Implementing the Surface Response to Excitation Method (SuRE) with Non-contact Sensors

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IMPLEMENTING THE SURFACE RESPONSE TO EXCITATION METHOD (SuRE) WITH NON-CONTACT SENSORS

A dissertation submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

MECHANICAL ENGINEERING

by

Sergio R Gonzalez Jr.

2013
To: Dean Amir Mirmiran  
College of Engineering and Computing  

This dissertation written by Sergio R. Gonzalez Jr., and entitled Implementing the surface response to excitation method (SuRE) with non-contact sensors, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this dissertation and recommend that it be approved.

___________________________________  
Yiding Cao  

___________________________________  
Igor Tsukanov  

__________________________________  
Ibrahim Nur Tansel, Major Professor  

Date of Defense: November 15, 2013  

The Thesis of Sergio R. Gonzalez Jr. is approved.

________________________________  
Dean Amir Mirmiran  
College of Engineering and Computing  

_________________________________  
Dean Lakshmi N. Reddi  
University Graduate School  

Florida International University, 2013
DEDICATION

This dissertation is dedicated to those Professors, (past, present and future), who work tirelessly to bring enlightenment to their students and the promise of hope to the world. Also to my Mother Emerita Gonzalez, my late Father Sergio Gonzalez R.I.P., Sister Nitza Maria, Sons Sergio, Joel, Family, to my wife Hilda Rosa Gonzalez, to all the Professors who were my mentors in these years as a Graduate and Undergraduate Student, Secretary Martha Soledad, to our “Maite”. A Special mention and gratitude go to Dr. Cesar Levy and to Dr. Ibrahim N. Tansel, and co-students who worked with me all this time, with all my affection.
ACKNOWLEDGMENTS

This is the most difficult page to write in the entire dissertation because how to express my gratitude, admiration, friendship to all who supported me to get here to this point? Words are a mere abstract definition of the feelings of gratitude and appreciation to all my Professors who gave guidance, attention, suggestions, feedback, encouragement, hugs (from my wife) and above all patience from everybody. I would like to acknowledge the members of the dissertation Committee for their support, patience and good sense of humor. Their gentle but firm direction has been most appreciated, the contributions made by American Piezo at a time that I needed more than one helping hand or a hug, students like Fidel Prieto, Javier Rojas, Hadi Fekrmandi, Ngin Mang. My dear Professor and friend, head of the dissertation committee Dr. Ibrahim Nur Tansel, with his deep knowledge, sense of humor and his humbleness, who made possible this work. My heartfelt appreciation is offered to him not only as my dissertation chair, but also as my friend. Also would like to acknowledge all the Professors of the Mechanical and Materials specially my dear Professor Dr. Cesar Levy with his patience and good heart, Dr Yiding Cao, Chair and Co-Chair of the Mechanical Department, Dr. Dulikravich, Dr. Surendra Saxena with the Graduate Seminars, Dr. Jones, Dr. Wu (Retired), Dr. Munroe and Dr Igor Tsukanov with his knowledge and intelligence that all made possible many achievements during these years of study.
Structural health monitoring (SHM) systems generally install low cost excitation component and/or sensors to the machines or buildings permanently to monitor the health of it. Non Destructive Evaluation (NDE) systems use high cost sensors to perform the inspection of structures. It would be advantageous to inspect the some aerospace structures and parts in vacuum environment by using the remotely monitoring systems such as laser vibrometer. In this study, a scanning laser vibrometer is used to detect the location of the problem at the structure. For data collection and analysis recently, developed surface response to excitation (SuRE) method was used.

First the software of the scanning laser vibrometer was used to evaluate the capabilities of the system. The vibration of simple structures such as the cone of a speaker and a beam was tested when they were excited below 200 Hz and the mode shapes were studied.

Later, the scanning laser vibrometer was used for implementation of the SuRE method. The surface vibration of beams and plates were monitored while their surfaces were excited at high frequencies with a piezoelectric exciter. External force was applied to one
point of the surface of the considered structures. The scanning laser vibrometer evaluated
the vibration of different points on the structure according to given program and obtained
the frequency response before and after the external load was applied. The sum of the
squares of the differences of the frequency responses were obtained for each point on the
surface and presented with a contour plot.

Use of the scanning laser vibrometer was convenient at the test conditions. The
calculated mode shapes were very similar to the expected ones when the simple
structures were tested. The locations of the external forces were identified correctly
when the beams and plates were tested. The study indicated that the scanning laser
vibrometer and SuRE method may be used for identification of defects and/or loose
fasteners.
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<td>A</td>
<td>Amplitude</td>
</tr>
<tr>
<td>Avg</td>
<td>Average</td>
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<td>c</td>
<td>Speed of propagation</td>
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<tr>
<td>cos</td>
<td>cosine</td>
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<tr>
<td>Cr</td>
<td>Chrome</td>
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<td>DCT</td>
<td>Discreet Cosine Transform</td>
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<td>DDS</td>
<td>Digital Direct Signal, Sensor</td>
</tr>
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<td>DFT</td>
<td>Discreet Fourier Transform</td>
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<td>DSP</td>
<td>Digital Signal Processor</td>
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<td>DCT</td>
<td>Discreet Cosine Transform</td>
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<td>Eds</td>
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<td>e.g.</td>
<td>For example</td>
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<td>EMAT</td>
<td>Electromagnetic Acoustic Transducer</td>
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<td>F</td>
<td>Fourier, Force</td>
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<td>FORTRAN</td>
<td>IBM Mathematical Formula Translating System</td>
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<tr>
<td>f</td>
<td>Frequency</td>
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<td>FFT</td>
<td>Fast Fourier Transform</td>
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<td>grams</td>
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<td>HP</td>
<td>High Pressure, Horse Power, Hewlett Packard</td>
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<td>Hz</td>
<td>Hertz</td>
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<td>IBM</td>
<td>International Business Machines</td>
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<td>illus.</td>
<td>illustration</td>
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<tr>
<td>Abbreviation</td>
<td>Definition</td>
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<tr>
<td>ISBN</td>
<td>International Standard Book Number</td>
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<tr>
<td>k</td>
<td>A constant</td>
</tr>
<tr>
<td>K</td>
<td>Degree Kelvin</td>
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<tr>
<td>Kg</td>
<td>Kilograms</td>
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<tr>
<td>LASER</td>
<td>light amplification by stimulated emission of radiation</td>
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<td>Log</td>
<td>Logarithm</td>
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<td>MATLAB</td>
<td>high-level language and interactive environment for numerical computation</td>
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<tr>
<td>Mm</td>
<td>millimeter</td>
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<tr>
<td>m/s</td>
<td>meter/second</td>
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<tr>
<td>MUAIS</td>
<td>Multiscan Ultrasonics Automated Inspection Systems</td>
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<td>Ni</td>
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<td>PC</td>
<td>Personal Computer</td>
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<td>PZT</td>
<td>Piezoelectric Network</td>
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<tr>
<td>RMS</td>
<td>Root Mean Square</td>
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<td>SAFT</td>
<td>Synthetic aperture focusing technique</td>
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<td>SAW</td>
<td>Surface Acoustic Waves</td>
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<td>SHM</td>
<td>Structural Health Monitoring</td>
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<td>sin</td>
<td>Sine</td>
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<tr>
<td>Sgn</td>
<td>Sign Function</td>
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<tr>
<td>SSD</td>
<td>Sum of the squares of the differences</td>
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<td>Spec</td>
<td>Specification, Specified</td>
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<td>Short Time Fourier Transforms</td>
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SuRE  Surface Response to Excitation Method
SWF  Stress Wave Factor
T    Period
  t   Time
Vib  Vibration
Vol  Volume
V    Voltage
VII  Number Seven Roman numeral
  w  angular frequency, velocity
  x  a variable
2D   Two-dimensional
3D   Three-dimensional
  %  Percent
  #  Number
>    Larger than
<    Smaller than
ε    Epsilon
Θ    Theta
λ    wavelength
π    Phi
Σ    Summation
φ    Phase
Ω    Omega
I. INTRODUCTION

