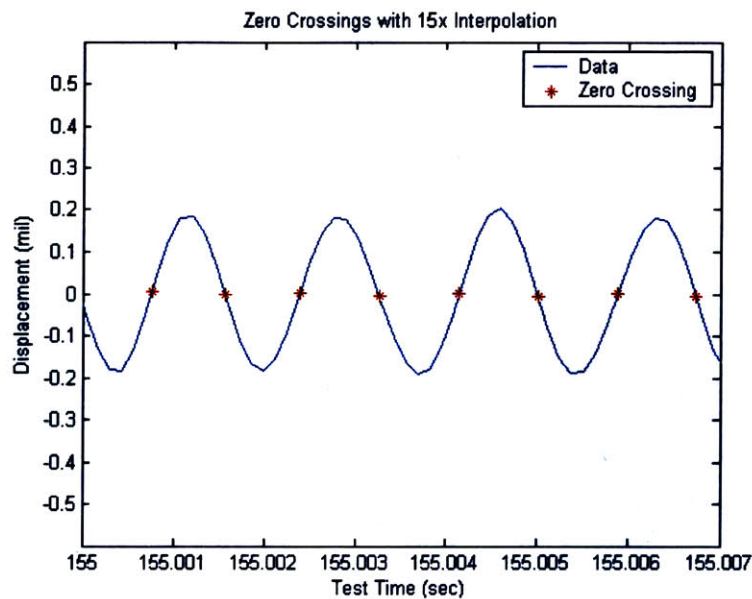
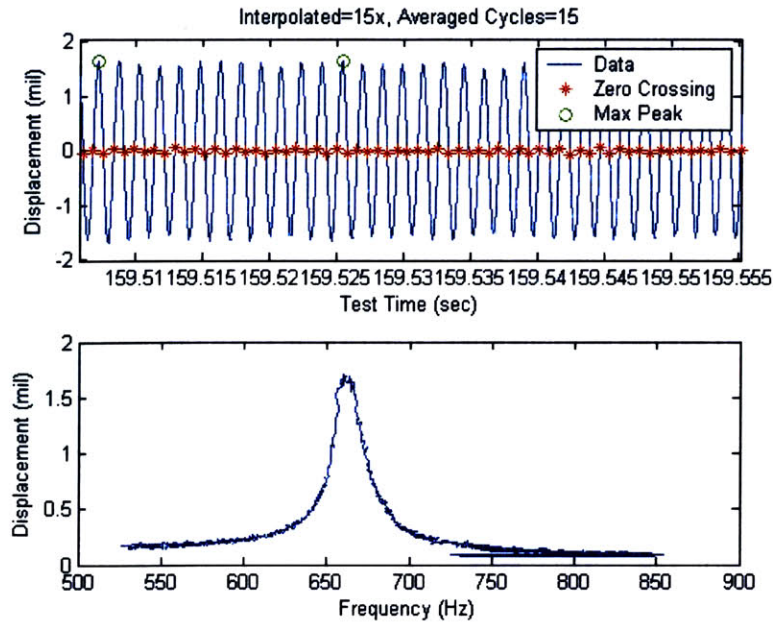


Figure 5-26 Zero Crossings with Linear Interpolation of Data

It can be seen that the zero crossings are now identifying points closer to zero which will result in a more accurate frequency calculation.

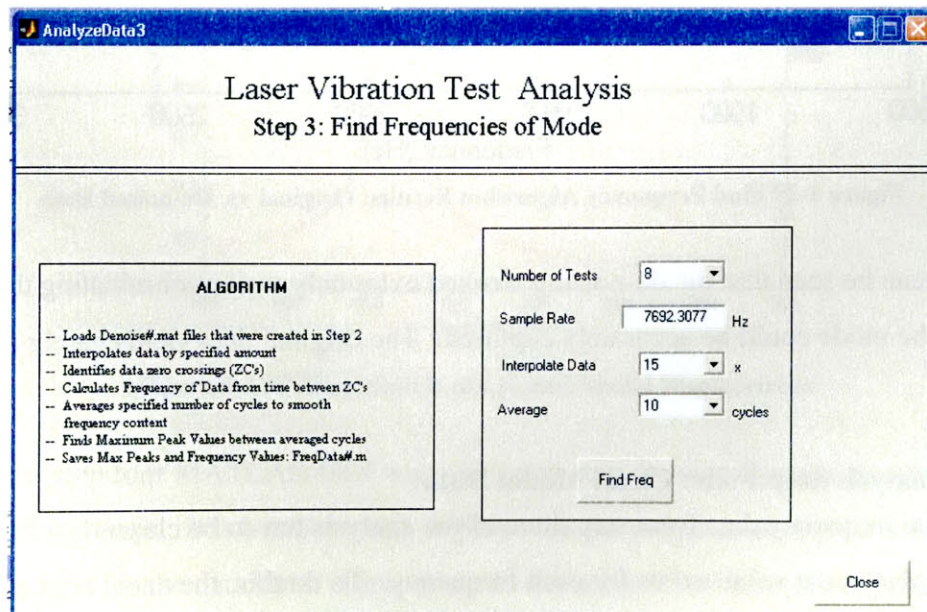
### 5.2.3.3.3 Find Frequencies

After the data has been interpolated, the time between zero crossings is used to calculate frequency. The more cycle times that are averaged, the smoother the frequency output but the less data points there will be describing the first mode. The maximum positive displacement is saved along with the averaged frequency value for each set of cycles. The *find frequency* algorithm results are shown in Figure 5-27 on the next page.



**Figure 5-27 Find Frequency Algorithm Results**

The *zero crossing* and *find frequency* algorithms are used in the *Step Three: Find Frequencies of Mode* GUI. The program allows the user to change the interpolation scale and the number of cycles that will be averaged. The output is a file containing the frequency and displacement values for each sensor.



**Figure 5-28 Step Three Analysis GUI: Find Frequencies of Mode**

#### 5.2.3.3.4 Find Frequency Results: Original vs. De-noised

Now that a find frequency function exists to determine the frequencies of the sensor's output, a step back is going to be taken to look at how well the algorithm worked on the de-noised data (output from Step Two) versus the original data (output from Step One). This will help evaluate the importance of de-noising the data. See the plot below.

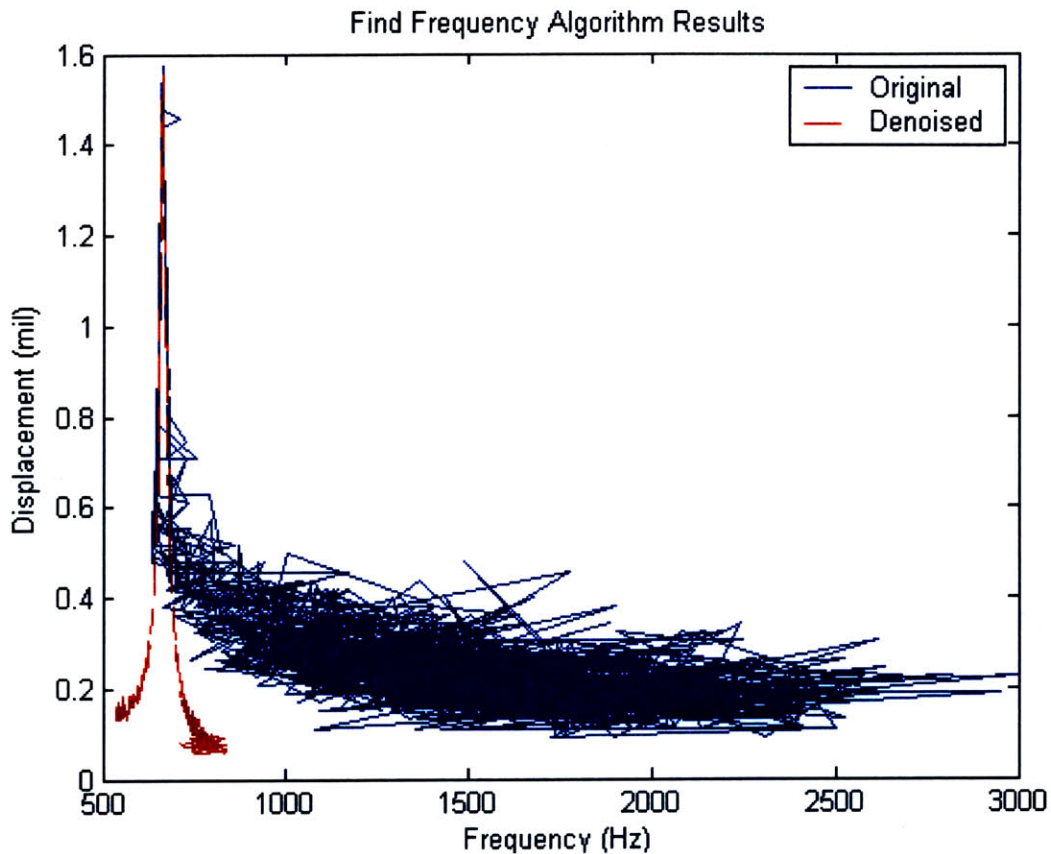


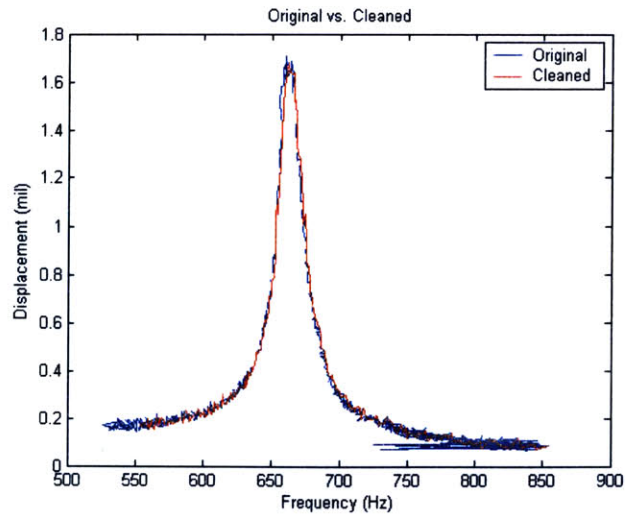
Figure 5-29 Find Frequency Algorithm Results: Original vs. De-noised Data

It can be seen that the de-noising worked extremely well in eliminating the 60 Hz noise so the mode could be accurately captured. The original data yields barely readable results.

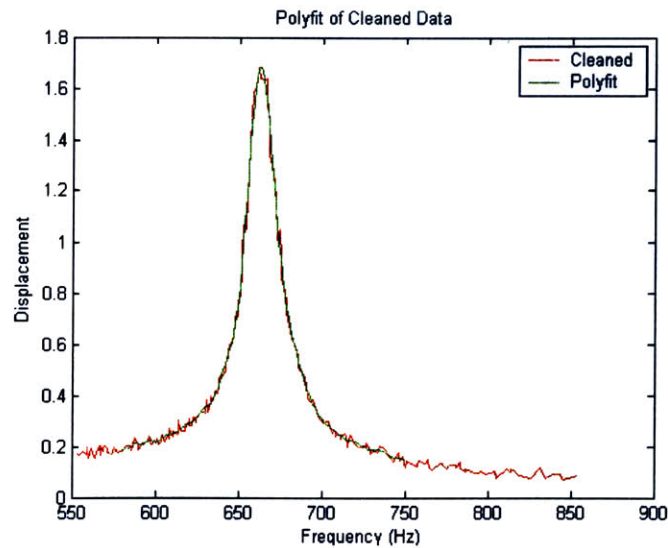
#### 5.2.3.4 Analysis Step Four: Clean Modal Data

The frequency data from step three of the analysis has to be cleaned so that a single displacement value exists for each frequency. To do this, the data is run through a *clean mode* algorithm that deletes redundant frequency values so the remaining displacement data is a valid function. Then the data is fit with a polynomial function

where discrete frequency and displacement data can then be found. See below to view the results of cleaning and polyfitting the data.



**Figure 5-30 Original vs. Cleaned Modal Displacement**



**Figure 5-31 Polynomial Fit of Cleaned Modal Displacement**

The step four MATLAB GUI was written to step the user through the cleaning and polyfitting steps. It is a tedious task to play with the polynomial degree and range to find the best fit for the data but it is important to the accuracy of determining the first mode of the board. The user visually determines the best range and degree for the fit. The GUI can be seen on the next page.



