VOICE-DRIVEN STROBOSCOPIC LASER ILLUMINATION WITH MEMS

A Major Qualifying Project Report

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Professor Cosme Furlong
Abstract

The need exists for doctors to examine the human vocal cords in order to diagnose vocal disorders and to examine post-operation conditions. Current technology allows doctors to use methods such as video laryngoscopy in order to evaluate vocal chord motions in two-dimensions. However, it is the third dimension, where the mucosal wave propagates, that doctors are most concerned with. Fortunately, recent developments have proven that three dimensional analysis of the vocal folds will be possible through the use of laser fringe projection, assuming that images appear perfectly still when viewed through a standard speed video camera. In principle, still vocal images can be achieved by strobing a light at the same frequency at which the vocal chords are oscillating.

The Voice Driven Stroboscopic Laser Illumination Project incorporates the use of Micro-Electro-Mechanical Systems (MEMS) accelerometers that measure the fundamental frequency of the vocal folds and strobe a laser illumination source at the same frequency. This was achieved through the creation of a Virtual Instrument in LabView that was interfaced with a Data Acquisition system (DAQ) and a laser diode light source. The system and governing theory was validated by successfully ‘freezing’ the motions of an oscillating cantilever beam. In addition, the system demonstrates that a MEMS accelerometer can be used to effectively measure the fundamental frequency of vocal fold vibration.
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Executive Summary

Each year thousands of people experience problems with their voices that interfere with common daily activities. Those who suffer represent many walks of life; however, many rely heavily on their voice in order to fulfill their job requirements. Voice professionals such as these may be singers, actors, radio personalities, public speakers, teachers, doctors, and business men. In all cases, the interruption caused by vocal disorders must be addressed promptly so they can return to their normal way of life. Fortunately, there is a special discipline within the Medical Sciences that specializes in treatment and rehabilitation of the vocal chords.

Laryngologists, or specialized doctors who study the disorders associated with the vocal chords and larynx, use cutting-edge technology to diagnose vocal disorders. Currently, those with vocal disorders may be examined with multiple technologies. Initially, if doctors rule out an infection such as laryngitis, patients may be evaluated using stroboscopic laryngoscopy. This technique employs the use of an endoscope, stroboscopic light source, and camera. During the procedure, the laryngologist inserts an endoscope down the throat through the nasal cavity or mouth in order to capture footage of the vocal chords. Similarly, if a more detailed analysis of the vocal folds is needed, a doctor may use other laryngoscopic technologies such as videokymography or high-speed video to view different aspects of vocal chord motion.

While the current techniques available for analyzing the vocal chords serve as powerful medical tools for laryngologists, there are two fundamental shortcomings that these systems all have in common. The first is that they provide doctors with two-dimensional motions when the vocal folds vibrate in a three-dimensional fashion. Two-dimensional images are not capable of
portraying the motions of the mucosal wave which propagates in the third dimension. A correct understanding of this waveform is crucial for diagnosing improper vibrations that may be less obvious in two dimensions. Moreover, the ability to view mucosal wave displacements is one improvement that would lead to more concise, less traumatic, and more successful vocal surgery since the surgeon could pinpoint the exact area of oscillatory deficiency.

The second fundamental flaw with current technology is that the data obtained from current techniques is qualitative in nature resulting in a subjective diagnosis to a given condition. Laryngologists study the two dimensional images and evaluate the motions of the vocal chords compared to other footage they have seen. Today, the correct diagnosis of unusual vocal disorders relies heavily upon the experience of the laryngologist. In fact, studies have been performed where multiple laryngologists have diagnosed the same ailment in a myriad of different ways.

The need clearly exists for a technology that provides laryngologists with three dimensional, quantitative data of vocal chord vibration. Fortunately, a technique called laser fringe projection has been developed, largely due to efforts of the Center for Holographic Studies and Laser micro-mechatronics at WPI, to study objects in three dimensions. This technology makes uses of laser fringes and computer aided design software (CAD) to generate three dimensional renderings of objects in focus. If this technology could be adapted for use on the vocal chords, it would enable doctors to view the vocal chords in three dimensions while giving them the opportunity to rotate the object and view its motion at different time steps. More specifically, laryngologists would have quantitative data of the vocal fold vibrations that could be used with high confidence to make the correct diagnosis.

-x-
In order to make laser fringe protection viable in the field of laryngoscopy, several goals must be achieved. First, the laser projection components must be placed on an endoscope so they can be projected on the vocal chords. Following this, crisp images of the fringes must be obtained and analyzed using a CAD software package. These images must be obtained while the vocal chords appear absolutely still.

In theory, clear images of the fringes can be obtained if the stroboscopic light source used in laryngoscopy is matched to the fundamental frequency or the frequency that the vocal folds are oscillating at. Many current stroboscopic light sources use microphones to match the light source to within 5 Hz of the true frequency. The question is, how closely does the light source need to match the fundamental frequency and how will this be accomplished?