The detection of the defects of the structure is important to avoid accidents due to structural failure and to reduce maintenance costs. During the last two decades many researchers have worked on this topic. Constant technological advances combined with newly developed signal processing techniques leaves a huge research potential open in order to develop tools, devices and instruments to monitor structural damage and to diagnose the problems accurately well ahead of any catastrophic event. Structural health monitoring (SHM) techniques were developed on the basis of experimentation, simulation and analytical approaches with the goal of detection of small defects and irregularities at the early stages of the aging of the structure. In this study a scanning laser vibrometer (SLV) will be used to estimate the location of the defects. The goal is to study the surface response characteristics of the structures without attaching a large number of sensors.

The main goal of SHM is to evaluate the performance of the structure, to determine the problems during the normal operation of the system and request the proper corrective actions. However, industry and research community hasn’t reach to these goals yet in the aerospace industry. It is necessary to develop new sensors, analysis methods, communication tools and software to achieve these goals.

When the researchers want to study the motion of the surface waves they need to attach the conventional sensors to many locations of the plate. Similarly, to find the best location to attach an exciter and sensors many experiments has to be performed after the piezoelectric elements are attached to many locations of the plate. The SLV is capable of
monitor the vibrations of the plate at the programmed locations without attaching any sensors. Experiments which would take several days can be performed in a few hours with the SLV. In this study, the performance of the SLV will be studied.

The Impedance [1-4] and Lamb Wave methods [5, 6] are widely studied SHM methods. Both methods are capable of detecting many types of defects, including cracks, change in surface shape due to pressure, corrosion and delamination. Attaching single piezoelectric element to the surface is enough to perform impedance method. The impedance analyzer is used to collect and analyze the data. By means of these studies it was observed that the impedance method was more sensitive to compressive forces and may be used to detect the loose bolts more easily [7-9]. However, this approach cannot estimate the location of the defects unless multiple piezoelectric elements are used. The Lamb Wave method evaluates the delay of the arriving waves to the sensor location. Based on this information, it is possible to estimate the location of the defects [5]. Researchers have used multiple piezoelectric elements for sensing to improve the sensitivity and performance of the method at the defect detection and estimation of its location [10, 11].

An alternate approach to the impedance analyzers replaces them with a circuit [12-15] to perform the analysis with a spectrum analyzer or monitored the phase shift [16] or used a digital multimeter to obtain spectral characteristics [17,18]. A specialized hardware had to be developed for the implementation of the impedance method with low cost hardware and minimal power consumption [22].

Another alternative to these methods was developed at FIU and called surface response to excitation (SuRE) method [19-21]. The surface is excited with a piezoelectric element and the propagation of the surface waves are monitored with another piezoelectric element or sensor.
Since, the laser vibrometer may monitor the surface waves, the SLV was used to evaluate the transfer functions between the excitation point and scanned points in this study. Based on this information, it was possible to estimate the location of the defect. In this study a Polytech PSV-400 SLV (Laser Doppler Vibrometer) was used. Either the beam was directed to the surface directly or with the help of a mirror.

For development of the SHM techniques the propagation of elastic surface guided waves on the structures has been studied extensively and many methods were developed [23]. The majority of the studies used either the Lamb wave method or the impedance method. In the following paragraphs detailed information will be given on these methods.

The surface guided waves (Lamb waves) are created by using piezoelectric elements in the SHM applications. Their propagation is monitored at the same location and/or additional locations with the piezoelectric elements. The structural irregularities or defects are detected from the change of the characteristics of the monitored signals. In general, development of additional wave patterns and their delay indicated defects and their locations. A very interesting and sophisticated approach for implementation of the Lamb wave approach is presented at reference 24. This approach may be used for many structures including very large ones since the generated Lamb waves are capable to travel along the surface of most of the materials without diminishing the signal strength [25-27]. In these studies, the sampling frequency should be selected very high to catch the motions of the waves. These data acquisition systems are quite expensive. Also, the complexity of the wave propagation and the reflections from the boundaries create very
complex wave patterns [28]. Researchers should isolate the waves coming from the possible defects and estimate their locations from the delay time.

The impedance method is the second well known SHM technique [29]. In this approach the impedance of a piezoelectric element attached to the surface of the structure is evaluated by using an impedance analyzer. A single piezoelectric element is enough for data collection. The impedance analyzer calculates the impedance at a selected frequency range. Generally, the analysis is below 100 kHz range because of the limitation of the impedance analyzers. Since the cost of the impedance analyzers are high many researchers have developed alternate methods to reduce the cost and to make the method more convenient [12-18].

Surface response to excitation (SuRE) [30] method was developed to detect the small changes at the part characteristics with a low cost setup. SuRE uses a piezoelectric element to excite the surface of the part and monitors the surface response with a sensor. This sensor is generally another piezoelectric element same as the one used to excite the surface of the material. Most of the researchers calculate the sum of the squares of the differences of the real part of the impedance or magnitude of the transfer function when they use impedance and SuRE method respectively. As stated previously the SuRE method requires a separate sensor in addition to the piezoelectric exciter.