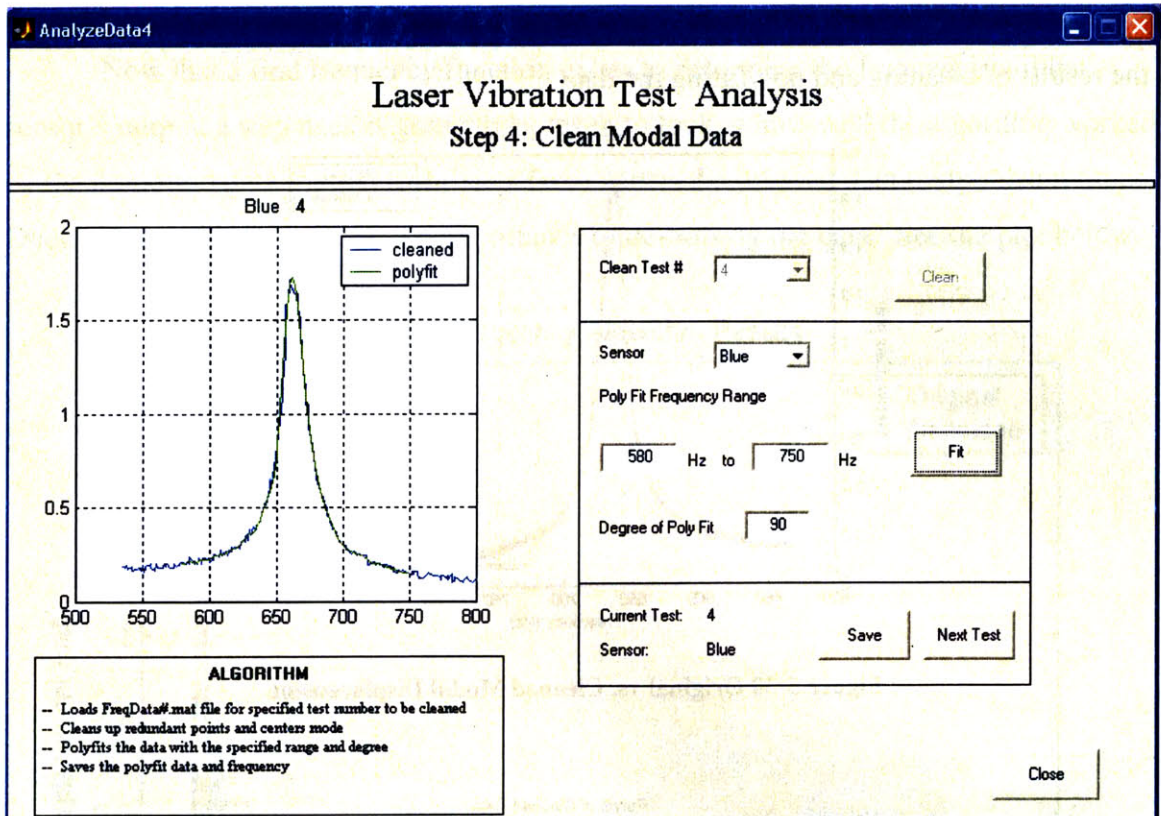
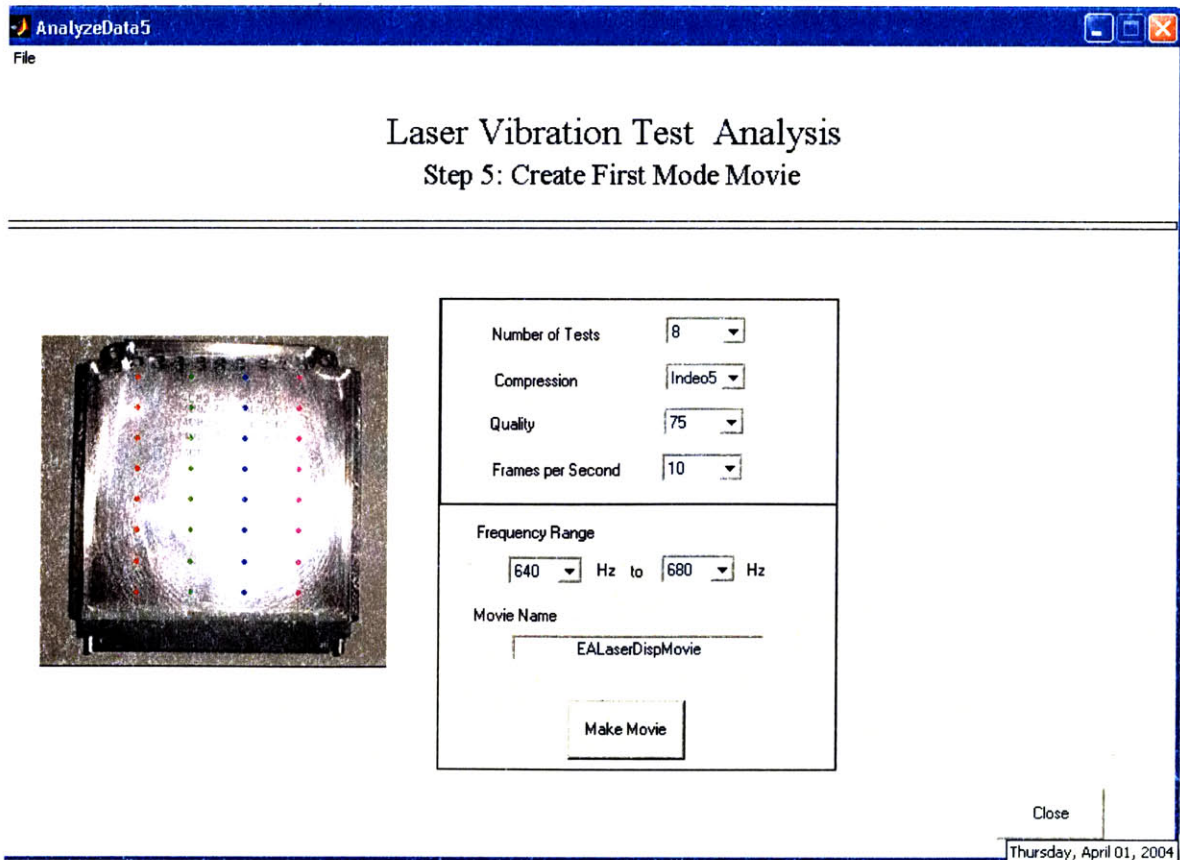


Figure 5-32 Step Four Analysis GUI: Clean Modal Data

### 5.2.3.5 Analysis Step Five: Create Movie

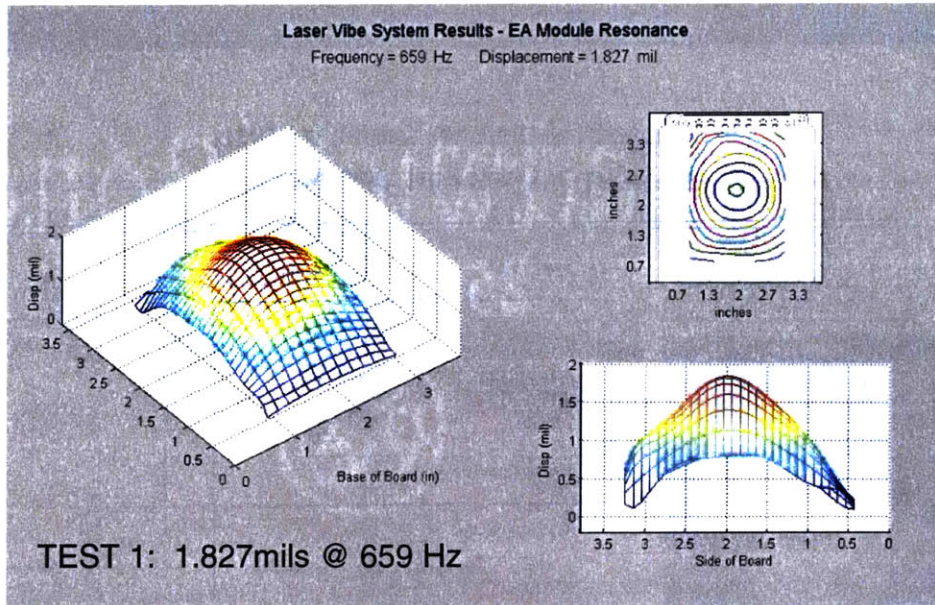
The final step in analyzing the sensor data is to subtract out the minute vibration table displacement and mesh the four sensor's displacement for all eight tests into an 8x4 matrix for each frequency value in the first mode range. These matrices of displacement data are polyfit (3<sup>rd</sup> order polynomial horizontally and 7<sup>th</sup> order polynomial vertically) for a finer resolution of displacement points. The displacement matrices are then used to create a movie file where each frame corresponds to its associated frequency value. The sensor coordinate locations are used to give an accurate depiction of the electronic board displacing. To accomplish all of this, the *Step Five: Create First Mode Movie* GUI was written.



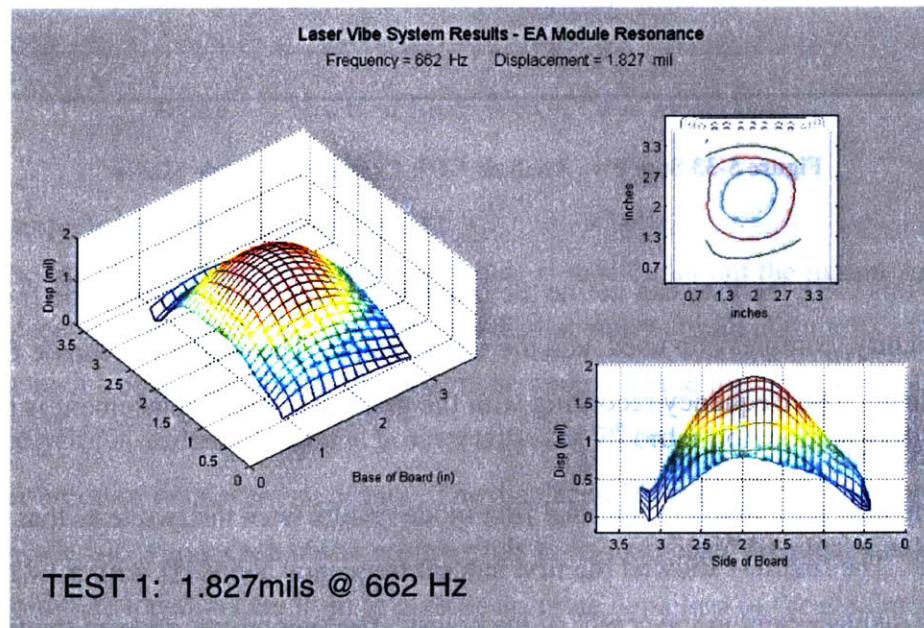
**Figure 5-33 Step Five Analysis GUI: Create First Mode Movie**

In this GUI, the user can define the frequency range for the movie, the frames per second, quality, compression used, and the movie name. The output is a movie file in *.avi* format. The frequency recording with the greatest board displacement is the first natural frequency.

The next page displays the final first mode results from the two tests that were performed. The first test showed the first natural frequency at 659Hz with a 1.827mil maximum displacement in the center of the board. The second test showed the first natural frequency at 662 Hz with 1.827mil displacement in the center of the board. This output proves that the system will provide repeatable results.

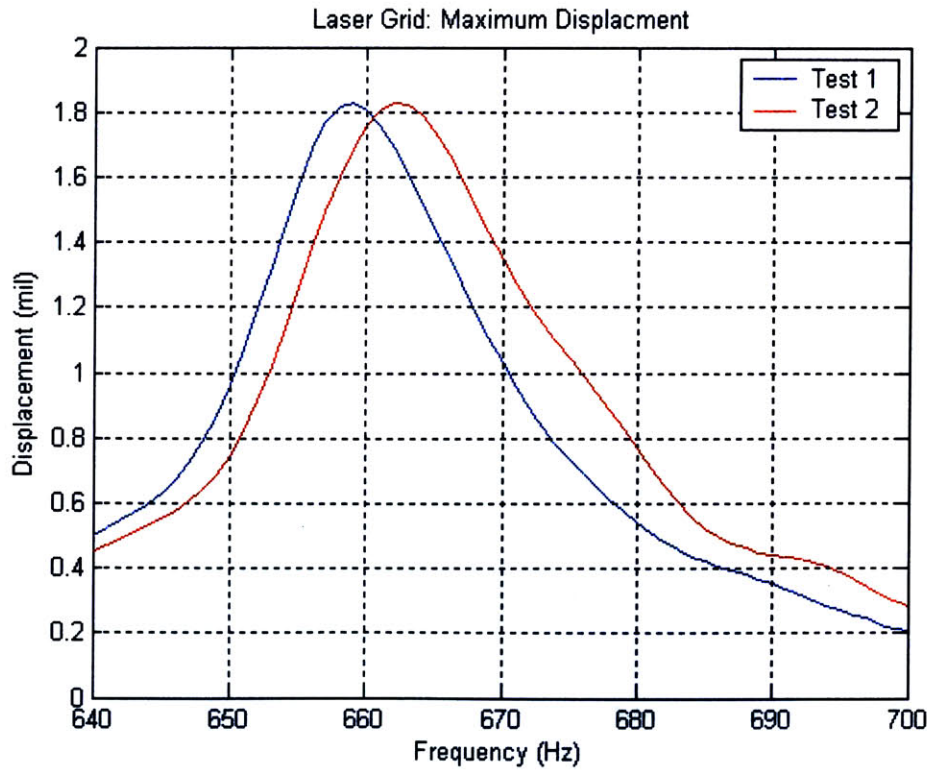


**Figure 5-34 Test One First Mode Results**



**Figure 5-35 Test Two First Mode Results**

The maximum displacement for each frequency over the first mode range can be seen in Figure 5-36.



**Figure 5-36 Laser Grid Results: Maximum Displacement**

The only difference between the tests that should be noted is the labeling dot as seen in Figure 3-3 was left on from the area scaling tests during Laser Test 1 but it was removed for Laser Test 2. A discussion of these results and how they compare with accelerometer testing will be explored in the next chapter.

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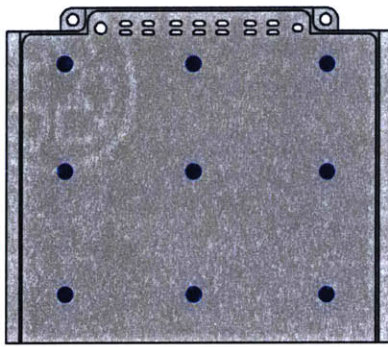
## **Chapter 6 System Performance**

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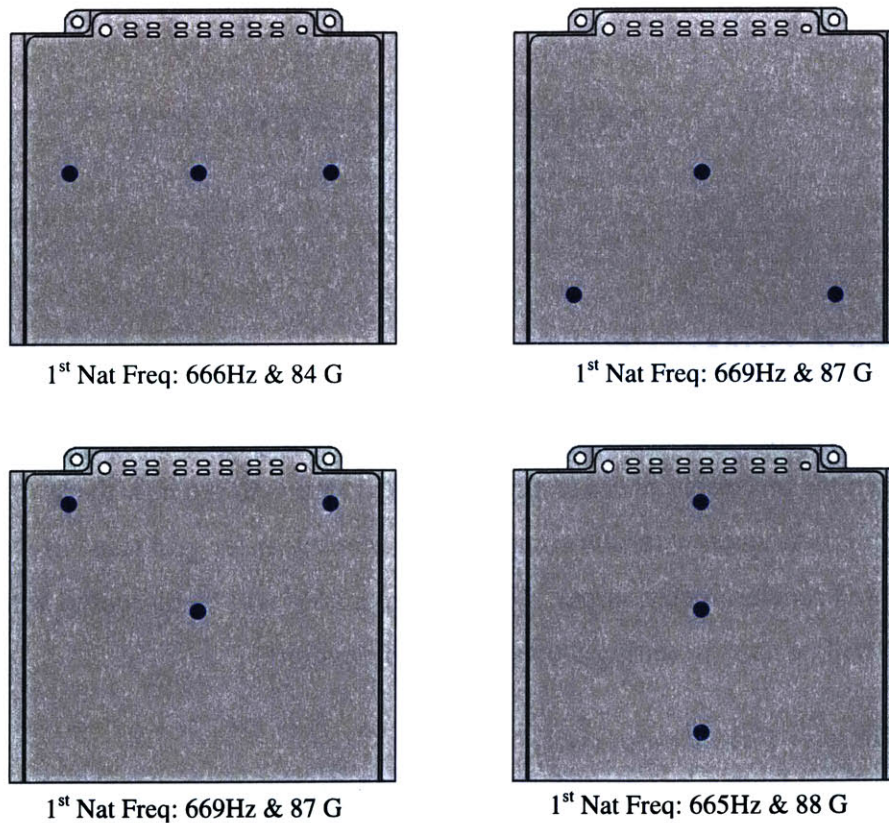
The laser vibration measurement and analysis system showed repeatable results for the bare frame electronic board testing. The next step is to see how these displacement and frequency results compare with accelerometer grid tests, as well as, the center mounted accelerometer output. These comparisons will be discussed within this chapter and will be used in setting the system specifications.