The goal of our project was to develop the stroboscopic technology that was necessary to freeze the motions of the vocal chords. The final product needed to be adapted for use on the human neck, where the fundamental frequency could be tracked and used to drive a stroboscopic light source. Our group determined that these goals could be accomplished through four major stages of development. First, we needed to create a Virtual Instrument (VI) in LabView that would track the fundamental frequency of the vocal folds. Second, we had to design a mechanical system to validate the theory of obtaining still images with stroboscopy along with our VI’s ability to track the correct frequency. Next, we needed to design a throat-based apparatus using Micro-Electro-Mechanical Systems (MEMS) to measure the vibrations on the neck. Finally, we were required to validate that our neck apparatus, when used in conjunction with our VI, would correctly track the fundamental frequency of the voice.
The main component to the success of our project was the development of the VI in LabView. Our group created a program that would read an input signal from a MEMS accelerometer and use a Fast Fourier Transform (FFT) to create a power spectrum of the signal. From there, functions programmed into LabView were able to eliminate DC offset and track the fundamental frequency with a resolution of 1 Hz. Since our group determined that higher resolution was necessary, we derived an interpolation algorithm within the VI that would allow the program to achieve resolutions of .1 - .01 Hz. This tracking of the fundamental frequency was used to create a digital pulse signal that drove a stroboscopic laser diode light source.

Following the development of the VI, our group designed a shaker-driven cantilever beam system to emulate 100 Hz vibrations of the vocal chords. Using an accelerometer mounted on the base of the beam, we were able to measure the frequency of the beam’s vibrations and input that data into our VI. When our stroboscopic laser diode light source was projected onto the side of the moving beam, we were able to see perfectly frozen images of the object as demonstrated in Figure 1. From this experiment we successfully determined that resolutions of at least .1 Hz were needed to achieve these results.

Figure 1: Frozen Cantilever Beam
The next phase in the project was to adapt the use of a MEMS accelerometer to the human throat. Our group accomplished this goal by selecting an accelerometer with low noise and then designing a circular mount that would align the axis of excitation perpendicular to the neck. This mount was then placed in a commercial neck brace and pressed against the throat. In addition to selection of a low noise accelerometer, our group constructed a low-pass filter that increased the signal-to-noise ratio of the apparatus. This enabled correct peak tracking sensitive enough to be effective even when the user was barely phonating. Figure 2 and Figure 3 show the mount used to house the accelerometer and the collar being worn during measurements.

![Model of Compression Mount](image)

Figure 2: Model of Compression Mount
The final step of the project was to validate that our MEMS collar and VI were actually tracking the fundamental frequency of the voice and not being deterred by harmonics or accelerometer noise signals. To achieve this, our group took a series of simultaneous measurements with an accelerometer and a microphone. The results of these experiments proved that our project correctly tracked the fundamental frequency of the voice, assuming that the microphone was correctly calibrated. In addition, the measurements proved that an accelerometer was superior to a microphone because it would not incorrectly track harmonics that occasionally became present due to resonance in the throat. Figure 4 shows how closely the plots of the accelerometer and microphone were and validates that our project tracks the fundamental frequency.
In conclusion, our project successfully demonstrated that a MEMS accelerometer could be used in conjunction with peak-tracking software and stroboscopic illumination to freeze objects in motion. We also demonstrated that LabView could obtain resolutions of much less than 1 Hz and could be used effectively to track peaks and generate the pulse signal necessary for stroboscopy. Likewise, we were able to prove that an accelerometer, when placed correctly on the neck, could accurately track the fundamental frequency of the voice. Based on these results, we can conclude that the use of fringe projection in laryngoscopy is viable and that further research must be performed to make this system a reality.

Figure 4: Accelerometer vs. Microphone Data
1 Introduction

The Voice Driven Stroboscopic Laser Illumination with MEMS project may be difficult for a new reader to fully appreciate at first glance. What does the system do? Why does a light source need to be stroboscopic? What is a Micro-Electro-Mechanical System (MEMS)? These may be some common questions that shuffle around in someone’s thoughts as they read the title page to the report. It is true, the project’s span is immense, but in its simplest form, the project is a necessary step in the development of a 3D tool that laryngologists can use to provide better diagnosis to the thousands of patients who suffer from vocal disorders each year.

Current technology used to analyze the vocal chords provides laryngologists with two-dimensional qualitative images of the vocal chords. Based on these results, doctors must use their experience to diagnose problems associated with this organ. The problem with this type of analysis is that is completely subjective to the point where multiple doctors may diagnose the same disorder in multiple ways. Less experienced laryngologists may be especially susceptible to incorrect interpretations since they have little benchmark data to base their decisions upon. Fortunately, laser fringe projection technology exists that could provide doctors with the tools they need to provide diagnosis to their patients based on three-dimensional, quantitative data.

In order for laser fringe projection to be possible, the object of study must be completely still. Until this point in time, this has not been an issue since a large part of the technology’s application has been on static objects. If this technology was to be used as part of a system to
analyze the vocal chords, there would need to be some technique to “freeze” the vocal chords so they would be perfectly still. Herein lays the motivation of our project.