The ceramic piezoelectric elements are relatively inexpensive and their sensitivities are very high. However, from previous statements herein it is not practical to attach tens of piezoelectric elements to the surface of a part to find the best locations to attach the exciting and monitoring piezoelectric elements. In this study, a scanning laser
vibrometer was used to evaluate the surface response characteristics after creating a grid or array of points with the Doppler Effect laser vibrometer; so the programmed points at the grid are monitored and their data is analyzed. The main advantage of the SLV is its flexibility. The number of test points can be increased very easily and tested surfaces are extremely small compare to any piezoelectric element.

The majority of researchers used the laser vibrometers for SHM by evaluating modal parameters like mode shapes, natural frequencies and damping ratios [31-32]. Sharma [33] used the Doppler Effect laser vibrometer to obtain information in calculating the strain energy distribution for defect detection. Staszewski et al [35-36] has used the Doppler Effect laser vibrometer to “capture” lamb waves to evaluate the integrity of an aluminum plate. Another important advantage of the laser based systems is not changing the mass or stiffness of a part [37] for the tests.

The Time Reversal Acoustics (TRA) method is a new trend in SHM. It sends and receives acoustic waves between the transducers to detect defects. Fink [38] and Wu et al [39] has discussed the TRA method. Sohn et al [40] has implemented the TRA for damage detection in composite plates.
II. THEORETICAL BACKGROUND

II.1 The Piezo Electric Materials

Piezoelectrics are a class of materials where a strain results in an electric field inside the material. In most cases, this can lead to a voltage out of the material, which can be read and interpreted by a computer or operator. Piezos have two modes. In direct mode, a strain is applied in a voltage is obtained. In converse mode, the opposite is true. A voltage is applied and results in a small movement or deflection of the material [41].

The Piezoelectric ceramics belong to the group of ferroelectric materials. The Ferroelectric materials are crystals which are polarized or polar without an electric field being applied. This state is also termed spontaneous polarization. Characteristic of this state is the thermodynamically stable reversibility of the axis of polarization under the influence of an electric field, described graphically by a hysteresis loop. Refer to figure 2.1. Ferroelectric Hysteresis.

The piezoceramics are of different composition with different metals at the molecular level with different ions, for example Ni, Bi, Nb, Sb. With these ions the piezoceramic may adjust to different individual piezoelectric and dielectric parameters as required.
The reversibility of the polarization, and the coupling between mechanical and electrical effects are of crucial significance for the wide use of piezos. Figure 2.2 shows the crystalline structure on a piezoceramics. From a crystallographic point of view, these piezoelectric materials exhibit a very peculiar crystalline structure. [41].
In the event of large changes of the electric field or mechanical stress, shifting occurs and the polarity of whole regions can be reversed as a result of domain reforming. These processes, and the irreversible displacement of domain walls, are some of the reasons for the familiar phenomenon of ferro-electric hysteresis.

During manufacturing, after the sintering process the polycrystalline piezoelectric ceramics are in a thermally depolarized state after this sintering process. If we observe from a statistical point of view, there is an almost uniform distribution of spontaneous polarization directions among the domains, and the material is isotropic, i.e. not piezoelectric. By applying a strong electric field (E) normally called like so, the spontaneous polarization is Ferro electrically reoriented to the saturation polarization (Ps). This produces a residual polarization parallel to the direction of the field, and the material is anisotropic, i.e. piezoelectric. There is more information regarding piezo
electric materials but don’t want to extend more and don’t believe is necessary. The use of the piezo electric material is to transmit the excitation at certain frequency to the tested material in question. The piezos, as called, are glued to the surface and wired to the equipment used to send the exciting frequency to the material. That is the explanation in lay terms. The word piezo comes from the Greek word Force.

Figure 2.3. The ceramic piezos. (Courtesy of Ref 65)
II.2 The Piezo mechanism

We can use the piezos to convert audio signals to sound waves. The nature of the piezoelectric effect is closely related to the occurrence of electric dipole moments in solids. The latter may either be induced for ions on crystal lattice sites with asymmetric charge surroundings (as in for example BaTiO3 and PZTs) or may directly be carried by molecular groups (as in cane sugar).[44]. The dipole density or polarization (dimensionality [Cm/m3]) may easily be calculated for crystals by summing up the dipole moments per volume of the crystallographic unit cell [53]. As every dipole is a vector, the dipole density P is also

![Figure 2.4. The ceramic piezos. (Courtesy of Ref 65)](image)

a vector or a directed quantity. Dipoles near each other tend to be aligned in regions called “Weiss Domains”. These domains are randomly oriented, but can be aligned using the process of Poling (not the same as magnetic poling), a process by which a strong Electric Field is applied across the material, usually at an elevated temperature [43]. Not all piezoelectric materials can be poled [54].

Of decisive importance for the piezoelectric effect is the change of polarization P when applying a mechanical stress. This might either be caused by a re-configuration of the dipole-inducing surrounding or by re-orientation of molecular dipole moments under
the influence of the external stress. Piezoelectricity may then manifest in a variation of the polarization strength, its direction or both, with the details depending on 1. The orientation of P (polarization) within the crystal, 2. Crystal symmetry and 3. The applied mechanical stress. The change in P appears as a variation of surface charge density upon the crystal faces, i.e. as a variation of the electrical field extending between the faces, since the units of surface charge density and polarization are the same, \([\text{C/m}^2] = [\text{C/m}^3]\). However, piezoelectricity is not caused by a change in charge density on the surface, but by dipole density in the bulk. For example, a 1 cm³ cube of quartz with 2 kN (500 lbf) of correctly applied force can produce a voltage of 12500 V [53]. Piezoelectric materials also show the opposite effect, called converse piezoelectric effect, where the application of an electrical field creates mechanical deformation in the crystal.

II.3 The Scanning Laser Vibrometer (SLV):

The SLV was used in all the experiments for non-contact measuring, for the four experiments. The SLV is a very expensive measurement tool. In SI measuring system goes to areas in the square mm to areas in the square meters. As previously exposed, this generation of SLV belongs to the laser-Doppler Effect vibrometer family that in the case of the one we have in our Mechatronics Laboratory is a precision optical transducer that is used for determining vibration velocity and displacement at fixed points.
As previously implied entire surfaces can be scanned with the SLV. Because of the laser beam bounces back from the surface and is read in the Vibrometer hard to reach locations can be scanned without much difficulty.

The area of testing regardless the shape of the structure part or material can be flexibly divided using an interactive grid that allows different shapes grids and number of points. Once the alignment is done by positioning a few points the grid can be laid out in the surface.

We can continue with the description of the Laser Doppler Vibrometer (LDV) and summarize that is a scientific instrument that is used to make non-contact vibration measurements of a surface. The laser beam from the LDV is directed at the surface of interest, and the vibration amplitude and frequency are extracted from the Doppler shift of the laser beam frequency due to the motion of the surface. The output of an LDV is generally a continuous analog voltage that is directly proportional to the target velocity component along the direction of the laser beam.