### **6.1 Accelerometer Grid Comparison**

The output from a 3x3 grid of accelerometers for the same electronic board used in the laser tests and tested under the same vibration profile will be used to judge the accuracy of the laser system. In order to reduce the mass loading effects, pico-sized accelerometers made by Endevco were used; each is 0.14 grams in mass. Four tests were performed using 3 accelerometers for each test. One accelerometer was kept in the center of the board as a control. The other two were moved around the board creating a 3x3 grid. See the figures on the next page for the accelerometer locations and results.



**Figure 6-1 Overall Accelerometer Grid Locations on Electronic Board**

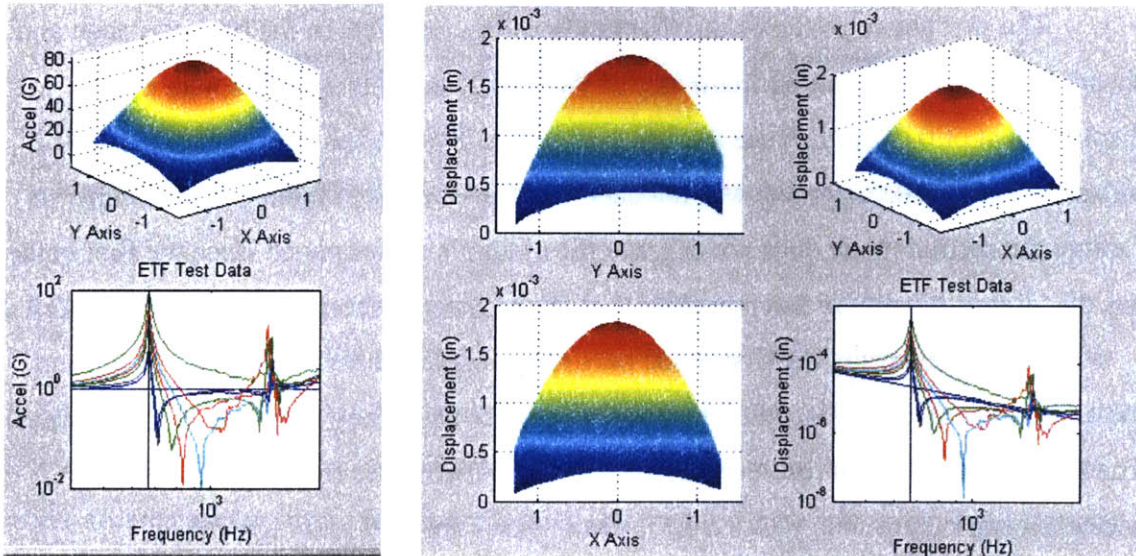


**Figure 6-2 Individual Accel Grid Location and 1<sup>st</sup> Natural Frequencies**

During the four tests that were run, the center accelerometer experienced the maximum acceleration during all tests. Unlike the test that prompted the topic for this thesis, there was only a maximum 4 Hz shift in the natural frequency and a 4 G difference

in response amplitude. This illustrates that even using the 0.14g accelerometers on the board, will result in a slight output difference from test to test and needs to be kept in mind when comparing the laser results. While the accelerometer output is being used as the real electronic board output, in actuality, the lasers could be capturing the real output and the accelerometers could be giving output with slight mass loading effects [14].

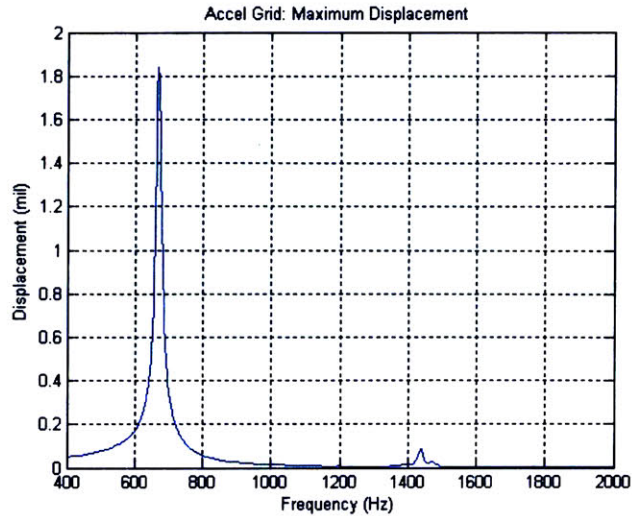
The accelerometer data used the 3x3 accelerometer output to create a meshed board response. The center control accelerometer was averaged for all four tests worth of data. Then the meshed output was fit with a second order polynomial in both the vertical and horizontal directions to display the 3-D acceleration and displacement of the board. The first natural frequency occurred at 668Hz with a response amplitude or 83.9 G's. This correlates to a maximum first mode displacement of 1.84 mil at 668 Hz.



**Figure 6-3 Accel Grid 3-D Output: Acceleration and Displacement at First Natural Frequency**

Unlike the Laser Vibration System, the accelerometer data can display the displacement for the entire 20-2000Hz test, not just areas where the displacement is over the noise band. The maximum displacement of the board during the entire test is shown in Figure 6-4.





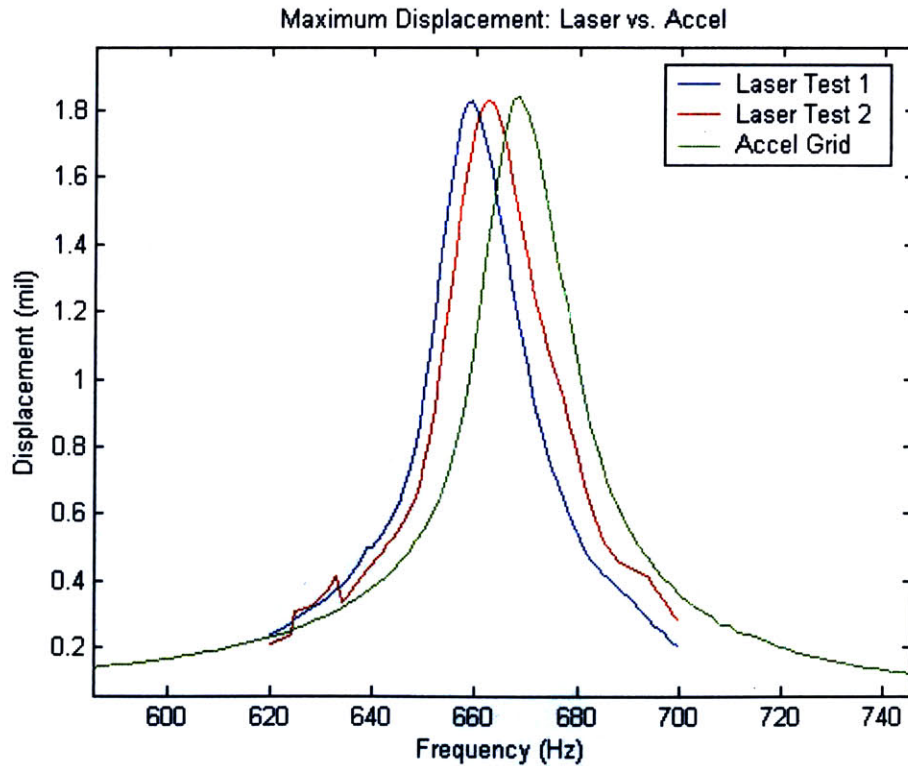
**Figure 6-4 Accel Grid: Maximum Displacement of Electronic Board During Sine Sweep**

The plot above confirms the first mode values reported on the previous page and shows that the second natural frequency of the board occurs at 1438 Hz with a displacement of 0.087mil. Since the Laser Vibration System has a noise band up to 0.2 mils, the board’s second mode was not captured with the laser system. The inability to capture the second mode does not degrade the system’s performance since the first mode has the largest magnitude and therefore is of the greatest concern during a vibration test.

When comparing the first mode maximum displacements for the laser tests and the accelerometer grid test, other than the slight peak shift, they match up extremely well. The largest difference in results is the 10 Hz shift between the first laser test and the accelerometer output; this yields a 1.5% error. See Table 6-1 and Figure 6-5.

	<b>1st Nat. Freq.</b> Hz - (% Error)	<b>Displacement</b> Mil - (% Error)
<b>Accelerometer Grid</b>	668	1.84
<b>Laser Test 1</b>	<b>658 - (1.5%)</b>	<b>1.83 - (0.7%)</b>
<b>Laser Test 2</b>	<b>662 - (0.9%)</b>	<b>1.83 - (0.7%)</b>

**Table 6-1 First Natural Frequency Comparison: Accelerometer versus Laser**



**Figure 6-5 First Mode Max Displacement Comparison: Laser versus Accelerometer Output**

## 6.2 Center Accelerometer Comparison

The first mode of the electronic board, as seen in Figure 6-3, is where the center of the board has the greatest displacement. During each laser vibration test, a test control accelerometer captured the board’s response close to this center location. The average center accelerometer output for all eight laser test position runs versus the 8x4 laser grid results can be seen below.<sup>7</sup>

	Laser Test 1		Laser Test 2	
	Nat. Freq Hz	Disp mil	Nat. Freq Hz	Disp mil
<b>Center Accel</b>	659	1.77	664	1.82
<b>Laser</b>	658	1.83	662	1.83

**Table 6-2 Center Accelerometer vs. Laser Results**

<sup>7</sup> The laser test results approximate the board’s center displacement through fitting the 8x4 grid with polynomial functions. The laser did not actually record the center of the board except in sensor selection testing seen in Chapter 4.

### 6.3 Laser Versus Accelerometer Discussion

The center accelerometer output is closer to the natural frequency and dynamic response than the comparison between the accelerometer grid and laser grid results. This shows that the lasers are doing a better job at identifying the natural frequency of the board than the accelerometer grid results are illustrating. There is a possibility the accelerometer grid testing is changing the dynamics of the board through the addition of the two accelerometer's mass. Earlier in Figure 6-2, it was shown that three pico-sized accelerometers moved around on the face of the board caused the natural frequency at the center accelerometer to range between 665 Hz and 669Hz.

Intuitively, the addition of the accelerometers should lower the natural frequency since mass is being added to the board. This assumption is based on the equation below.

**Equation 6-1** 
$$\omega = \sqrt{\frac{k}{m}}$$

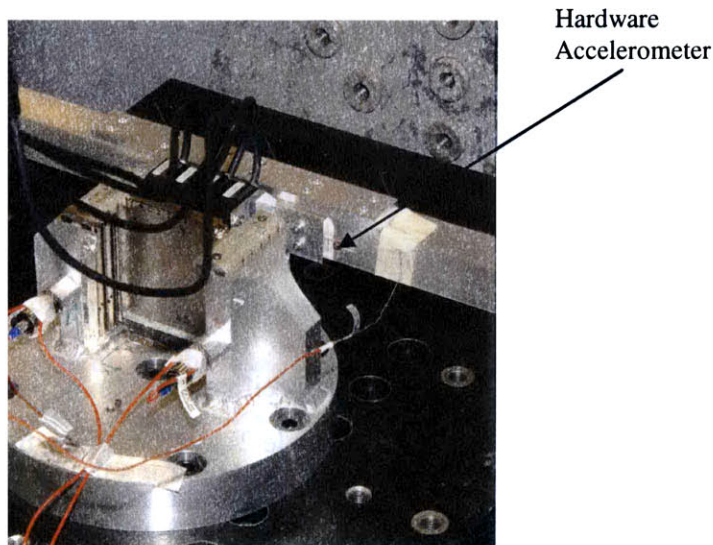
where  $\omega$  is the natural frequency,  $k$  is the spring constant, and  $m$  is the mass of the object.

Another more interesting relation between mass-loading and its effect on the natural frequency of a board was seen during an experimental study describing the effects of masses and their location on the natural frequencies of plates. It was found that the fundamental frequency increases as the mass moves away from the center of the plate [14]. This could explain why the natural frequency for the accelerometer grid testing is greater than the laser test results. Also, the 3 Hz difference among the laser testing can be explained by the removal of the labeling dot from the center of the board for the second laser test – reduction in mass would cause an increase in natural frequency. It is also possible this slight first mode variation is unrelated and is just the slight error in accelerometer output between tests.

### 6.4 Hardware Vibration

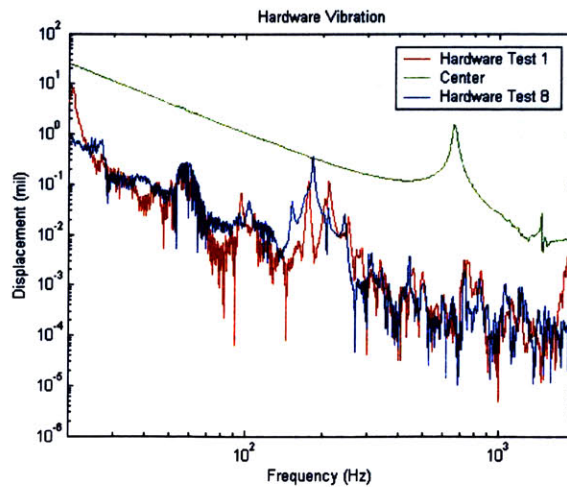
The hardware mounted accelerometer is located on the sensor cross bar next to the sensor heads. It is measuring the amount of vibration seen by the laser displacement sensors in the horizontal direction to ensure false displacements are not being recorded.

The prototype system with the one LK-11 attached saw displacements of concern at 200Hz while with the heavier LC-2440 sensor attached, the displacements were minimal. Along with the four sensors, weights were added to the top of the cross bar to help reduce the amplitude of the 200Hz peak. See figure below for accelerometer location on the final system.



**Figure 6-6 Hardware Accelerometer Location**

The hardware accelerometer output can be viewed below. The center accelerometer is also plotted to show the magnitude of board displacement seen by the lasers.