According to the theory of stroboscopic illumination, an oscillating object can appear perfectly still if it is viewed only once during its cycle. Therefore, if a light were to be flashed once during the cycle, the image would appear “frozen” at that particular location. If this theory is applied to the study of the vocal chords, the vibrating vocal folds can appear perfectly still if a light is strobed at the same frequency of vibration. This task would be elementary if the vocal chords moved at a constant known frequency; unfortunately, this is not the case. A working stroboscopic illumination system would need some method of reading the frequency of vocal fold oscillation which is also known as the fundamental frequency.

The goal of The Voice Driven Stroboscopic Laser Illumination with MEMS project is to develop the technology necessary to freeze the motions of the vocal folds. A successful project will employ the use of a MEMS accelerometer to continuously measure the fundamental frequency enabling the light source to dynamically adjust to a changing voice. Likewise, the project will validate the theory of stroboscopic illumination on an oscillating object in addition to verifying that the final result is capable of measuring the fundamental frequency of the voice correctly.

This report will discuss the background research and theory that is a necessary prerequisite to the full understanding of our developments. In addition, the methods and phases of the project that led to the successful development of a final product will be discussed. The report will be concluded with relevant results, conclusions and recommendations that support future development of laser fringe projection as applied to the vocal folds.
2 Background

2.1 Anatomy and Oscillation of the Vocal Chords

The human vocal chords are two ligaments that are located horizontally across the larynx as seen in Figure 5. These two ligaments vibrate in response to pressure changes created during phonation to produce the majority of the sounds that we hear in speech and singing. The main frequency at which the vocal chords oscillate during phonation is called the fundamental frequency and usually represents the most predominant frequency that can be heard (Titze, 2000).

![Figure 5: Human Vocal Chords](image)

During phonation, the movement of the vocal chords can be described in three dimensions as referenced to Figure 5 and Figure 6. First, the vocal folds move inwards and outwards in the X direction depending on the exact stage of phonation (left to right in Figure 5). Likewise, the vocal chords can also expand and contract in the Y direction (up and down in Figure 5) which causes them to change thickness and results in additional displacement in the Z
direction (in and out of the paper in Figure 5). A forth motion of importance exists when the vocal chords achieve sustained oscillation in the form of a “mucosal wave” that propagates in the Z direction (Dr. Franco, 2007). This can be demonstrated in Figure 7 which shows how the mucosal wave forms and propagates when the two vocal folds make contact. Healthy movements of the vocal chords in all directions are required for a voice to achieve a high quality tone that may be characteristic of a well-trained singer.

Figure 6: X-Y-Z Coordinates Applied to Body Plane System

Figure 7: Schematic of Mucosal Wave Propagation
There are many diseases that can cause the vocal chords to oscillate differently or become irritated. In many cases, even minor inflammations are sufficient to prevent a voice professional such as a singer or radio personality from performing their job. These conditions can be separated into two main categories called organic (or congenital) and functional disorders. Congenital disorders can be classified as any type of identifiable lesion, sore, or growth that may appear on the vocal chords. Functional disorders are classified by cases when vibrations produced by the vocal chords are irregular but no lesions or growths are present on the vocal folds. The latter is far more difficult to analyze since the deficiency cannot easily be seen by the two-dimensional observational techniques that exist today (Titze, 2000).

Figure 8: Vocal Cyst
Some vocal disorders are sustained due to overexertion or infection, others may be genetic and present since birth, and some cases are due to growths that appear during someone’s life. Congenital ailments are often encountered by voice professionals or any other individual who has subjected their vocal chords to a severe strain such as sustained screaming or loud singing. In many cases, overexertion results in the formation of vocal nodules, vocal polyps, cysts (Figure 8), and contact ulcers. These ailments can be easily diagnosed and treated by therapy, periods of rest, and sometimes surgery. For the cases where patients are born with severely deformed vocal chords, corrective surgery and speech therapy may be the only methods available to correct the voice. In these cases, a detailed analysis of vocal chord motion is required and can sometimes be very difficult to obtain (NIDCD, 2007).
### 2.3 Current Technology Available to Analyze the Vocal Chords

The most common form of vocal fold analysis used by laryngologists today is laryngoscopy. In this technique, the doctor inserts a camera down a patient’s throat using a flexible endoscope that enters through the nasal cavities or a rigid endoscope inserted through the mouth. Next, a light source is projected on the vocal chords, which allows a camera to capture images of the organ in motion so that they appear semi-still. Figure 9 shows the components of laryngoscopy.

![General Components of a Laryngoscopy System](image)

**Figure 9: Components of Laryngoscopy**

Currently, there are three distinct laryngoscopy techniques that exist. The first technique, shown in Figure 10, is called digital video stroboscopy. In this technique, a strobing light source is used to slow down the motions of the vocal chords enough so they can be
examined by a laryngologist who views a video capture of the vocal chords. The strobing light system can adjust to within ± 5Hz of the true frequency to produce near-still images of the vocal chords, or it can be set to allow for fluid motion to be observed (KayPen 9295, 2008).