Some advantages of an LDV over similar measurement devices such as an accelerometer are that the LDV can be directed at targets that are difficult to access, or that may be too small or too hot to attach a physical transducer. In addition, the LDV makes the vibration measurement without mass-loading the target, which is especially important for MEMS (Micro electro Mechanical Systems) devices.
II.3.1 Principles of Operation [64]

A Scanning laser Vibrometer is generally a two-beam laser interferometer that measures the frequency (or phase) difference between an internal reference beam and a test beam. The most common type of laser in an LDV is the helium-neon laser [47] though laser diodes [46], fiber lasers, and other lasers are also used. The test beam is directed to the target, and scattered light from the target is collected and interfered with the reference beam on a photo detector, typically a photodiode. Most commercial Vibrometer work in a heterodyne regime by adding a known frequency shift (typically 30–40 MHz) to one of the beams. This frequency shift is usually generated by a Bragg Cell, or acousto-optic modulator.

A schematic of a typical laser Vibrometer is shown below. The beam from the laser, which has a certain frequency, is divided into a reference beam and a test beam with a beam splitter. The test beam then passes through the Bragg cell, which in turn adds a certain frequency shift. This frequency shifted beam then is directed to the target. The motion of the target adds a Doppler shift to the beam given by the equation

$$fd = 2\cdot v(t)\cdot \cos(\alpha)/\lambda,$$

where $v(t)$ is the velocity of the target as a function of time, $\alpha$ is the angle between the laser beam and the velocity vector, and $\lambda$ is the wavelength of the light.

The light scatters from the target in all directions, but some portion of the light is collected by the LDV and reflected by the beam splitter to the photo detector. This light has a frequency. This scattered light is combined with the reference beam at the photo-detector. The initial frequency of the laser is very high (> 1014 Hz), which is higher than
the response of the detector. The detector does respond, however, to the beat frequency between the two beams, typically in the tens of MHz range.

The output of the photo detector is a standard frequency modulated (FM) signal, with the Bragg cell frequency as the carrier frequency, and the Doppler shift as the modulation frequency. This signal can be demodulated to derive the velocity versus time of the vibrating target.

Figure 2.5. Basic components of a laser Doppler Vibrometer.
II.3.2 LASER Vibrometer Applications [64]

SLV’s are used in a wide variety of scientific, industrial, and medical applications. Some examples of their use are provided below:

- **Aerospace** – LDVs are being used as tools in non-destructive inspection of aircraft components [49].
- **Acoustic** – LDVs are standard tools for speaker design, and have been used to diagnose the performance of musical instruments [50].
- **Architectural** – LDVs are being used for bridge and structure vibration tests [51].
- **Automotive** – LDVs have been used extensively in many automotive applications [52], such as structural dynamics, brake diagnostics, and quantification of noise, vibration and harness (NVH), measurement of accurate speed [53].
- **Biological** – LDVs have been used for diverse applications such as eardrum diagnostics [54] and insect communication [55].
- **Calibration** – Since LDVs measure motion that can be calibrated directly to the wavelength of light, they are frequently used to calibrate other types of transducers [56].
- **Hard Disk Drive Diagnostics** – LDVs have been used extensively in the analysis of hard disk drives, specifically in the area of head positioning [57].
• Landmine detection – LDVs have shown great promise in the detection of buried landmines. The technique uses an audio source such as a loudspeaker to excite the ground, causing the ground to vibrate a very small amount with the LDV used to measure the amplitude of the ground vibrations. Areas above a buried mine show an enhanced ground velocity at the resonance frequency of the mine-soil system. Mine detection with single-beam scanning LDVs [58] [59] an array of LDVs [60], and multi-beam LDVs [61] has been demonstrated.
II.3.3 Types of Laser Doppler Vibrometer [64]

Single-point Vibrometer – This is the most common type of LDV. Vendors include Sunny Instruments Singapore, Polytec, MetroLaser, B&K, Brimrose and Piezojena.

Scanning Vibrometer – A scanning LDV adds a set of X-Y scanning mirrors, allowing the single laser beam to be moved across the surface of interest.

3-D Vibrometer – A standard LDV measures the velocity of the target along the direction of the laser beam. To measure all three components of the target's velocity, a 3-D Vibrometer measures a location with three independent beams, which strike the target from three different directions. This allows a determination of the complete in-plane and out-of-plane velocity of the target.

Rotational Vibrometer – A rotational LDV is used to measure rotational or angular velocity. Differential Vibrometer – A differential LDV measures the out-of-plane velocity difference between two locations on the target. Multi-beam Vibrometer – A multi-beam LDV measures the target velocity at several locations simultaneously [61].

Self-mixing vibrometer – Simple LDV configuration with ultra-compact optical head. These are generally based on a laser diode with a built-in photo detector, leading to a very rugged and compact optical system [62] [63].

Continuous Scan Laser Doppler Vibrometry – A modified LDV that sweeps the laser continuously across the surface of the test specimen to capture the motion of a surface at many points simultaneously
II.4 Damage Detection

The SuRE method calculates the transfer function between the excitation signal and the surface oscillation at the studied or determined grid location. Either the magnitude of the transfer function or the spectrum of the monitored oscillation is calculated since the excitation signal has a constant amplitude at all the frequencies. The characteristics of this transfer function change when the structure has a defect or a force is applied. The tool used in representing the difference of the magnitude of the transfer functions is the normalized squared differences calculated. The magnitude of the baseline (reference) transfer function was represented in the B matrix. The altered magnitude of the transfer function after the load was applied was the A matrix. The size of each matrix was N by M, could be an A by B matrix but this nomenclature is most commonly used. Where, N is the frequency values between 20 kHz and 30 kHz. M is the number of scanned points at the grid. The difference between the baseline and the altered transfer functions is calculated using (2.1).

\[ D_{i,n}^2 = (B_{i,n} - A_{i,n})^2 \quad i = 1 \text{ to } M, n = 1 \text{ to } N \tag{2.1} \]

To avoid the compensation of the negative and positive values the squares of the differences is calculated. The average of the squared differences is calculated with the following equation:

\[ AVE = \frac{1}{MN} \sum_{i=1}^{M} \sum_{n=1}^{N} D_{i,n}^2 \tag{2.2} \]

The normalized difference is calculated by using the calculated two parameters with the above equations.
\[ \delta_{i,n} = \frac{d_{i,n}^2}{AVE} \]  

(2.3)

The average of the differences for the considered frequency interval is calculated for each point with a vector \( \vec{\delta} \). The contour plot is prepared by considering the position of the \( M \) normalized squared differences at the grid.

\[ \vec{\delta_i} = \frac{1}{N} \sum_{n=1}^{N} \delta_{i,n} \]  

(2.4)

Using the computer program MATLAB an Algorithm was developed for these sets of equations in order to obtain some readings that could be easily interpreted by the person performing the experiments. The algorithms has some limitations but for the purposes of these experiments is a sound an excellent idea to be used.