**Figure 6-7 Magnitude of Hardware Vibration**

At 200 Hz the hardware experiences a sizable resonance. Hardware Test 1 accelerometer output (positioned so sensors are capturing the top of the electronic board) has a peak at 200 Hz and 0.12 mil, while the hardware accelerometer output for Test 8 (sensors capturing the base of the board) has a displacement of 0.3 mil around 200 Hz. This difference exists because as the cross bar and sensors are moving down the vertical rails, there is a longer moment arm on the sensor fixturing system.

While the 200Hz peak is of concern for the system performance, since the hardware introduced negligible displacement levels in the first mode region, it is not a concern for the specific test completed in this thesis. However, for laser tests examining object responses in the 200Hz region, there should be hardware modification or a close watch of the hardware's displacement during testing.

### 6.5 System Specifications

Drawing on the results presented, system specifications can now be determined. The original ideal specification were defined in Table 2-3 to determine how well the system is performing compared with the desired performance set in the preliminary design stage.

<b>Metric</b>	<b>Imp</b>	<b>Units</b>	<b>Ideal</b>	<b>Final</b>
Sample Rate	5	Hz	10k	7.8k
Deflection of Object	5	mil	±4	± 39
Resolution	5	mil	0.05	0.008 mil
Cost	4	\$US	<25k	<25k
Full Field	4	in <sup>2</sup>	450 (12 in diam)	4 points
Time to Assemble and Disassemble	3	min.	30	30
Measurement Area	3	in <sup>2</sup>	See Full Field	4 discrete points horizontally with 1cm vertical resolution
Test Time	3	min.	3	30

**Table 6-3 System Specifications: Preliminary versus Final**

Overall, the system outperforms the ideal specifications. The system's final specifications prove it to be a versatile system that can be used for a wide range of vibration tests. The  $\pm 39$  mil measurement range at a sample rate of 7.8 kHz with 0.008mil resolution is outstanding. Also, the displacements for any test object surface type can be read with this system. The only drawback is the noise band that masks all the displacements below 0.2mil. The amazing part of this system is that it is integrating four off the shelf displacement sensors into a non-contact measurement and analysis system that has cost less than \$25k. The closest non-contact measurement system is a bulky single point laser vibrometer sensor from Polytec PI that retails for \$25k, while a scanning system starts at 160k.

The entire system has a hassle free setup with a time to assemble and disassemble at less than 30 minutes. Most of that time spent zeroing the sensor position and waiting for the lasers to warm up for the most stable measurements. The 30 minute test time is based on the amount of time it takes to capture the 8x4 grid of displacement during the sine sweep along with the time it takes to raise or lower the cross bar.

Two of the three most important preliminary specifications, were almost 10x better than expected. Overall this system has proven a viable alternative to accelerometers and because it does not physically touch the test object, it will provide more accurate vibration test results.

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## **Chapter 7 Conclusions and Recommendations**

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Prompted by accelerometers mass loading an electronic board during vibration testing, the goal of this thesis was to design a non-contact vibration measurement and analysis system to capture the un-altered dynamic performance of an electronic board during vibration testing.

A product development process was used to guide the design process. First, customer needs were identified to help set preliminary specifications. After non-contact measurement methods were explored, three concepts were proposed: holographic interferometry, area scaling, and displacement sensor grid. Concept testing, preliminary analysis and comparison ratings determined that the displacement sensor grid concept would be the best method for this system.

A prototype hardware and software package was built to test the two laser displacement sensors under consideration. The Keyence LK-11 laser displacement sensor was determined to be the better sensor over the Keyence LC-2440 since it was more



compact, cheaper per unit, less sensitive to noise, and could read the displacement of any surface type. Also, the prototype hardware and software system were evaluated during the sensor selection vibration testing improvements. This feedback was used to design the final non-contact system.

Four Keyence LK-11 laser displacement sensors were incorporated into the final system. The setup arranges the four sensors side by side setting the minimum distance between the laser points at 0.7 inches. The vertical movement mechanism allows the row of sensors to be vertically positioned in 1cm increments up or down the face of the electronics board. For the testing conducted in this thesis, the system allowed for an 8x4 displacement grid of the electronic board to be captured.

The final software was written in MATLAB to acquire and analyze the board's displacement during the 20-2000Hz sine sweep. A five step analysis program starts by cropping the first natural frequency region from the sensor's displacement data. This first mode displacement data is de-noised using wavelet de-noising techniques. Then, the frequencies and maximum positive displacements are determined using the data's sinusoidal zero crossing times. Finally, all of the first mode displacements are meshed into an 8x4 grid where they are fit with a 3<sup>rd</sup> order polynomial in the horizontal direction and a 7<sup>th</sup> order polynomial in the vertical direction to output a movie depicting the electronic board displacing through its first mode region.

## **7.1 Conclusions**

This thesis has shown laser displacement sensors are a low cost and highly accurate way to perform non-contact vibration measurements. Overall, the final system outperformed the specifications set earlier in the preliminary design stage. While it does not produce full field modal displacement output like holographic interferometry techniques, it can record 4 points horizontally with 0.7 inch resolution and numerous points vertically at 1cm resolution with the current hardware setup.

Combined with the data acquisitions and analysis software, the laser displacement system found the natural frequency and maximum displacement amplitudes within 1.5% and 0.7% accuracy, respectively, when compared with previous acceleration grid results. The system has a maximum sample rate of 7.8kHz. It can record displacements up to

$\pm 1$  mm, and it can read the displacement of objects with any surface type or material. The sensors have a  $0.2\mu\text{m}$  or 0.8 micro-inch resolution.

The only drawback to these sensors is that displacements below 2 mils were indistinguishable because of a sensor noise band. Work was done to reduce this noise, but the only successful action to note is that running the laptop off of its battery instead of the power supply cord during testing reduced the noise band from 4 mils to 2 mils.

The four sensors are integrated into a clean, easy to setup hardware/software package. It takes less than 15 minutes to fully configure to test setup, however, the sensors need 30 minutes warm up time to provide a stable output. The software package provides easy to use MATLAB GUI's to acquire and analyze the output. While it was specifically written for outputting a movie file using the 8x4 displacement grid of the electronic board's first mode, it can be easily adapted for other vibration test cases.

## **7.2 Recommendations**

While this system proves using laser displacement sensors a viable method for non-contact vibration measurement, further work can be done to develop a more accurate and versatile non-contact test measurement and analysis system.

Currently, the sensor mount setup is relying on the test object being a flat surface. A sensor mount providing individual sensor adjustment towards or away from the test specimen would ensure that sensors did not impact a test object with an uneven surface. Individual adjustment would allow for electronic board component analysis to be easily performed and it would introduce a more accurate way to null the sensor's position.

The idea of clamping to the side rails of the vibration table to isolate the sensors was a fast, low cost method that proved successful. However, it was a tedious task to ensure the sensors were in the correct position since the tops of the rails are not perfectly smooth. If a mount were drilled to the inside or top of the vibration table side rails, it would provide a more accurate way of dangling the sensors 1 cm in front of the test object.

Since the test system is capturing displacements on the order of a thousandth of an inch, a more rigid system might reduce laser point position error and transferred vibration levels seen in the hardware mounting the sensors. The hardware was adequate for the

level of accuracy needed in capturing an 8x4 grid of board displacements, however, the weight of the sensor themselves probably caused slight off center twist that changed the laser point position and might be the reason why the four sensors could not be positioned perfectly planar with the board.

Although, the software was written for the specific electronic board test, it does reveal the analysis methodology that can be applied to any test case. The software should be expanded, however, to allow for multiple test configurations.

Finally, the system performance and accuracy were established through comparison with electronic board accelerometer output. Different test profiles should be run to validate the performance of this system in more than the one test profile presented in this thesis. The 2-mil noise band should be further investigated to increase the lower displacement limit capabilities of the system.

With the numerous benefits of non-contact instrumentation, test facilities should incorporate this low cost and versatile method of non-contact measurement into their testing practices.

## References

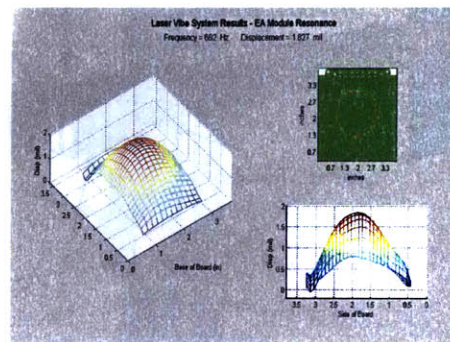
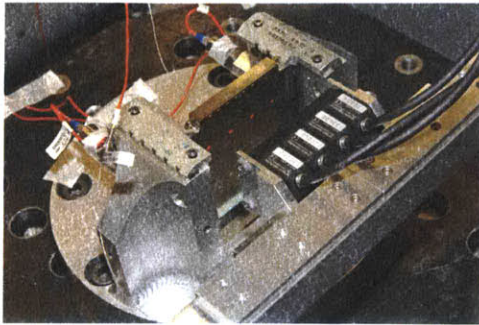
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# NON-CONTACT VIBRATION SYSTEM

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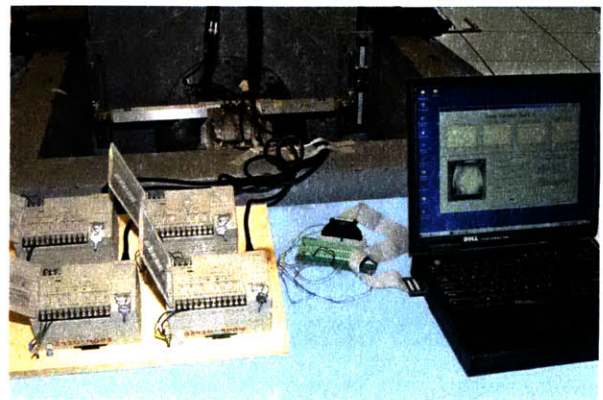
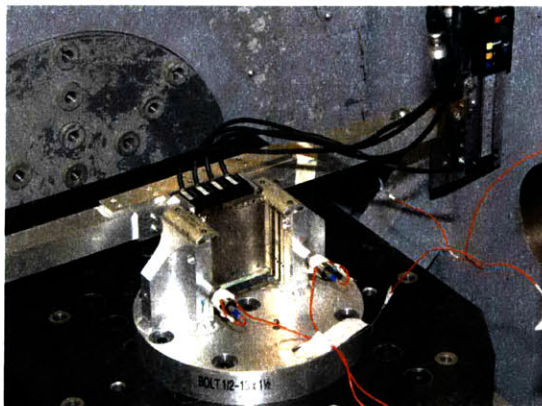
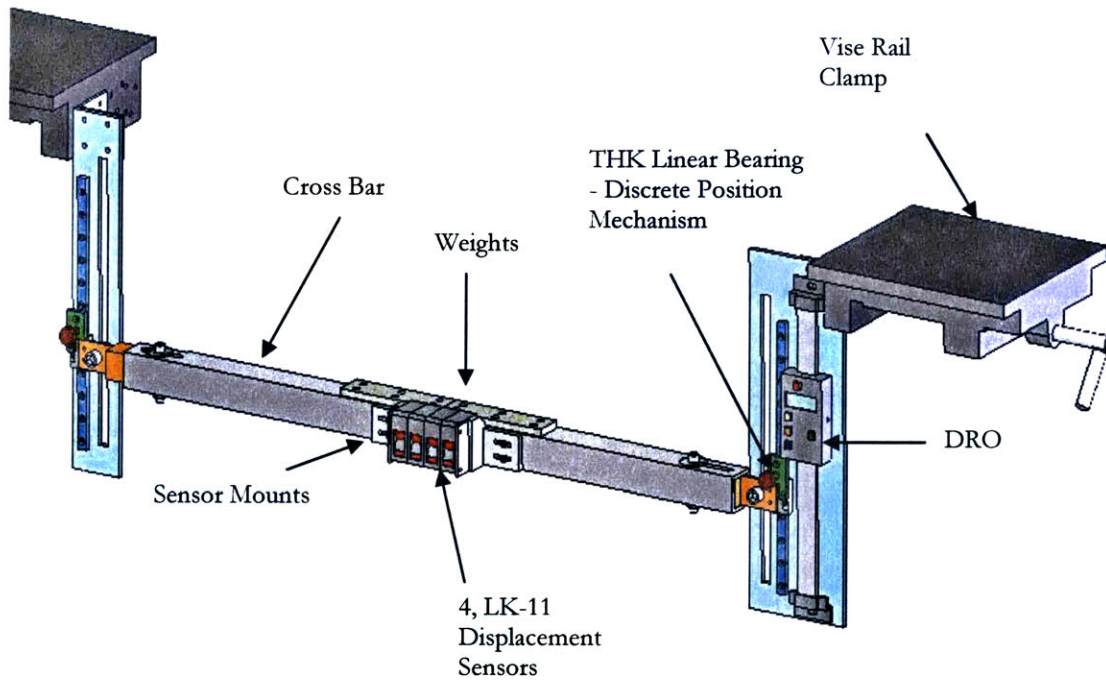
## Non-Contact Vibration Measurement Hardware Manual



# Hardware Manual

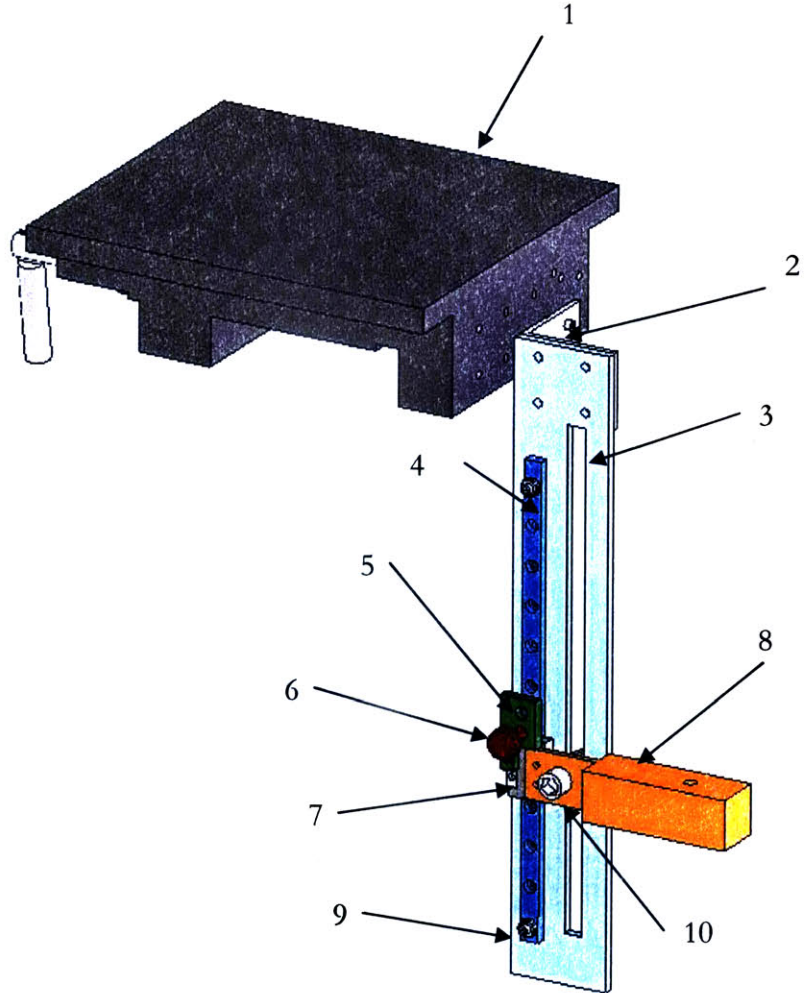
# Hardware Setup

This Hardware Manual will help you properly setup and configure the non-contact vibration measurement system for vibration testing. For more information on the test setup and results, please see Chapter 5 and 6 of this thesis.