A second technique, called Videokymography (VKG), scans a thin line of the vocal chords at a very rapid rate (See Figure 11). The large quantity of scan data is compiled on a video and allows the laryngologist to view vibrational data in a slow, frame-by-frame manner similar to high-speed camera footage (KayPen 8900, 2008). The last commonly used method is high-speed video which enables doctors to see detailed movements of the vocal chords as they would appear in digital video stroboscopy (KayPen 9700, 2008).
Each of the current methods used to analyze the vocal chords has its own unique advantage that it can offer to a laryngologist. In some cases, doctors may use more than one system if more detailed information about the vocal chords is needed in order to make a better diagnosis. To date, no one system is capable of examining all of the important aspects of vocal fold motion.
2.4 Limitations of Current Technology

Despite the differences among systems, they all share a common tie; their results provide doctors with two-dimensional, qualitative data that the laryngologist must be able to interpret in order to prescribe the correct treatments. There are two fundamental flaws with these results. First, two dimensional images only provide doctors with the ability to view motions in the transversal plane (x-y plane in Figure 6). This point of view is suitable for recognizing easily seen disorders such as vocal polyps or nodules, but lacks the ability to show concealed disorders that may only be diagnosed by studying the displacements of the mucosal wave. In order for laryngologists to inspect all important aspect of the vocal chords, they need to have a method for seeing the magnitude of the three-dimensional motions of the mucosal wave propagating in the $Z$-direction.

The second fundamental flaw with current technology is that the data obtained from analysis is in a qualitative format. When data is of this nature, heavy emphasis is placed on the training and experience of the individuals who interpret the results. That is, the data is completely subjective and can be interpreted differently if viewed by multiple people. Studies have been performed where multiple laryngologists have examined the same videos of oscillating chords only to produce a different diagnosis of the same problem (Dr. Franco, 2007). When conflicting theories arise based on subjective data, how does one determine which is correct?
2.5 **A Need for Improved Methods of Vocal Fold Analysis**

The need exists for a method of laryngoscopy that will provide doctors with the ability to view vocal fold motions in three-dimensions in a quantitative manner. A technology of this type would allow doctors to fully visualize the elastic motions of the mucosal wave and would supply them with numerical data indicating the wave displacement as a function of time. With this information, a doctor could determine whether or not the vocal cords are hyper-elastic (excessive wave displacements) or hypo-elastic (insufficient wave displacements) (Titze, 2000). This type of information would be especially applicable to vocal surgery since the doctor would be able to pinpoint small areas of the vocal chords that needed correction thereby minimizing the trauma to the patient while increasing the probability of success. In a similar manner, post-operation evaluations would be more effective since the surgeon could numerically compare the motions of the mucosal wave before and after surgery to verify that no further operations would be necessary.

While being able to view three dimensional motions is important in itself, a new technology capable of providing quantitative data would change the way functional vocal fold disorders are diagnosed. Once the technology is created, doctors could begin to compile numerical information obtained from healthy vocal chords and compare that data to vocal chords with known disorders to create a benchmark. With this data, doctors would no longer have to rely solely on experience and intuition to be confident that they are prescribing the best possible treatment to their patients. Ultimately, this new technology would provide a consistent means of diagnosing vocal disorders, meaning that even novice laryngologists would be capable of making
a proper diagnosis. In the end, a new and improved method of vocal fold analysis would signify better medical care to the thousands of people who seek cures for their voice disorders each year (Dr. Franco, 2007). Fortunately, this technology exists in the form of laser fringe projection.

2.6 Laser Fringe Projection

Fringe projection is a mode of illuminating a surface such that quantitative data about the depth of the object can be extracted from it. The theory of this technology is based around three objects: the target in question, an illumination source, and an observation point. For our purposes, the target can be any object that we are interested in viewing in three-dimensions. The illumination source will be a laser that projects fringes (lines) on the target, and the observation point will be a camera viewing the target. An example setup can be seen in Figure 12 (Franco, Furlong, Hulli, Rodriguez-Vera, 2007).
The purpose of the setup is to be able to calculate $\Delta z$, or the depth of the target. If the target is the vocal chords, then $\Delta z$ will be the magnitude of the mucosal wave between the folds (see section 2.1). Based on the distance away from and the angle between the vocal folds, the laser, and the camera, one can build a triangulation between the three points such that:

$$\Delta z = \frac{\Delta x}{M \sin \theta}$$  \hspace{1cm} (2.1)

Where:

$\Delta z = \text{Depth of Object (m)}$

$\Delta x = \text{Surface Height (m)}$

$M = \text{Optical Magnification}$

$\theta = \text{Angle between Line of Sight of Laser and Camera}$

Using the equation above it would be possible to measure the depth of the mucosal wave, and using the data points collected, form a 3D model of the vocal chords. Laryngologists are looking for a way to measure the mucosal wave accurately, as it is a key aspect of the vocal
chords that they miss when using a 2D method of observation (Franco, Furlong, Hulli, Rodriguez-Vera, 2007).