Another way to say it is that is the same technical background since we are using the same method on all these experiments, but we can write basically the following: The SuRE method [8] was developed for SHM applications without using an impedance analyzer by considering the similar trend by the major researchers [43-46]. One piezoelectric element excited the surface and another one monitored the vibration. The magnitude of the transfer function between the input and the output or the spectrum of the monitored signal was calculated. The magnitude and spectrum both captured the same characteristics of the structure (material).

Depending on the condition of the structure (material) and loading some frequencies were transmitted and better compared to others. The sum of the squares of the differences the magnitudes of the transfer functions is calculated to evaluate the structural (material) integrity or changes at the loading conditions by using the following equation:
Where \( M_{j,i} \) is the magnitude of the transfer function or the spectrum of the jth data, it is compared with the magnitude of the reference signal represented in the equation by the \( M_{r,i} \) term. The magnitude of the transfer function is calculated at a number of different frequencies up to \( n \). In the equation for the Sum of the terms the \( i \) is the index from 1 to \( n \). The reference signal was taken at the beginning without any loading. In this study, only the loading was changed without introducing any defects to the beam.

Theoretically, and as experimentally demonstrated in a no loading case the magnitude or the spectrum should be identical when taking readings and the sum of the difference between the test cases and the reference (\( E \)) should be and is zero. The magnitude of \( E \) is supposed to increase when load is applied.

In addition, to what was previously presented for ceramic piezo electric we could provide some theoretical equations and principles to clarify more on the subject behind the ceramic piezo materials, Piezoelectricity is the combined effect of the electrical behavior of the material [54]:

\[
D = \varepsilon E
\]  (2.6)

\( D \) is the electric charge density displacement (electrical displacement), \( \varepsilon \) is permittivity and \( E \) is electric field strength, and if Hooke's Law:

\[
S = sT
\]  (2.7)

Where \( S \) is strain, \( s \) is compliance and \( T \) is stress.
May be combined into the so-called *coupled equations*, of which the strain-charge form is:

\[
\{S\} = \left[ s^E \right] \{T\} + [d^t]\{E\} \quad (2.8.a)
\]

\[
\{D\} = [d]\{T\} + \left[ \varepsilon^T \right]\{E\} \quad (2.8.b)
\]

Where \([d]\) term is the matrix for the direct piezoelectric effect and \([d^t]\) is the matrix for the converse piezoelectric effect. The superscript \(E\) indicates a zero, or constant, electric field; the superscript \(T\) indicates a zero, or constant, stress field; and the superscript \(t\) stands for transposition of a matrix.

The strain-charge for a material of the 4mm \((C_{4v})\) crystal class (such as a poled piezoelectric ceramic such as tetragonal PZT or BaTiO₃) as well as the 6mm crystal class

\[
\begin{bmatrix}
S_{1} \\
S_{2} \\
S_{3} \\
S_{4} \\
S_{5} \\
S_{6}
\end{bmatrix} =
\begin{bmatrix}
s_{11}^E & s_{12}^E & s_{13}^E & 0 & 0 & 0 \\
s_{21}^E & s_{22}^E & s_{23}^E & 0 & 0 & 0 \\
s_{31}^E & s_{32}^E & s_{33}^E & 0 & 0 & 0 \\
0 & 0 & 0 & s_{44}^E & 0 & 0 \\
0 & 0 & 0 & 0 & s_{55}^E & 0 \\
0 & 0 & 0 & 0 & 0 & s_{66}^E = 2(s_{11}^E - s_{12}^E)
\end{bmatrix}
\begin{bmatrix}
T_{1} \\
T_{2} \\
T_{3} \\
T_{4} \\
T_{5} \\
T_{6}
\end{bmatrix}
\begin{bmatrix}
0 & 0 & d_{31} \\
0 & 0 & d_{32} \\
0 & 0 & d_{33} \\
0 & d_{24} & 0 \\
d_{15} & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
E_{1} \\
E_{2} \\
E_{3}
\end{bmatrix}
\]

\[
(2.9.a)
\]
may also be written as (ANSI IEEE 176):

\[
\begin{bmatrix}
D_1 \\
D_2 \\
D_3
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & 0 & d_{15} & 0 & 0 \\
0 & 0 & 0 & d_{24} & 0 & 0 \\
0 & 0 & 0 & d_{31} & d_{32} & d_{33}
\end{bmatrix}
\begin{bmatrix}
T_1 \\
T_2 \\
T_3 \\
T_4 \\
T_5 \\
T_6
\end{bmatrix} +
\begin{bmatrix}
\varepsilon_{11} & 0 & 0 \\
0 & \varepsilon_{22} & 0 \\
0 & 0 & \varepsilon_{33}
\end{bmatrix}
\begin{bmatrix}
E_1 \\
E_2 \\
E_3
\end{bmatrix}
\]

(2.9.b)

Where the first equation represents the relationship for the converse piezoelectric effect and the latter for the direct piezoelectric effect [54].

Although the above equations are the most used form in literature, some comments about the notation are necessary. Generally \(D\) and \(E\) are vectors, that is, Cartesian tensor of rank-1; and permittivity \(\varepsilon\) is Cartesian tensor of rank 2. Strain and stress are, in principle, also rank-2 tensors. But conventionally and obligatory to clarify, because strain and stress are all symmetric tensors, the subscript of strain and stress can be re-labeled in the following way, for example: 11 \(\rightarrow\) 1; 22 \(\rightarrow\) 2; 33 \(\rightarrow\) 3; 23 \(\rightarrow\) 4; 13 \(\rightarrow\) 5; 12 \(\rightarrow\) 6. (Different convention are used by different authors in different pieces of literature. Say, some use 12 \(\rightarrow\) 4; 23 \(\rightarrow\) 5; 31 \(\rightarrow\) 6 instead.) That is why \(S\) and \(T\) appear to have the "vector form" of 6 components. Consequently, \(s\) appears to be a 6 by 6 matrix instead of rank-4 tensor. In total, there are 4 piezoelectric coefficients, \(d_{ij}, e_{ij}, g_{ij},\) and \(h_{ij}\) defined as follows:

\[
d_{ij} = \left( \frac{\partial D_i}{\partial T_j} \right)^E = \left( \frac{\partial S_i}{\partial E_j} \right)^T
\]

(2.10.a)
Where the first set of 4 terms correspond to the direct piezoelectric effect and the second set of 4 terms correspond to the converse piezoelectric effect. A formalism has been worked out for those piezoelectric crystals, for which the polarization is of the crystal-field induced type that allows for the calculation of piezoelectrical coefficients $d_{ij}$ from electrostatic lattice constants \[51\].