## Subassembly One

*Left Vise and Vertical*



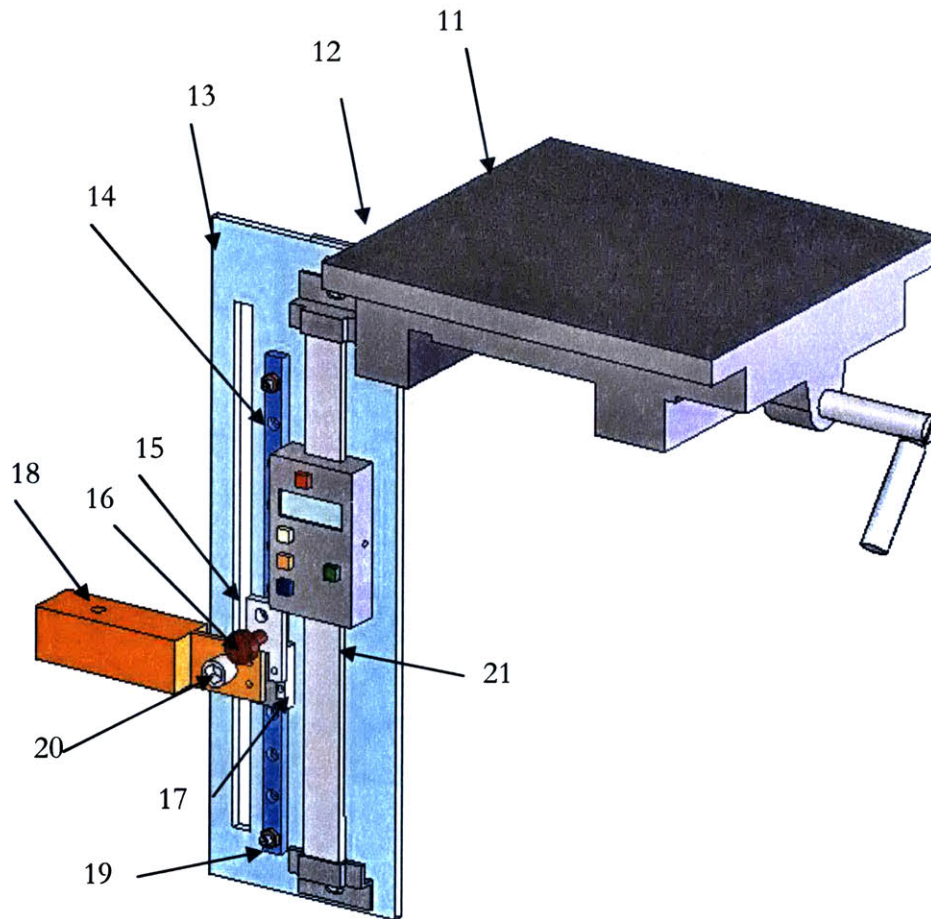
### Key Parts

1. *Vise Clamp*
2. *L-Bracket*
3. *Vertical*
4. *THK Linear Bearing Rail*
5. *2-Hole Bracket*
6. *1/4 - inch Pin*
7. *THK Linear Bearing Truck*
8. *Bronze Cross Bar End*
9. *1/8-inch Nut/Bolt Bearing Stopper (2)*
10. *3/8-inch Slot Bolt/Washer/Nut*



## Subassembly Two

### *Right Vise and Vertical*

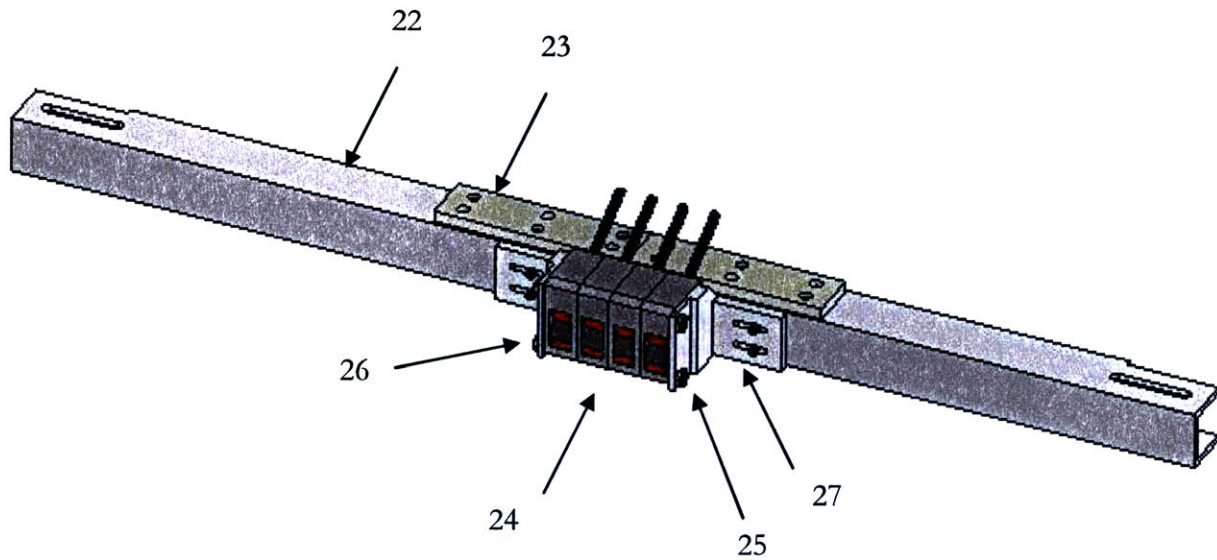
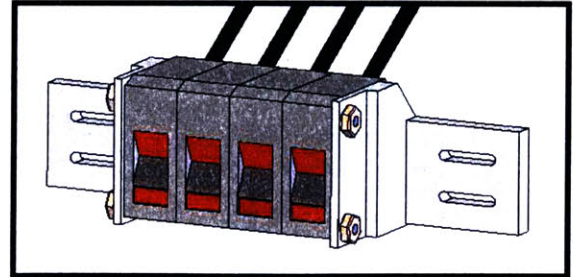


### **Key Parts**

- 11. *Vise Clamp*
- 12. *L-Bracket*
- 13. *Vertical*
- 14. *THK Linear Bearing Rail*
- 15. *2-Hole Bracket*
- 16. *1/4 - inch Pin*
- 17. *THK Linear Bearing Truck*
- 18. *Bronze Cross Bar End*
- 19. *1/8 inch Nut/Bolt Bearing Stopper (2)*
- 20. *3/8-inch Slot Bolt/Washer/Nut*
- 21. *Digital Read Out (DRO)*

## Subassembly Three

### *Crossbar and Sensors*



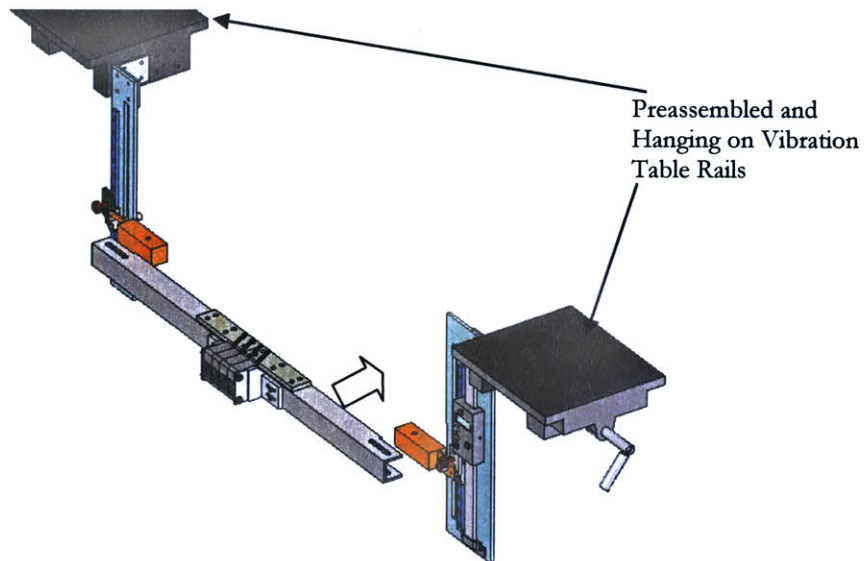
### ***Key Parts***

- 22. Cross Bar
- 23. Weights
- 24. Keyence LK-11 Laser Displacement Sensor (4)
- 25. Mount Plate Right
- 26. Mount Plate Left
- 27. Mount Slot Bracket (2)

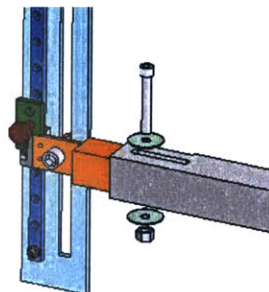
## Assembly Steps

### Step One: Assemble Hardware

- **Clamp** Subassembly One and Two **vises** to vibration table **side rails**
- **Slide Sensors/Crossbar** Assembly onto **Bronze Bar Ends**



- Insert  $\frac{1}{4}$  inch diameter bolts, washers, and nuts to **secure the cross bar** to the two bronze bar ends. Leave bolts loose so sensors can be positioned with respect to electronic board.

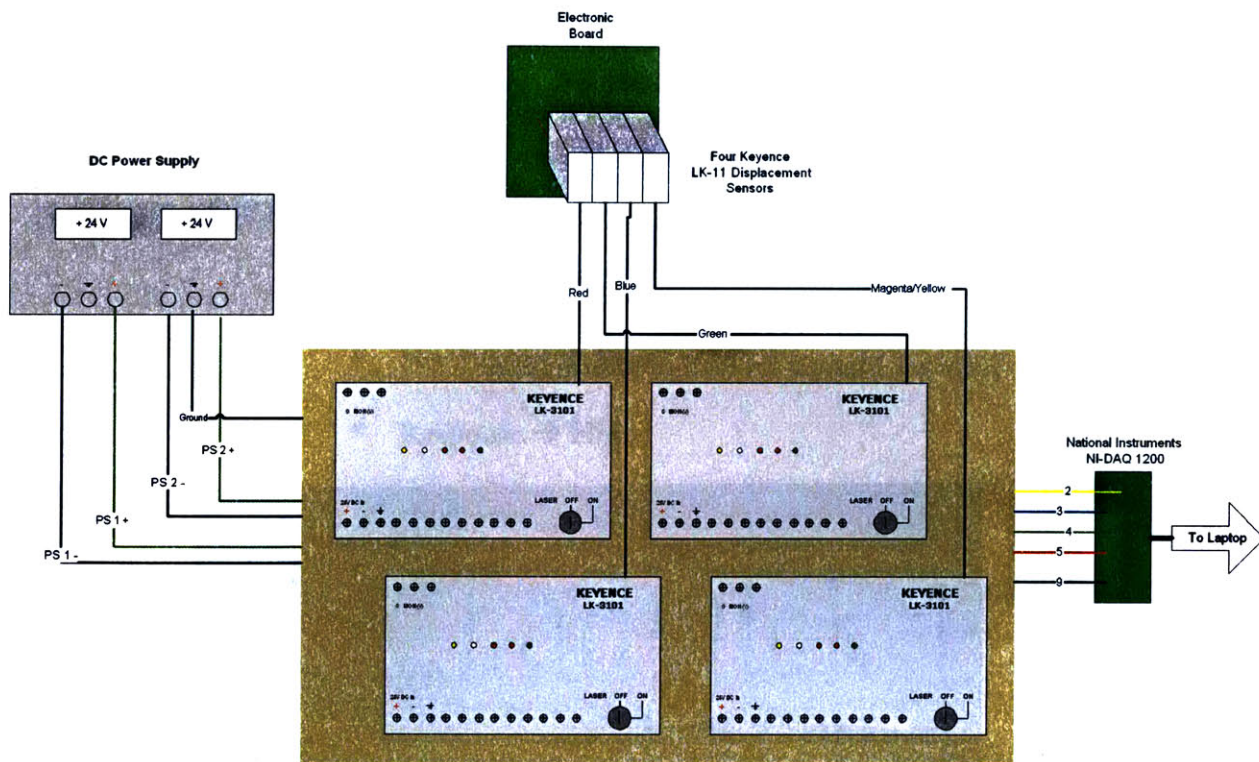


- **Mount electronic board** to vibration table.
- **Center Lasers** with respect to the electronic board by using the slots on the cross bar. Ensure the fixture will not hit the sensors. There is a very small clearance.
- **Tighten  $\frac{1}{4}$ " bolts** to secure cross bar to bronze bar ends.

## Assembly Steps

### Step Two: Power Laser Sensors

- Connect sensors to controllers with extension cables. Ensure the sensor number matches the controller number.
- Tune both **DC Power Supply** Channels to + 24 V.
- Ensure **Lasers** are **Connected** to **controllers**
- Ensure **Laser keys** are in the **OFF** position
- Hook up **Ground**
- Hook up **PS 1** and **PS 2** wires to power laser controllers with 24V DC each.