This type of laser fringe projection could be adapted for use on the vocal chords if a few developments were made. First, the fringe projection mechanisms would need to be modified for use on an endoscope. Secondly, the fringe capture process must take place on objects that appear static. This could be accomplished in a laryngoscopic application if a dynamically adjusting stroboscopic illumination source could pulse a light at the same frequency at which the vocal chords are oscillating.

### 2.7 State-of-the-Art Light Sources

In terms of stroboscopic light sources, the state of the art is a system similar to that of KayPENTAX’s 9100B stroboscope. It flashes in intervals of 5 microseconds in an attempt to freeze the motions of the vocal chords. The light source is used in conjunction with a throat-based microphone that adjusts the flashes based on the patient’s pitch and volume. Using this method the unit can obtain both video and still-photos according to the manufacturer. For this purpose, the light source usually uses xenon or halogen bulbs (KayPen 9295, 2008). While this system may seem like it is perfect for the purpose of this project, the light source is only capable of tracking the frequency to a range of ±5 Hz (Dr. Franco, 2007). This range of accuracy is not
enough to track the vocal chords meaning that the vibrational data would not be usable for quantitative measurements.

Alternative light sources make use of a high-speed video camera. By taking video at 2000 frames per second, the system can capture many images of one vocal fold vibration cycle. While this method will yield useful data, the setup will require a 300-watt lamp and a very high-powered computer due to the large amount of data being collected over a short period of time (KayPen 9700).

While the stroboscopic techniques that currently exist are sufficient for digital stroboscopy, they will not track the fundamental frequency of the voice accurately enough to be used with laser fringe projection. For this reason, a technology has to be developed that will consistently track the frequency of vocal fold vibration to within .1 Hz of resolution. This technology must also be capable of adjusting dynamically to changes in the voice and cannot be deterred by any harmonics that may be present.

2.8 MEMS Technology

MEMS stands for Micro-Electro-Mechanical Systems. This technology is centered on taking an entire mechanical apparatus’ setup and miniaturizing it onto a silicon wafer. Using an integrated circuit and MEMS sensors on the same chip, it is possible to put an entire electro-mechanical system on a medium that is mass-producible. This allows for sensor systems such as
accelerometers that are smaller, more reliable, more accurate and cheaper than their large-size counterparts (memsnet.org, 2008). See Figure 13 for a comparison of two accelerometers. The one on the left is a PCB 393C, and on the right is an Analog Devices ADXL 203EB. While both have a sensitivity of 1000 mV/g, the latter model would be much easier to implement into a wide variety of applications (analog.com, 2008).

Figure 13: Piezoelectric vs. MEMS Accelerometer

MEMS devices have a variety of applications. For example, in most automobiles made today, there are at least ten sensors. These include position sensors on the brakes and transmission, an oxygen sensor on the exhaust, temperature sensors in the air conditioning systems and seats, and a torque sensor in the drive train. MEMS are also used in biotechnology for Scanning Tunneling Microscopes and in communications, helping to decrease the size and cost of necessary circuitry (memsnet.org, 2008).
3 Methods

3.1 Determine Experimental Parameters

The first step of our project development was to determine the parameters that our Virtual Instrument, mechanical validation test, and final throat-mounted system would be governed by. Based on our background research, we concluded our governing design parameters would be determined by the natural frequency ranges of the human voice, the nature in which waves propagated through human tissue, and by the amplitudes of vibration that could be anticipated on the exterior surfaces of the human throat.

3.1.1 Determining the Average Speaking Frequency of the Human Voice

According to information gathered by Titze, the average speaking voice of male adults was approximately 125 Hz while the average speaking voice of female adults was approximately 200 Hz. Likewise, it was concluded that the average speaking and singing frequencies of adults could be predicted based on the voice class of an individual (Titze, 2000). Table 1 demonstrates common frequency ranges found among singers.
As seen in Table 1, the majority of the singing and speaking ranges fall below 500 Hz with a few rare exceptions reaching over 800 Hz. Since the majority of laryngoscopy is performed at frequency ranges close to the average speaking voice of the individual, there would be little reason to design a system to function over 500 Hz. Therefore, our group chose a frequency range of 0-500 Hz concluding that it would be appropriate for practically any frequency encountered during normal speech (Dr. Franco, 2007).

Upon knowing the frequency range to expect during normal phonation, our group determined that the virtual instrument would have to be capable of taking at least 1000 samples per second in order to avoid biasing of the signal. Since biasing occurs when the sampling rate is less than twice the signal frequency, our group concluded that a sampling rate of 1024 samples per second using an available 200 kS/second DAQ system would be sufficient to achieve the desired result. Likewise, we presumed that the mechanical validation system should be designed to operate on the order of 100-200 Hz if it were to accurately emulate the expected frequencies of the human voice (NI.com, 2008).