With this we have presented a very complete Theoretical background of the piezo materials. This also complements the previous exposition on ceramic piezo materials.
III. EXPERIMENTAL SETUP

We will introduce Four (4) Experimental setups in this dissertation.

III.1 CONVENTIONAL TESTS WITH SCANNING LASER VIBROMETER

III.1.1 Acoustic Application: Speaker, Test # 1

One of the applications of the Scanning Vibrometer is for speakers design and to diagnostic the operational and optimal range of performance. The experimental was divided into two set of test. The first test was to determine the optimal operational range, a maximum 10 kHz frequency was used. The equipment (vibrometer) plot the data obtained. A video was generated that makes easy the visualization of the behavior of the speaker through the frequency range. During the second test the frequency range was reduced to the optimal range, to a maximum of 2 kHz, where a better and stable performance is corroborated.

Equipment:

- 1.Polytec PSV 400 Scanning Vibrometer:
  - 1.a.PSV-400 Scanning Head
  - 1.b.OFV-5000 Vibrometer Controller
  - 1.c.Polytec DMS Data Management System
- Polytec PSV-400 Junction Box
The laser beam is placed at a distance of 48 inch in front of the speaker, leveling and centering the laser light beam with the center of the speaker. The Scanning Vibrometer is connected by the two wires attached to the speaker. The scanning Vibrometer generated the excitation to the speaker. The reading surface was selected to be at the membrane of the speaker being careful not to take points at the fixed metal round edge of the diameter of the speaker.
Figure 3.2. Speaker Radio Shack, 40-1333D, 8 Ω (a) front (b) back side.

**Parameters of the Experiment**

- **Distance**: 48 inch (from laser beam to speaker)
- **Frequency**: 10 kHz
- **Type of signal**: Periodic Chirp
Figure 3.3. Example of scanning process for 2 different scanning grid types taken during preliminary test. (a) Frequency response, (b) test points on the speaker.

III.1.2 Acoustic Application: Speaker, Test # 2

The second test was conducted reducing the frequency to 2 kHz using the same equipment and set up with Test # 1. Since the experimental setup was the same the figures were not included into the Thesis.

Parameters of the Experiment

Distance:  48 inch
Frequency:  2 kHz:
Type of signal:  Periodic Chirp
III.2 TESTING ALUMINUM BEAM FOR VIBRATION-Non Destructive Inspection

A common use for the Scanning Vibrometer is to perform non-destructive testing to determine the behavior of a material and or to predict possible failure before it happens.

The following test was conducted using a single Aluminum (Al) plate with a fiberglass coating in the back. The Aluminum plate has 1 glued ceramic piezoelectric at each end for a total of two “piezos”.

The plate was secured with a bench screw vise at the left end as shown in the picture below leaving the “piezo” on that end free and not connected. The “piezo” at the opposite side, right hand side, had the Scanning Vibrometer connected, so this ceramic piezoelectric, only this one, was used for the tests.

(a)
Figure 3.4. Example of scanning process for different scanning grid types during preliminary test. (a) Aluminum plate with fiberglass backing set up (b) Example of scanning process for different scanning grid types during preliminary test.

III.2.1 Aluminum Plate Test Set-up

Equipment:

Polytec PSV 400 Scanning Vibrometer:

- PSV-400 Scanning Head
- OFV-5000 Vibrometer Controller
- Polytec DMS Data Management System
- Polytec PSV-400 Junction Box
- Monitor and key board

Material: Al 6061, Dimensions: 16 in long x 1 5/8 in wide x 0.062 in thick
2 ceramic piezoelectric glued at the center line of the plate and at 2 inch of each end. Ceramic piezoelectric with two wires soldered on the same face.

Figure 3.5. Top view 2 ceramic piezoelectric glued and connected to wires at each end.

Figure 3.6. Back view with fiberglass coating.

Parameters used in the experiment:

Distance: 53 inch
Frequency: 40 kHz
Type of signal: Sweep
Points 59
III.3 TESTING ALUMINUM THIN SLENDER PLATE SURFACE WAVES

The experimental set up is shown in Figure 3.7. The experimental setup was prepared to study the surface response of an aluminum thin slender plate or slender plate as we will call it in this portion of the experiment, when loads were applied to different locations of the slender plate while a piezo excited the thin plate surface.

Figure 3.7. Experimental set up including: laser vibrometer scanning head, junction box and control center, amplifier, slender plate frame.

A ceramic piezo of ¾ inch diameter was attached to an aluminum slender plate. Dimensions of the beam or slender beam for this experiment: 2” wide, 1/32” thick and a length of 36 inches (Figure 3.8). An epoxy adhesive was used to attach the piezos to the
aluminum slender plate. Two additional slender plates were prepared similarly by using the aluminum slender plates of 1/16” and 1/8” thick.

The aluminum slender plates were set in the experimental setup presented in figure 3.9.

A frame was prepared and the Aluminum slender plate was secured in the frame. A total of ten threaded bolts in the frame were used to apply a load to the slender plate at preselected locations.

The Polytec PSV-400 generated the excitation signal. The sweep sine wave is generated in the 20-40 kHz frequency interval to keep the signal/noise ratio to the minimum. The signal was magnified by using a TEGAM Power Amplifier Model 2348 to a 30 Vpp Amplitude. The piezo is excited with the magnified signal by the Power Amplifier.

![Figure 3.8. The aluminum slender plate with the attached piezoelectric element.](image)

Acquisition was performed with the Doppler Effect laser vibrometer PSV-400. After a number of points were set in a grid The PSV-400 Polytec scanning laser vibrometer directed the laser beam to the pre-programmed grid number of points and measured the surface vibrations.
III.4 TESTING AN ALUMINUM PLATE

The simplified diagram of the experimental setup is presented in Figure 3.11. The surface response characteristics of an aluminum plate were studied while load was applied to the different points of the plate. A piezo from American Piezo Company (APC), Model APC-850 and ¾” diameter, glued with epoxy to the Plate. Prior, American Piezo Company donated two piezos to the writer and factory glued the piezos to two identical plates donated by another source. The plates were used in another set of experiments. Going back to this experiment, the plates, in this experiment is a 24”x24” plate of tempered 2024 aluminum plate and 1/16” thick. The plate was placed inside a wood frame and held horizontally on top of a test structure used in a previous experiment and modified by Dr. Tansel and the
writer for this experiment in particular. A mirror is placed at a 45 degrees angle. After acquisition and determining the number of points the PolyTech PSV-400 scanning Doppler Effect laser Vibrometer directed the beam towards the mirror in the x axis or the horizontal. The beam reflects in the glass mirror surface and goes in the vertical direction or y direction reading the preset number of points in the plate located above. Please see the figures for clarity:

![Image of Doppler Effect laser vibrometer PSV 400.](image)

**Fig-3.10.** The Doppler Effect laser vibrometer PSV 400.

Figure 3.11 and Figure 3.12. While very advanced in the course of the experiments this writer investigated a special mirror was required from the same manufacturer of the Doppler Effect laser vibrometer or by another source, but this type of mirror has to be a special that will not distort the image rather
Figure 3.11. The schematic of the experimental setup.

maintain the integrity of the laser beam after reflection, something a regular mirror will not be able to accomplish, because these types of mirrors are designed for the eye with a different purpose and use. Due to lack funds we continued and kept working on the experiment with the regular mirror. This mirror created multiple weak reflections as predicted. The laser beam which reflected from the bottom surface of the aluminum test plate went back to the lens of the scanning laser vibrometer by obviously following the same path.
This particular experimental setup allowed applying loads using a 24 pounds load in each of the four locations as a concentrated load in each pre-determined location. In addition, by selecting a specific target area in 4 different locations of the plate and predetermining the number of points on to be read by the laser in each location and the positioning of the applied force the pressure point or location was very easy to control in order to check the experiment with ease. This experimental setup allowed us to apply a known force to any point of the upper surface of the test plate by simply placing a weight. In these test, the weight was a 10.8 kg (24 pounds). Also, the pressure was easily controlled by selecting the dimensions of the contact area between the weight and the plate.
Figure 3.12. The structure of the experimental setup.

The controller of the scanning Doppler Effect laser vibrometer generated a sweep sine wave that was used for this experiment. The excitation signal frequency was started from 20 kHz to avoid audible noise and went up to 40 kHz with 1.5V peak to peak Amplitude. The amplitude of this signal was magnified to 30 V peak to peak by passing it through the famous TEGAM model 2348 Power Amplifier used in the previous slender plate experiment. The magnified sweep sine wave was applied to the piezoelectric Amplifier.

First, in each location that would be experimented on the test plate a reference signal was collected without any loading. That was to be used as the baseline readings. All the
points at the grid were scanned doing a certain number of passes for the baseline. After the loading was placed in the upper part, via a 24 pounds weight, of the plate the points at the grid were scanned again several times in the four (4) different locations predetermined by the experimenter. The results, as in all the testing were processed with the MATLAB Algorithm as explained herein before.
IV. RESULTS AND DISCUSSIONS

In this section results of four studies will be presented. First the scanning laser vibrometer will be used with a speaker to animate the cone motion. Later, the same program will be used to animate the motion of a beam. The existing mode shape analysis program of the scanning laser vibrometer will be used for these two studies. The results of the other two studies will discuss load location estimation at a beam and at a plate by using the SLV. The developed programs in this study will be used for the analysis of the experimental data in these two studies.

IV.1 CONVENTIONAL TESTS WITH THE SCANNING LASER VIBROMETER

IV.2 Acoustic application: Speaker, Test #1

Mode shape analysis: Speaker, Test # 1 and # 2: From the Figures 4.1 - 4.3, it was observed that the optimal operation range of the speaker is below 2 kHz, and it has a spike at 450 Hz
Figure 4.1. Display on LASER CRT of Speaker Test.

Figure 4.2. Chart 1- Speaker Test 1 m/s up to 10 kHz with a Periodic Chirp signal.
Figure 4.3. Picture of the Scanning Vibrometer monitor showing the chart and the animation representation/

The 3-D animation of the speaker was prepared at 450 Hz. The cone of the speaker moved up and down without major deflections in Figure 4.4.
Figure 4.4. (a), (b) and (c) Pictures from the animation of the speaker at 450 Hz, showing the motion of the cone.
IV.1.3 Acoustic application: Speaker, Test # 2

The second test was performed by using the same equipment and set up with Test # 1. The response is presented in Figure 4.5. Based on these results, a series of test frequencies were selected and motion of the cone of the speaker was studied (Figures 4.6-4.8)

**Parameters**

Distance: 48 inch

Frequency: 2 kHz:

Type of signal: Periodic Chirp

![Figure 4.5. Chart 2- The spectral response of the speaker Speaker Test 2 up to 2 kHz with Periodic Chirp signal. m/s versus Frequency up to 2 kHz.](image)
The second test agreed with the previous results. The highest spike was at **447.5 Hz** with a Magnitude of **0.0010753 m/s**. For complete data refer to Appendix.

The test result is outlined in Table 4.1.

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Magnitude [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>440</td>
<td>0.0010478</td>
</tr>
<tr>
<td>441.25</td>
<td>0.0010543</td>
</tr>
<tr>
<td>442.5</td>
<td>0.0010648</td>
</tr>
<tr>
<td>443.75</td>
<td>0.0010708</td>
</tr>
<tr>
<td>445</td>
<td>0.0010687</td>
</tr>
<tr>
<td>446.25</td>
<td>0.001064</td>
</tr>
<tr>
<td><strong>447.5</strong></td>
<td><strong>0.0010753</strong></td>
</tr>
<tr>
<td>448.75</td>
<td>0.0010734</td>
</tr>
<tr>
<td>450</td>
<td>0.0010663</td>
</tr>
<tr>
<td>451.25</td>
<td>0.0010517</td>
</tr>
<tr>
<td>452.5</td>
<td>0.0010594</td>
</tr>
<tr>
<td>453.75</td>
<td>0.0010481</td>
</tr>
<tr>
<td>455</td>
<td>0.0010342</td>
</tr>
</tbody>
</table>

Table 4.1
The cone was flat when it was animated at 447.5 Hz. When the test was repeated at 192.5 and 896.3 Hz, the cone did not stay flat during the motion (Figures 4.7 and 4.8). It deflected.
Figure 4.6 (a), (b) and (c) Pictures from the 3-D animation at 447.5 Hz, showing cone motions. The cone was flat during the motion.
Figure 4.7. Pictures from the animation at 192.5 Hz showing some distortion.
Figure 4.8. Pictures from the animation at at 896.3 Hz showing some distortion. (a) (b) (c) and (d) different stages of the motion.
IV.2 STUDY OF THE VIBRATION OF AN ALUMINUM BEAM

An aluminum beam was excited with a piezoelectric element. The distribution of the vibration was studied by using the scanning laser vibrometer with exploratory purposes. The picture of the beam is presented in Figure 4.9. The monitored frequency response is presented at the Figure 4.10. The study indicated that the vibrations reach to different points of the beam and scanning laser vibrometer can measure them. The variation of the amplitude at the surface is presented at Figure 10. The animation of the plate motion is presented at Figure 12. Since we excited the surface the Figure 12 was not the mode shape analysis. It only indicated the correlation of the monitored waves with the excitation signal. As previously stated the beam with fiberglass backing; the material was Aluminum 6061, 16 inches long x 1 5/8 inch wide x 0.062 inch thick.