## Assembly Steps

### *Step Three: Hook up Data Acquisitions Card and Laptop*

- **Connect** colored output **wires** from the controller unit to the **NI DAQ Card**. Follow the wiring schematic on previous page.
  - Yellow → 2
  - Blue → 3
  - Green → 4
  - Red → 5
  - Ground → 9
- Turn **ON** laptop
- Ensure **NI DAQ 6.9.3** is installed
- Open **MATLAB**
- Open the directory where the software has been installed
- Type “**AcquireData**” in the Command window

**Refer to Software Manual for further information**



## Assembly Steps

### Step Four: Laser Settings

- Open **Front Covers** on each laser controller



- Set the sensors to **128 $\mu$ s sample cycle** ( $F_s=7812.5\text{Hz}$ )
- Set the **Mode** to **Normal**
- DIP Switches
  - **Alarm**  $\rightarrow$  **Hold**
  - **Key Protect**  $\rightarrow$  **Free**
  - **Response**  $\rightarrow$  **High**
- Turn **Laser Keys** to **ON**
- **Hold** down **Zero/Reset** button for **5 seconds** to ensure the sensors are **NOT** zeroed
- Turn **Lasers** to **ON** Position
- Please see **Keyence LK-3100 Series Instruction Manual** for more detailed information about operating the lasers and specific modes.

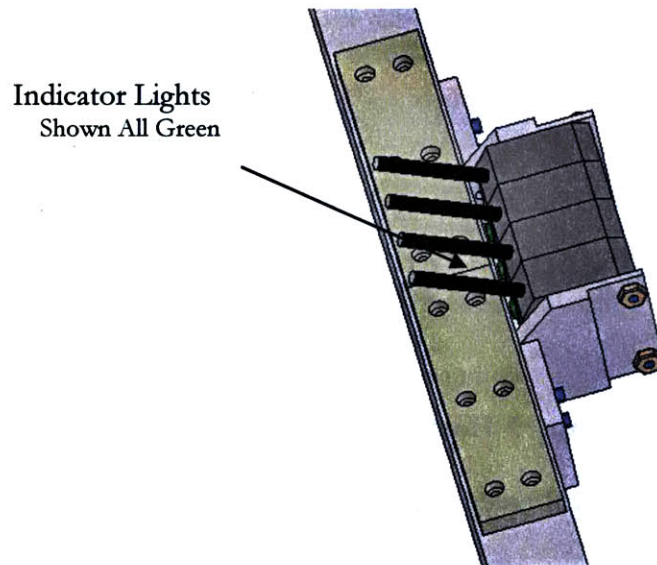
### IMPORTANT

1. **Laser Keys** must be in the **OFF** position **BEFORE** the **Power** is turned **OFF**
2. **Lasers** **CANNOT** be **Disconnected** from Controllers until the **Lasers** are **OFF** and the **Power** is **OFF**

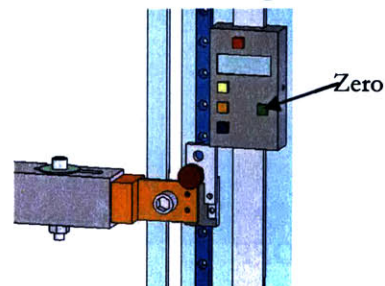
## Assembly Steps

### *Step Five: Adjust Laser Position for Test*

- **Center the laser output around 0 Volts** by positioning the sensors 1 cm from the electronic board.
  - With vises loose, and lasers ON, move the lasers about 1 cm away from the electronic board until the **lights on the back of the sensors are all green or a few are green and a few are solid orange** indicating the sensors are in a valid measurement distance.
  - **NOTE:** If the sensor lights are flashing orange, they are either out of range or stuck between the green and orange range which can cause false readings.

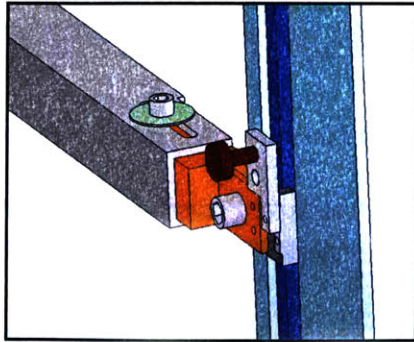


- **Preview the sensor output** by viewing the voltage output plots with the MATLAB program **AcquireData**.
- **Zero the Sensor's Vertical Position**
  - **Move the sensors so the laser points are on the top of the electronic board.**
  - **Move the Digital Read Out (DRO) down until it is resting on the bracket.**
  - **Hit Zero** on the **DRO** box.

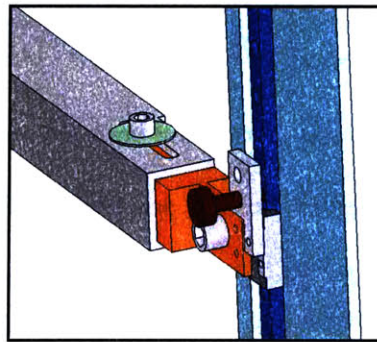


## ACQUISITION AND ANALYSIS SOFTWARE

- Now **Move** the sensors into the **first data collection position**. See below for how to use the vertical movement mechanism to lower the cross bar exactly 1 cm at a time.



Pin in top Bracket hole



Pin in bottom Bracket hole and lower bore on the Rail. Sensors are now positioned 1cm lower

- **Tighten** the **Slot Bolts** on each vertical
- **Push** the **DRO down** until it stops on the bracket.
- **Record** the **DRO measurement value** for the location of the first row of laser points. The DRO will indicate the distance from the top of the board so every laser position will now be known.
- **Tighten** all of the **bolts** to secure the cross bar in place.
- Please see **Software Manual** for software setup and functions.

**You are now ready to test!**

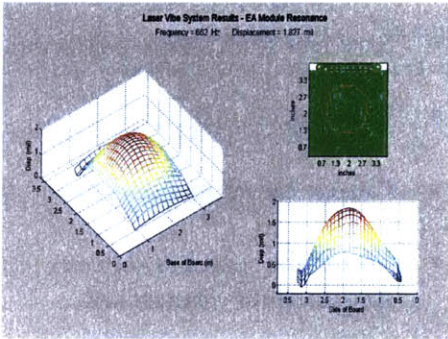
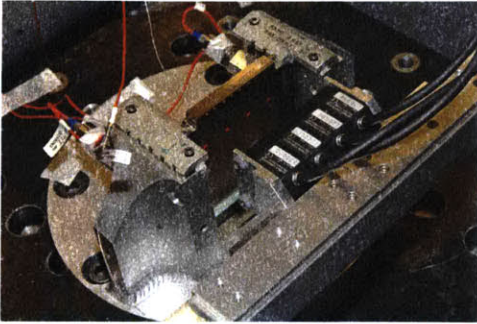


***IMPORTANT TESTING NOTES:***

- Sensors may need to be readjusted (moved towards/away from the board) when the vibration table is turned on.
- Software: Remember to Save each test run before you start taking data for another test.
- TURN Lasers to the OFF position BEFORE you remove Power!
- Sensors MUST be in the OFF position with Power Removed BEFORE they are disconnected from the controllers.

# NON-CONTACT VIBRATION SYSTEM

## Data Acquisitions and Analysis Software Manual



# Software Manual

## Data Acquisition

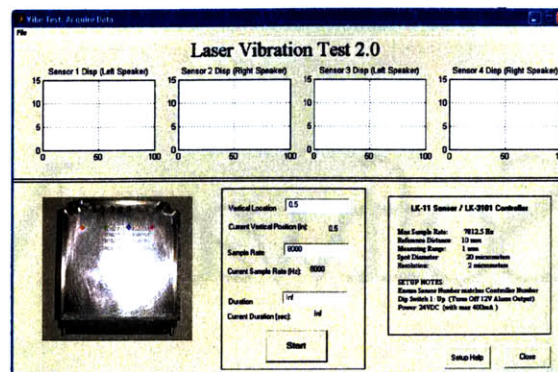
This program uses the MATLAB Data Acquisition Toolbox to acquire the voltage output from the Keyence LK-11 displacement sensors through a National Instruments NI-DAQ 1200 card. Two files exist for use: the *AcquireData.m* is for testing with the Non-Contact Laser Vibration System and a demo file, *AcquireData\_SoundCard.m*, was written to allow users who do not have the NI-DAQ card to see how the software works by simply capturing the data off their computer's sound card.

The *AcquireData.m* (Laser Vibration Test 2.0) is used to capture the output of the four displacement sensors during a test. A sensor coloring scheme has been used in this program so that the sensors are never confused. The Red sensor captures the displacement data on the left of the board, then the Green is to its right, the Blue is next, and then the Magenta. The Red Sensor displacement is the first column of data within the .daq file even though it is routed to the Channel 5 slot on the NI-DAQ 1200 board. Red= $\text{data}(:,1)$ , Green= $\text{data}(:,2)$ , Blue= $\text{data}(:,3)$ , Mag= $\text{data}(:,4)$ . This is just how the NI-DAQ 1200 reads the channels. Remember to save the data acquired after each test run.

### Data Acquisitions Demo

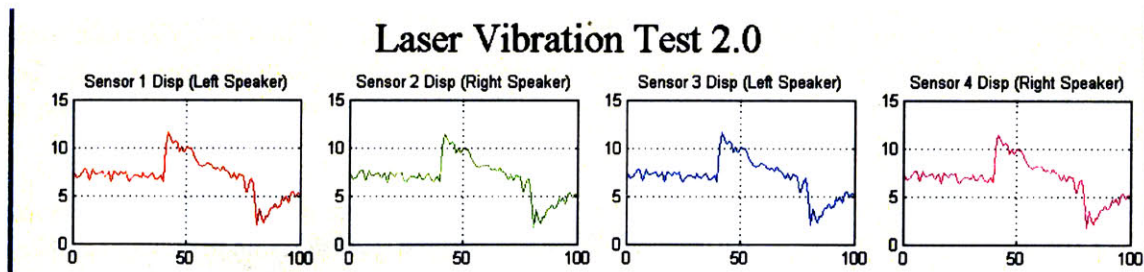
- Insert Laser Vibration CD
- Save files from CD to a directory on your computer.
- Open MATLAB
- Change the current directory to the directory where you saved the files.
- To run the sound card demo, type in the MATLAB prompt window:  
**Acquiredata\_soundcard**
  - Alternatively, type **Acquirdata** to run the vibration test program that acquires data from the NI-DAQ Card.

The Laser Vibration Test 2.0 window should open.



- Press the **Start** button and you will see the sound card data in the plot windows.

Plot windows with sound card output.



### Program Options

**Vertical Location:** User can view where the lasers are capturing the data. This value is prompted when you go to save the data so location information can be retained.

**Sample Rate:** User can change this value to anything. In `AcquireData.m`, the program will ensure it is a NI-DAQ-1200 sample rate and if not, it will change it to the closest one.

**Duration:** The User can specify the Duration for Vibe Test to capture the data. During a vibration test this value should be set on *inf* so the user can just stop the acquisition when the test is complete.

**Start/Stop:** Starts or Stops data acquisition from sound card or NI-DAQ 1200 card.

**Setup Help:** Provides a diagram of how the Laser Vibration System should be setup.

**Close:** Closes Laser Vibration Test 2.0.

**File → Save:** Saves the acquired data as a *.daq* file

**File → Send To → Workspace:** Sends the acquired data and  $F_s$  (sample rate) information to the MATLAB Workspace.

**File → Send To → SPTool:** Sends acquired data to the Signal Processing Tool

**File → Send To → Figure:** Plots the acquired data as a time plot and an FFT plot

# Data Analysis

The analysis programs use MATLAB in a five step series of m-files to analyze the test data and output an *.avi* file showing the electronics board first mode displacement. The Laser Vibration System can capture the displacement of the board with eight tests, one every 1cm down the board with Test1.daq corresponding to the top test, Test2.daq to the second from the test, and so on until Test8.daq is at the bottom of the board.

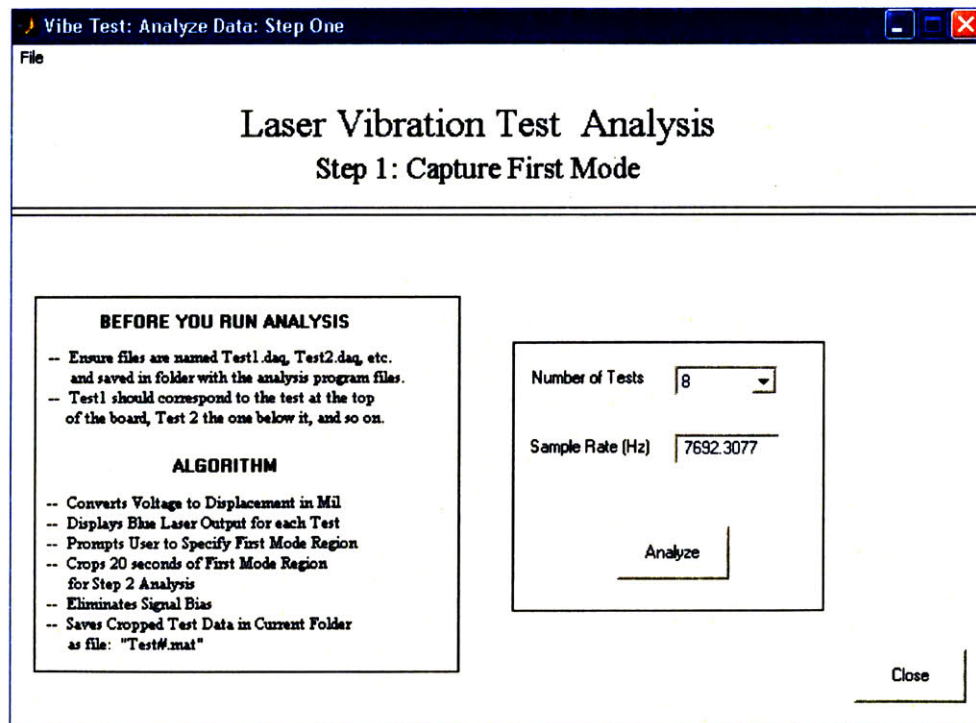
NOTE: The Test files from the second 20-2000Hz sine sweep test reported in this thesis are located on the CD and will allow the Analysis software to be used. This will provide a better understanding of the analysis steps taken to convert the raw displacement sensor voltage into a 3D movie file of the electronic board displacing through its first mode.