<table>
<thead>
<tr>
<th>Singing Voice Class</th>
<th>Average Speaking Frequency [Hz]</th>
<th>Singing Frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bass</td>
<td>98.0</td>
<td>82.4-329.6</td>
</tr>
<tr>
<td>Baritone</td>
<td>123.5</td>
<td>98.0-392.0</td>
</tr>
<tr>
<td>Tenor</td>
<td>164.8</td>
<td>130.8-523.3</td>
</tr>
<tr>
<td>Contralto</td>
<td>174.6</td>
<td>146.8-587.3</td>
</tr>
<tr>
<td>Mezzo-Soprano</td>
<td>196.0</td>
<td>164.8-880.0</td>
</tr>
<tr>
<td>Soprano</td>
<td>246.9</td>
<td>196.0-1174.7</td>
</tr>
</tbody>
</table>
3.1.2 Determining the Effect of Wave Mechanics

The second aspect of the design parameters to be addressed was the effect that wave mechanics have on the vibrations experienced on the external surface of the neck. The sound waves produced during phonation are longitudinal waves meaning that the wave displacement is parallel to the direction of wave propagation. This type of wave is characterized in Figure 14 by a set of compressions and rarefactions that determine the amplitude of the displacement. When this is applied to the context of our project, this means that the vibration displacements measured on the throat will be perpendicular to the surface of the throat or “coming out” of the throat’s surface. This fact was significant for our project since any accelerometer mounted to the throat would need its axis of excitation aligned perpendicular to the surface of the neck (Ling, 2003; Nave, 2005).

Figure 14: Longitudinal Wave
Another important decision our group had to make for determining the parameters of experimentation was whether or not the time delay and amplitude had to be accurately modeled or predicted if meaningful results were ever to be obtained by an accelerometer mounted on the throat. To address this issue, we researched the boundary behavior of waves in inhomogeneous media.

A wave passing through one medium will lose energy (amplitude) over distance. When this wave comes into contact with a different medium, a certain portion of the energy is reflected and the remainder is transferred to the new medium. Each time this occurs, the amplitude of the forward propagating wave will change. Fortunately, one property of the wave that remains constant in inhomogeneous media wave propagation is the frequency (Lieuwen, 2003; Nave, 2005).

When considering the time delay that would be present with a wave propagating through the tissue in the human throat, our group used the constant frequency assumption described in the preceding paragraph coupled with the wave speed equation from Nave (2005) where:

\[
\text{wave speed } (c) = f \times \lambda = \text{constant across media} \tag{3.1}
\]

From data presented in the article *The Use of Ultrasound in Medicine*, we were able to determine that the speed of sound in tissue varies from 1410-1630 m/s depending on the exact tissue structure. Variance in the speed of sound can be seen in Table 2. Fortunately, the speed of sound can be approximated as 1540 m/s for waves traveling through multiple forms of tissue (academia.hixie.ch, 1999).
Table 2: Wave Speeds in Various Media

<table>
<thead>
<tr>
<th>Tissue Type</th>
<th>Speed of Sound [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fat tissue</td>
<td>1410-1479</td>
</tr>
<tr>
<td>Liver tissue</td>
<td>1555-1607</td>
</tr>
<tr>
<td>Kidney</td>
<td>1558-1568</td>
</tr>
<tr>
<td>Muscle</td>
<td>1543-1631</td>
</tr>
</tbody>
</table>

Our group used the information about wave speed and considered the time that would be required for a sound wave leaving the vocal chords to propagate through tissue thicknesses between .0125 - .05 m representing conservative and liberal travel distances respectively. We calculated that the travel time would be on the order of 8.2 – 32 µs.

Based on the wave speed times and the complexity of the amplitude interactions of wave propagation in inhomogeneous media, we were able to make a few fundamental simplifications that would make our voice driven system much less sensitive to deviations from any “ideal” tissue conditions. First, our group concluded that there was no need to develop a sophisticated model of a sound wave’s pressure (amplitude) decay as long as the accelerometers chosen to take measurements could achieve large signal to noise ratios for small vibration amplitudes. We also concluded that the adjustment associated with estimating the exact thickness and reflectivity of each tissue layer would be mute when compared to the sensitivity of most accelerometers. Secondly, our group concluded that time delay associated with wave travel could be neglected since it is orders of magnitude less than the sampling rate we would be using with our data acquisition system (DAQ). At a sampling rate of 1024 samples per second, our DAQ system would be collecting one sample every 976 µs while a sound wave only takes 8.2 – 32 µs to reach the outer surface of the throat (NI.com, 2008).
3.1.3 Selection of MEMS Accelerometers

The final part of our preliminary research involved selecting several MEMS accelerometers that would fit the needs of our project. There were many variations and models of these devices, so it was important that we selected the right ones, for both the test bed cantilever and the throat-mounted collar. We had access to a number of different accelerometers in our lab, meaning that we would need to narrow the array of devices down to one or two models that would suit our applications.