Figure 4.9. Scanning Process, picture downloaded from the Scanning Vibrometer CRT monitor.
Figure 4.10. Excel Chart emulated the one displayed in the Vibrometer screen for the monitored frequency response measure for 59 points.

Figure 4.11. The amplitude of the vibrations (a) and 3-D representation of it (b).
Figure 4.12. (a-f) Aluminum beams 3-D animation when a piezoelectric element excited the surface.
IV.3 ESTIMATION OF LOAD LOCATION AT AN ALUMINUM BEAM

The fundamental assumption of the SuRE and the impedance method are similar. Impedance method assumes that real part of the impedance of any point on the structure within a carefully selected frequency range is like a fingerprint. For the SuRE method this is the magnitude of the transfer function or the spectrum of the monitored signal. This curve is representative and should be the same as long as the structural integrity or loading is not changed. The spectrum of the monitored signal without any change at the loading condition is presented in figure 4.13. The spectrums changed drastically when the load was applied. See changes in figure 4.14.

Figure 4.13. The spectrums of a point on the grid for two successive no measurements.
The effect of loading on the surface response of different points distributed in the slender plate was studied by using the SLV. The vibrations of 72 points located in a 3X24 grid were monitored by the SLV. First the spectral characteristics of all the points at the grid were obtained without any load. The force was applied to different points of the beam by tightening bolts one at a time with a torque wrench at the same amount of loading. The spectral characteristics of all the grid points were estimated one by one with the load. In Figure 4.15 the sum of the squares of the differences for the beam are presented at three different loading conditions. In each case, the biggest sums of the squares of the differences were observed at the location of the external force and the algorithm showed this area with red color.
Figure 4.15. The variation of the sum of the square of differences when the load was applied to different points. When the force was at the left (a), center (b) and right (c) of the beam.

Similar results were obtained when the tests were repeated with three other beams with different thicknesses (1/8”, 1/16” and 1/32”). Obviously the thinner beams were the most affected and identification of the location of the external load was the easiest and most accurate. Again, the aluminum beam in this experiment was 36” long x 2” wide x 1/32” thick slender beam or slender plate.
IV.4 ESTIMATION OF LOAD LOCATION AT A PLATE

To simulate the inspection of plates at hard to reach places, the laser beam of the SLV was directed to the horizontally positioned aluminum beam with an ordinary mirror. The mirror had 45° angle respect to the horizontal plane. A load with known weight was placed on the plate to apply a concentrated load. The normalized squared differences were calculated separately for each point at the grid. The magnitude of the transfer function without and with the load is presented in Figure 4.16. The magnitude characteristics significantly changed at some frequency intervals after the load was applied. The experiment was repeated three times. There were no loads in the first two experiments. In the third experiment loads were applied. The normalized sum of the squares of the differences for two no load and load- no load tests are compared at Figure 4.17. The difference was significant when the load was applied.

![Transfer Function](image)

Figure 4.16. FFT spectrum of a point on the grid before and after loading.
The magnitudes of all the transfer functions at the grid changed with the loading of the test plate with a significant weight. Generally, the ones close to the loading point had the most changes. First, the reference data was taken and transfer functions were calculated when there was no load. Later, the plate was divided into four quadrants and the weight was placed at the center of each quadrant of the test plate. The piezoelectric actuator was used to create the surface waves in the 20-30 kHz range and the vibrations of all the points at the programmed grid points were measured without any load and when the load was applied to
the center of each quadrant. The magnitude of the transfer functions between the excitation signal and vibration of the grid point were calculated. To confirm dimensions the plate was a 24”x24”x 1/16” thick plate of tempered 2024 aluminum.

Figure 4.18. The locations of the weight at four consecutive tests.

The contour plots were prepared by calculating the normalized squared differences between the magnitudes of the transfer functions obtained without any load and with load. The excitation frequency range was changed in the experiments. The most meaningful contour plots were obtained when the normalized squared differences were calculated between the 20 kHz to 30 kHz range. The location of the weight and the contour plot of the normalized
squared differences at the grid points are presented in Figure 4.19. In all the test cases the location of the external force was calculated accurately.
Figure 4.19. Estimation of the location of the weight (a) Top Left, (b) Top Right, (c) Bottom Left, (d) Bottom Right.
V. CONCLUSIONS

The Scanning Laser Vibrometer (SLV) is a very powerful experimental tool. It measures the vibration of the programmed points without attaching any weight to the considered part. This scientific instrument may collect the data from many points automatically without any input from the operator once these locations are programmed. The software calculates the transfer functions and mode shapes by using the Fast Fourier Transformation (FFT).

The Surface response to excitation (SuRE) method was developed to detect the defects of the parts with reasonable investments. It requires excitation of the surface at one point with a piezoelectric element. The propagation of waves to another point is monitored with a similar piezoelectric element or any contact or non-contact sensor. A spectrum analyzer is needed to generate the excitation signal and characterize the vibration of the test point. In this study, the SLV was used to measure the vibrations of desired points without attaching any sensors.

The SLV system and its software were tested by performing a series of experiments with a speaker and a beam. Tests with the speaker demonstrated that the SLV may be used to animate the motion of a dynamic system easily. The tests with the aluminum beam indicated that the created vibrations with a piezoelectric element may be monitored at the entire beam.

The SLV was used to estimate the location of an external force on an aluminum beam and a plate. The SuRE method was used for the analysis of the data. The location of the external force was estimated accurately in all the performed tests. Estimation accuracy
was the best at the thinnest aluminum beam. Since the external force created the minimum deformation at the aluminum plate the location of the contour plots were not as crisp as the beam tests.

The study indicated that the SLV and SuRE could be used together. The SLV-SuRE combination allows inspection of hard to reach parts in special applications such as inspection of the critical surfaces of a rocket at the launching pad or a small test object in a vacuum environment. An SLV located at the launch pad may collect the data and eliminate the need for transfer of the similar data from the SHM system of rocket wirelessly. Also, the SLV-SuRE combination may be used to determine the best locations for the exciting piezoelectric element and the sensor(s) of an SHM system without attaching any transducers to the part.

Note: See REFERENCES in next page.
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