## Step One: Capture First Mode

*Analyzedata1.m*

- Type **AnalyzeData1** to open the first step of the analysis

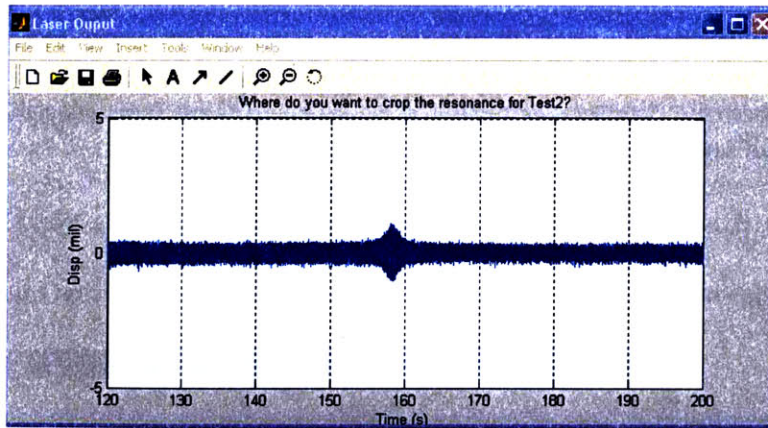
The following window should open:



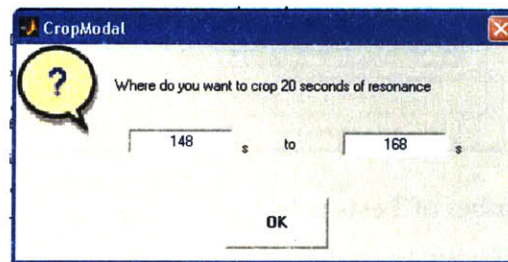
- Set the **Number of Tests** to 8
- Set the **Sample Rate** to 7692.3077 Hz
- Press **Analyze**

## ACQUISITION AND ANALYSIS SOFTWARE

A figure will appear with the specified Test data plotted with the axis zoomed into the first mode region.



Then a *CropModal* dialog box will appear asking what 20 second time range the first mode should be cropped around. Try to capture the displacement peak in the center of the 20 second range and do not to crop an area where noise has caused a hiccup in the data. The mode will differ from the noise in that the mode should have x-axis symmetry and the noise will not.



- Press **OK**

The program will run through all of the tests, and save the cropped modal regions as *Test#.mat* in the current directory, where # will refer to the test number for the data.

### *Program Options*

**Number of Tests:** User can pick how many tests will be loaded to have their first mode captured.

**Sample Rate:** User must specify the sample rate at which the data was acquired.

**Close:** This will close the program.

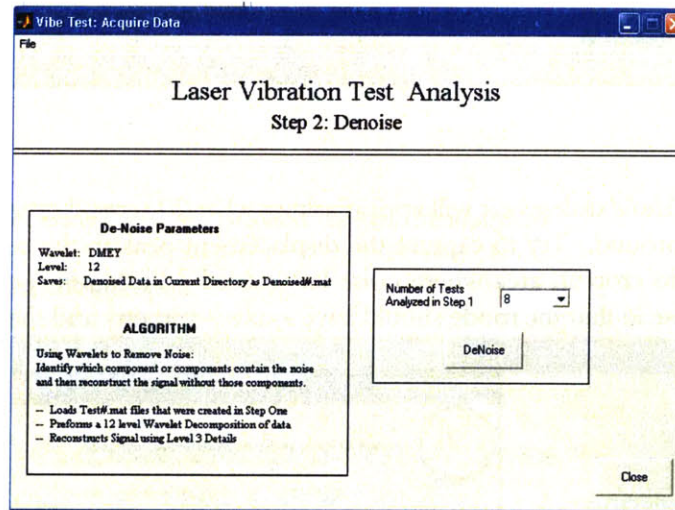
## Step Two: Denoise

*AnalyzeData2.m*

This analysis step de-noises the data by splitting the displacement signal into 12 levels using the DMEY wavelet. Then the displacement signal is recreated with the only details component, d3, that captures the sinusoidal resonant displacement and very little noise.

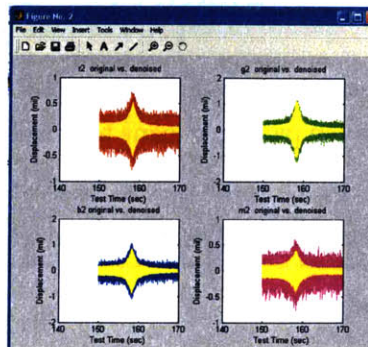
- Type **AnalyzeData2** to open the first step of the analysis

The following window should open:



- Set the **Number of Tests** to 8
- Press **DeNoise**

A figure window will appear showing each of the 8 tests with their original displacement data and the denoised output (yellow).



The De-noised data is automatically saved as Denoised#.mat in the current directory.

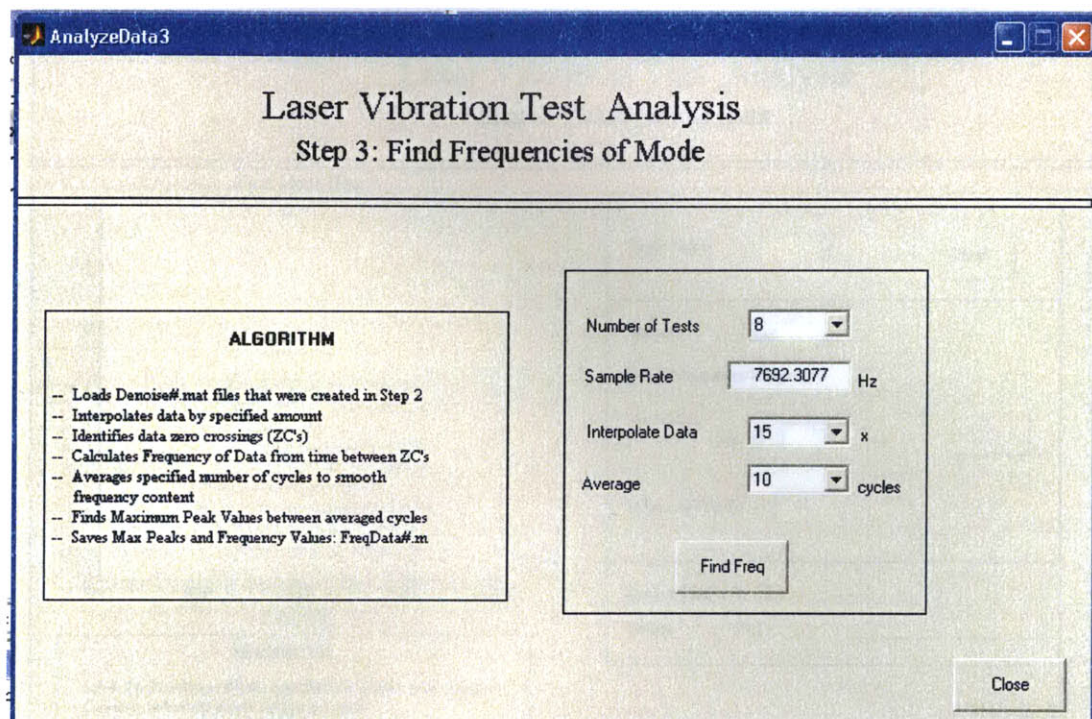
## Step Three: Find Frequencies of Mode

*AnalyzeData3.m*

This analysis step reads in *Denoise#.mat* displacement and time data for the specified number of tests and outputs displacement and frequency data as *FreqData#.mat*. The frequency content is determined by the zero crossing time within the sinusoidal data. The more the data is interpolated the better the frequency output but the longer this program will take. The frequencies can be averaged over a specified number of cycles to get smoother output.

- Type **AnalyzeData3** to open the first step of the analysis

The following window should open:



- Set the **Number of Tests** to 8
- Set **Sample Rate** to 7692.3077 Hz
- Set **Interpolate Data** to 15 x
- Set **Average** to 15 cycles
- Press **FindFreq**



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### *Program Options*

**Number of Tests:** User can pick how many tests will be loaded.

**Sample Rate:** User must specify the sample rate at which the data was acquired.

**Interpolate Data:** User can specify the number of times the data is interpolated. The greater the number the more data points are added between the existing data points.

**Average:** The Frequency found for each sinusoidal period can be averaged over a User selected number of periods to provide smoother output.

**Close:** This will close the program.

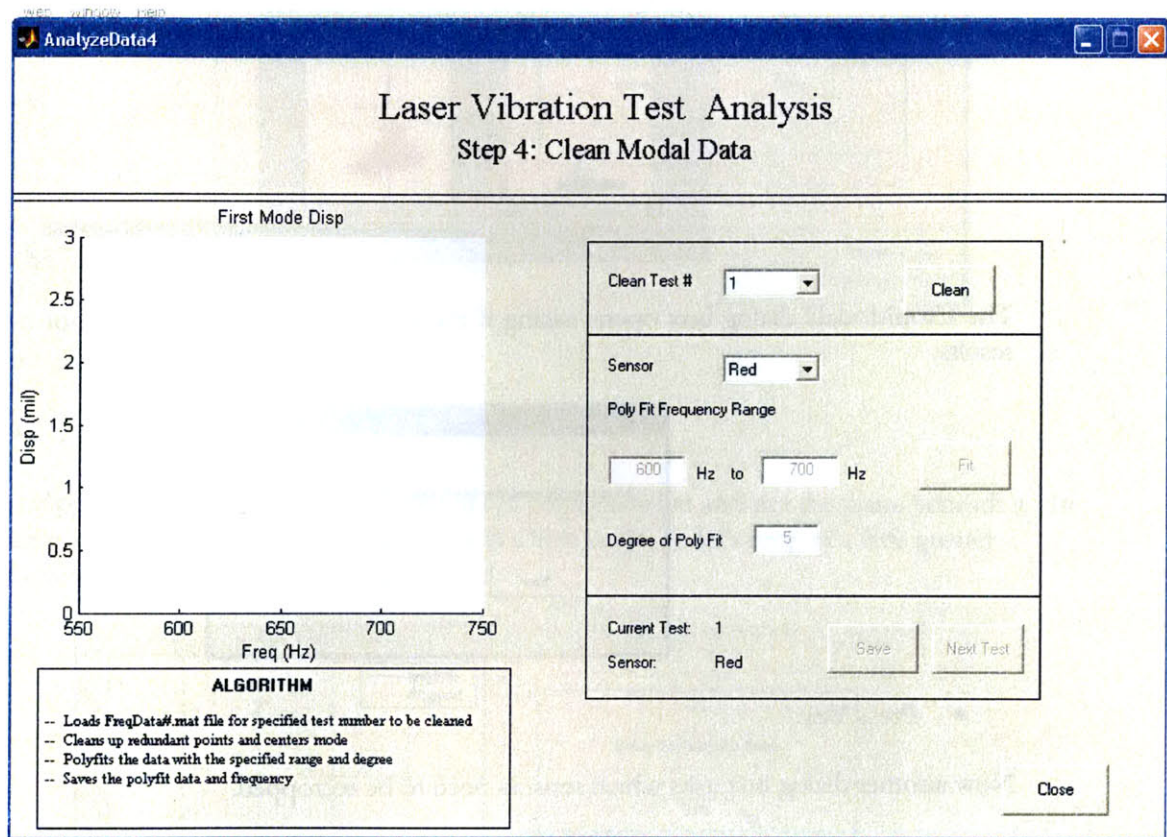
## Step Four: Clean Modal Data

*AnalyzeData4.m*

This analysis step reads in *FreqData#.mat* for the specified test file, cleans it of its redundant x-values, and fits a polynomial function to the data so that there is one displacement value for each frequency. If the data cleaning does not work correctly, more data cropping will have to be performed. The polyfit data is saved as *PolyData#color.mat*.

- Type **AnalyzeData4** to open the first step of the analysis

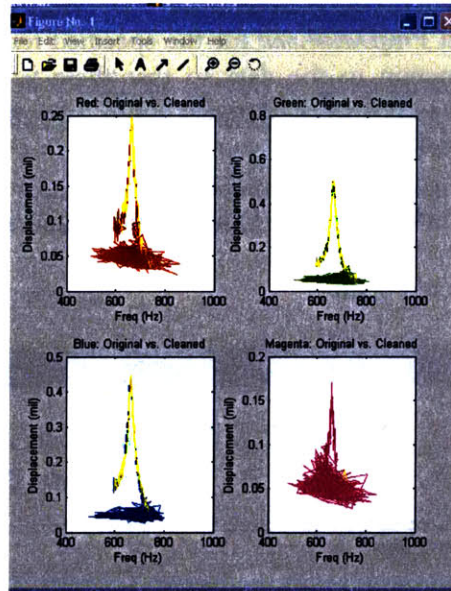
The following window should open:



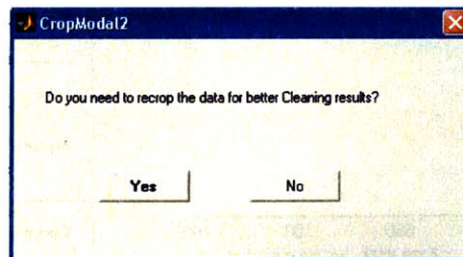
- Set **Clean Test #** to 1
- Press **Clean**

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The following figure opens displaying the original data with the cleaned data (yellow). The red, green, and blue sensor data was cleaned nicely but the magenta data had too much noise that the clean\_mode algorithm failed. The data for the magenta data will have to be recropped.

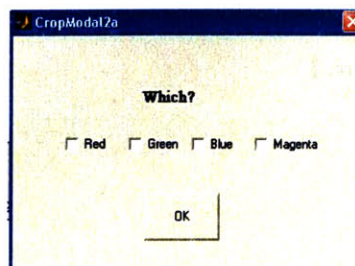


The CropModal2 dialog box opens asking if the data needs to be recropped for better cleaning results.