![Figure 15: ADXL 203EB](image)

To accomplish this, we retrieved the data-sheets for the available models. These were readily accessible in the boxes containing the units (in the case of a few models that our advisor happened to own) or online at the manufacturer’s website. Our group decided on two devices for our purposes; the ADXL 203EB (Figure 15) for a beam assembly and the ADXL 276 (Figure 16) for a throat-mounted collar. See Appendix I for the data and figures of these and other accelerometer models we considered (analog.com, 2008).
In terms of how we selected a model for use, there were four main aspects of the accelerometers that we were interested in. The first was the full-scale range of the device. This determines the maximum readings that can be taken from the accelerometer, measured in g’s of acceleration (9.81 m/s² * g). This number had to be at least 2 g’s of acceleration as we determined that this was a conservative upper limit based on ½ g accelerations measured on our throats. The second specification was the sensitivity of the device. This dictates the voltage output to the data acquisition system based on the acceleration experienced by the device, measured in millivolts (mV) per g. For our purposes, a higher sensitivity value was desirable, as we were working with a considerably small range of acceleration. The third value we were concerned with was the input voltage. The National Instruments (NI) DAQ system can only accept voltage ranging from -10 to 10 volts, so our chosen accelerometer had to fit within those values (NI.com, 2008). The final aspect of the device was its size. This was not really a problem with any of the models we looked at, as most MEMS accelerometers are smaller than a quarter. Nonetheless, size had to be considered if any mounts or enclosures were to be built. Table 3 contains the pertinent values we were concerned with (analog.com, 2008).
Table 3: Accelerometer Specifications

<table>
<thead>
<tr>
<th>Aspect / Model</th>
<th>ADXL 203EB (2 Axis)</th>
<th>ADXL 276 (2 Axis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full-Scale Range (±g)</td>
<td>1.7</td>
<td>35</td>
</tr>
<tr>
<td>Sensitivity (mV/g)</td>
<td>960 - 1040</td>
<td>55</td>
</tr>
<tr>
<td>Input Voltage (V)</td>
<td>3 - 6</td>
<td>4.75 – 5.25</td>
</tr>
<tr>
<td>Size (in)</td>
<td>.8 x .8 x .42</td>
<td>.38 x .29 x .15</td>
</tr>
</tbody>
</table>

### 3.2 Develop VI for Frequency Tracking

In order to successfully measure the fundamental frequency of the human vocal chords, our group chose to develop a Virtual Instrument (VI) using LabView version 8.5. We established that the VI would have to read one channel of dynamic analog input in the frequency range of 0-500 Hz, would need to distinguish the fundamental frequency from any noise, and would need to output a pulse signal at the fundamental frequency. Also, any VI that we created would have to be capable of reading the analog signal from a MEMS accelerometer as well as a microphone.

To begin, our group used the Data Acquisition Assistant within LabView to create a physical channel that would be capable of receiving a continuous dynamic signal in the range of ±5 V. On the block panel, we created two controls that would allow us to adjust the rate of sampling (rate) and the number of samples that the program would take for the following analysis (number of samples). Next, we chose to use the spectral measurement tool within LabView because it would be capable of generating a power spectrum using the Fast Fourier Transform (FFT). Using this tool, the complex signals that we would be receiving would be
broken down into their corresponding simple sinusoidal components. The simple constituents that are most predominate in the signal receive the most ‘power’ or the highest amplitude in the power spectrum of the FFT meaning that the fundamental frequency would have the largest overall amplitude. Figure 17 is a sample graph of the FFT power spectrum that shows a peak or fundamental frequency at approximately 64 Hz.

![Figure 17: FFT Power Spectrum](image)

The next step of the VI development was to verify that the power spectrum would identify the correct frequency. We used a signal generator to produce a 100 Hz sinusoidal wave with a peak-to-peak amplitude of 2 V, and connected the output to the physical channel created in our VI. Within the program, we added a waveform graph and the option to write the FFT values to a spreadsheet.
While running the VI, our group made observations of the power spectrum graph and concluded that the largest peak on the graph corresponded to the signal being created by the signal generator. However, by adjusting the view of the graph and changing the input frequency, we determined that the resolution was a function of the sampling rate and the number of samples. Namely, the sampling rate divided by the number of samples yields the resolution in Hertz.

\[
\frac{\text{sampling rate}}{\text{number of samples}} = \text{resolution [Hz]}
\]  

(3.2)

Therefore, the best possible resolution that could be obtained was 1 Hz since the number of samples could never exceed the sampling rate. Figure 18 demonstrates how the FFT power spectrum in LabView appears when the resolution is 1 Hz. It can be seen that the curve from 60 – 66 Hz is composed of a series of 6 straight lines. Each line spans the resolution of 1 Hz.