- Press **Yes**

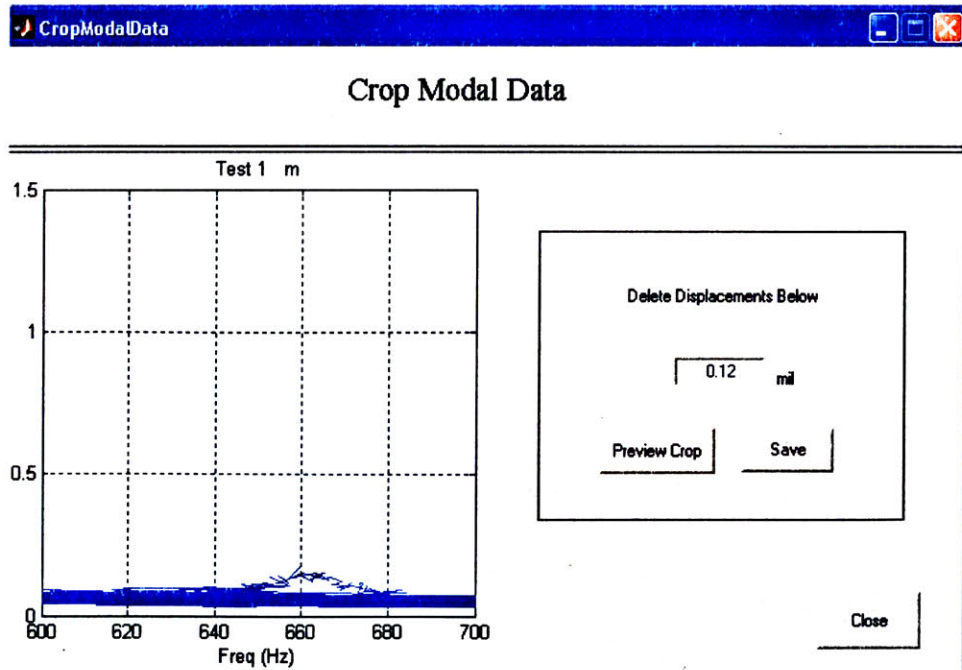
Now another dialog box asks which sensors need to be recropped.



- Check the **Magenta** box
- Click **OK**

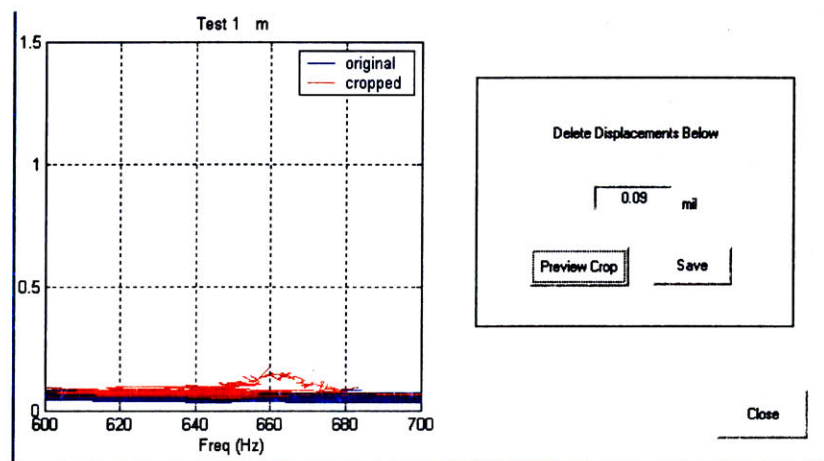
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Now the CropModalData GUI opens displaying the Magenta Sensor Data. This GUI will delete the data below the specified amount.



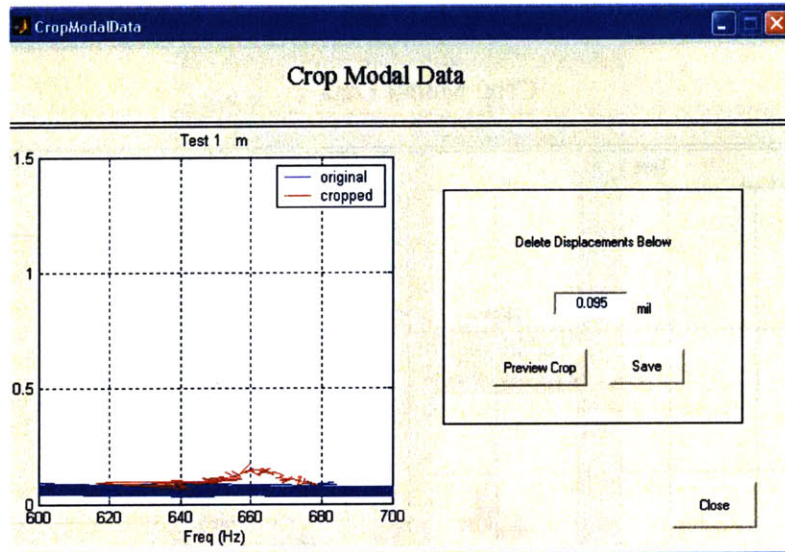
- Enter **0.09 mil**
- Press **Preview Crop**

The cropped data should just capture the hill of displacements and not the noise beneath it. In this case, deleting the data below 0.09 mils left a little noise, so let's crop at a little greater displacement.



- Enter **0.095 mil**
- Press **Preview Crop**

Cropping at 0.095 mil allowed us to just capture the modal displacement without the noise. Now let's save this.



- Press **Save**

If multiple sensors needed to be cropped, they will automatically appear in the Crop Modal Data plot window after the previous is saved.

When all of the sensors specified for recropping have been saved, you will be brought back to the Analyze Data window

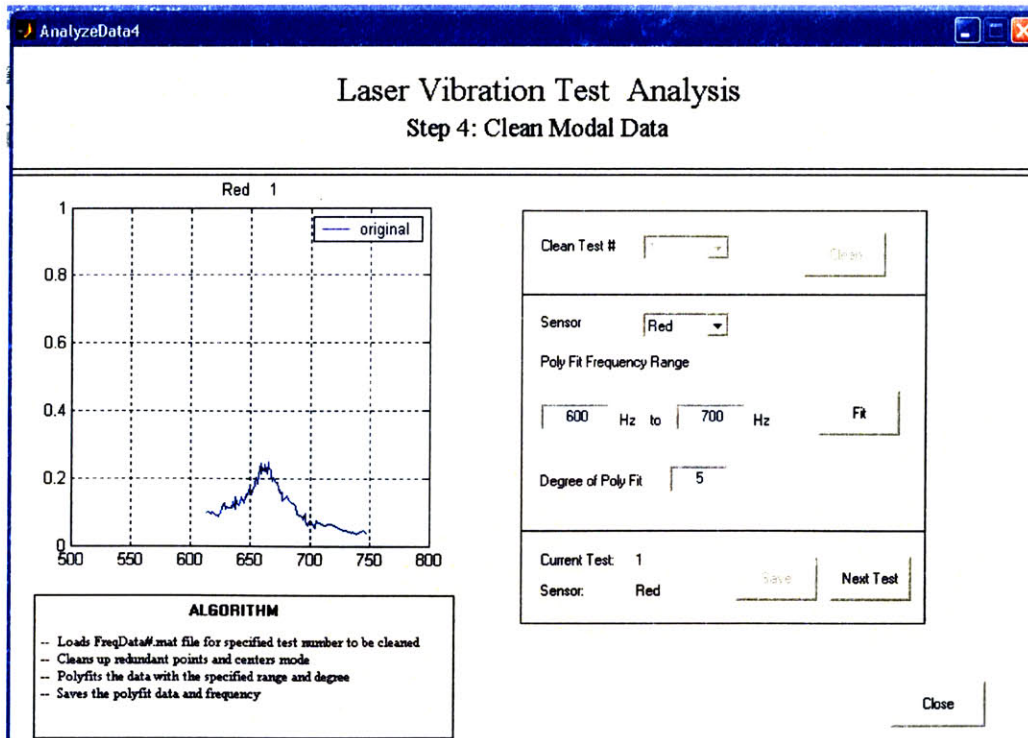
- Press **Clean**

When the figure opens showing the modal data and the clean data, all of the data should look good now. When the dialog box opens asking to recrop:

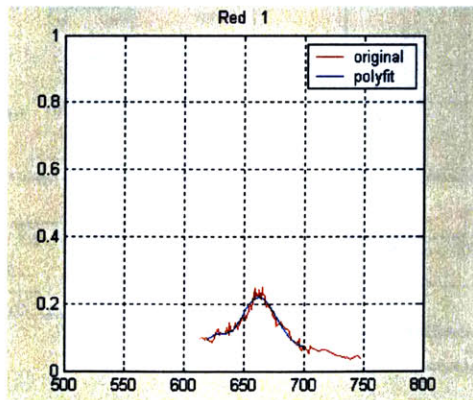
- Click **No**

Now the data for this test is ready to be fit by a polynomial function. The **Clean Data** button should be dark and will remain this way until the polyfits for each of the sensor's modal peaks are saved and the **Next Test** button is pressed.

**Please Note:** **Clean Modal Data** doesn't work if a noise hiccup is causing a peak in the data other than the first mode. The *FreqData#.mat* file will have to be opened through MATLAB to manually crop out this noise.

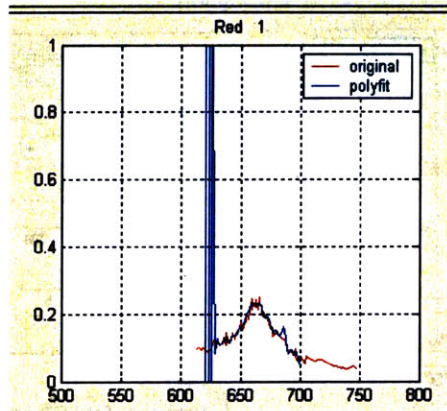


- Select the **Red Sensor**
- Change the **Frequency Range** to 620 Hz to 700 Hz
- Change the **Degree of PolyFit** to 10



This polynomial fit does a good job of fitting the data but the degree could be increased to help capture the peak better. Play with the range and degree until you like the way it looks. A small frequency range now will result in a small frequency range for the movie file of the electronics board displacing through the first mode region.

If the degree is too high for the frequency range, the polynomial will look like the plot below. Decrease the degree or just reduce the range so this can be avoided.



A better poly fit:

Once you like the polyfit,

- Press **Save**
- Repeat poly fit for each sensor
- Press **Next Test** to start the cleaning and data fitting steps over for subsequent tests.

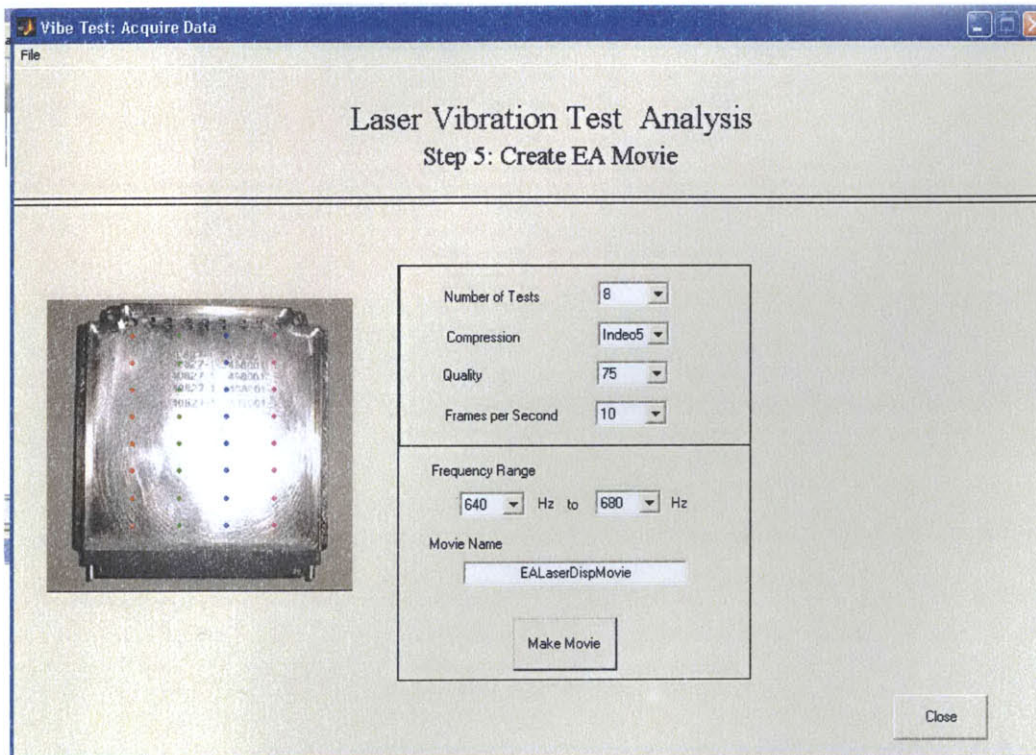
## Step Five: Create Movie

*Analyzedata5.m*

This analysis step reads in the sensor displacements output from Analyzedata4 and creates a movie file of the electronics board.

- Type **AnalyzeData5**

The following window should appear:

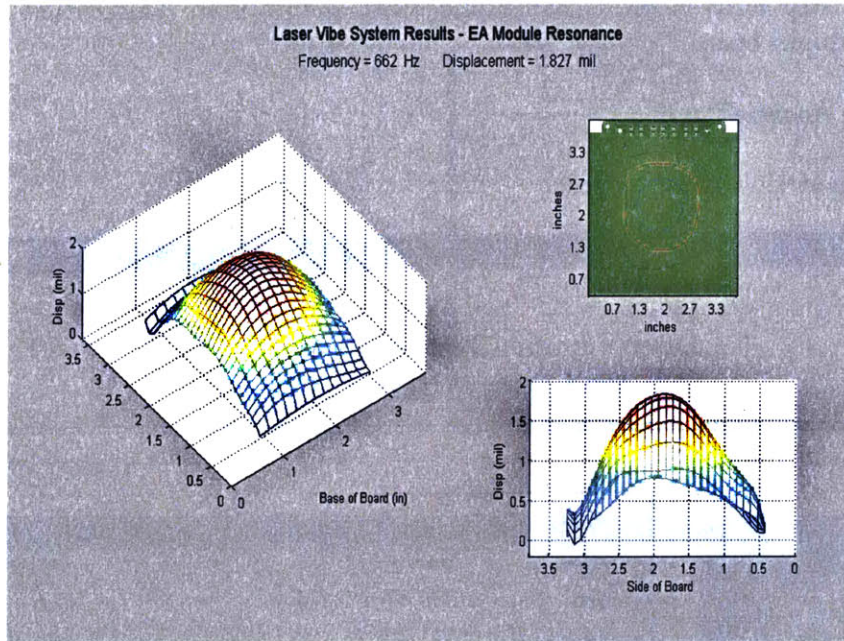


- Set **Number of Test** to **8**
- Set **Compression** to **Indeo5**
- Set **Quality** to **100**
- Set **Frames per Second** to **25**
- Set **Frequency Range** to **650 to 680 Hz**
- Press **Make Movie**



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A figure window will open to display each frame of the movie file as the displacement data from each sensor and test are meshed at each frequency in the range specified.



The movie will be automatically saved in the local directory with the **Movie Name** specified.

## To View Movie

Open Windows Media Player or Quicktime and select the movie file from the directory it was saved in.

## PROBLEMS VIEWING MOVIE

Install the Indeo 5 Codecs from CD by following the directions in the *ReadMe.txt* file located in the *IndeoVideo5* folder.