![FFT Resolution Example](image)

Figure 18: FFT Resolution Example
3.2.1 The Creation of Peak Tracking within the VI

The next task of the VI development was to create a means of tracking the highest peak on the power spectrum and displaying its value numerically on the front panel of the VI. To accomplish this, our group wrote data to a spreadsheet for input frequencies ranging from 40 to 140Hz with sampling rates of 512Hz and a number of samples of 512. We observed that the frequency we were reading was always equal to the index number (column) of the maximum value. For example, if we were using an input frequency of 100Hz with a resolution of 1, then the maximum value in a row would occur in the 100th column of the spreadsheet file. Additionally, we repeated the above procedure using resolutions of 2, 4, 8, and 16 Hz and determined empirically that the frequency ± resolution could always be expressed as:

\[ \text{frequency [Hz]} = \text{maximum value index} \times \text{resolution (rs)}; \]  
\[ (3.3) \]

\[ \text{frequency} \pm rs[\text{Hz}] = MI \times rs \]  
\[ (3.4) \]

In our VI, we used the Array Max & Min function within LabView to read the maximum, and output its index value (MI) within the array. Using the above equation, the frequency could be tracked to ± rs. However, if the frequency of the signal generator was set to any value between the resolutions (i.e. 100.5 Hz for a resolution of 1 Hz), then the VI would continue to read the incorrect frequency until the maximum FFT value shifted to the next index of the array.
3.2.2 Improving the Resolution of the VI

Our group observed the waveform graph of the power spectrum while varying the generated frequency and observed that there was always a line between the maximum power value and the power value corresponding to the following index of the FFT array (IV). The slope of this line was a maximum directly after the maximum power value shifted to a new index in the array and approached 0 directly before the next index shift. For example, while the VI was reading a frequency of 100 Hz with a resolution of 1 Hz, the maximum slope would occur when the signal generator was set to 99.5 Hz and the slope would approach 0 as the signal generator approached 100.5 Hz.

To determine if there was a correlation between the slope change as a function of the frequency change, our group re-evaluated our spreadsheet data over multiple data readings. We observed that for a Blackman-Harris window, the maximum value of the FFT array directly after an index shift was always 2.89 times the following FFT value in the array (It should be noted that this relationship varies with window type although a constant relationship does exist for all windows). Using this correlation, the slope of the line could be calculated for the time directly following the index shift. This information allowed us to calculate the slope (G) of the Maximum Value Vs Resolution plot for any frequency between the resolutions.

The next step of our algorithm used to improve the resolution was to take the maximum (Gmax) and minimum (Gmin) slope values from the Maximum Value Vs Resolution plot and form another linear plot of slope (G) vs. Frequency where the frequency limits were defined as:

\[
Lower Limit (LL) = Frequency (MI \times rs) - \frac{resolution (rs)}{2}
\]

(3.5)
Upper Limit (UL) = Frequency (MI \* rs) + \frac{resolution (rs)}{2}

(3.6)

The Lower Limit (LL) and the maximum slope (Gmax) formed the point (LL, Gmax) and the Upper Limit (UL) and the minimum slope (Gmin) formed the point (UL, Gmin). These two points were used to calculate the slope of the G vs. Frequency plot which was deemed slope (Z). Based on this slope (Z), the slope (G) values calculated in the VI during measurements could be interpolated to provide the frequency within .1 to .01 Hz of the true frequency being read into the system. Figure 19 demonstrates the technique used to achieve better resolution in the VI while Figure 20 provides a list of the major variables used. (For more a more detailed description of the interpolation algorithm and a list of defined variables, consult Appendix A.)

Figure 19: VI Interpolation Algorithms
3.2.3 Creating a Pulse Signal to Drive an Illumination Source

The most critical function of our final VI was to follow the fundamental frequency and drive a stroboscopic illumination source with a pulse signal at the same frequency being tracked. We were able to accomplish this by constantly feeding the true frequency value to an output channel that was created in our VI. This channel outputs a signal of a specified duty cycle through a PCI-MIO-16E-4 DAQ card to our laser-diode driver and allows us to drive a light source at the exact same frequency that our VI is tracking at any given time. This method allows the light source to be adjusted each time the virtual instrument detects a change in frequency.
3.3 Design & Construct Mechanical System to Emulate Vibrations

It was determined from our background research that the vocal folds on an average adult male vibrate between 110-140 Hz. In order to demonstrate that stroboscopic illumination could freeze vibrations of that magnitude, a mechanical simulation was designed to validate the theory. For the final design, our group chose to use a cantilevered beam since a light source could be efficiently projected on the side of the beam where a camera could then capture the image.

3.3.1 Design of a Vibrating Cantilever Beam

Our group designed two variations of the beam. The first design was a polycarbonate, one piece cantilever beam seen in Figure 21 that was designed to oscillate at a natural frequency of 140Hz. The beam was machined in one piece so that the boundary conditions applying to the effective length of the beam would be more accurate. The governing theory behind the design was that the 1/8 inch thick beam could be driven by a shaker with a 4 lb maximum driving force if it was driven at resonance. In order to specify the correct dimensions of the beam, the beam’s natural frequency was calculated using:
\[ \omega = 3.516 \cdot \sqrt{\frac{E \cdot I}{M \cdot L^4}} \]  

(3.7)

Where:

- \( \omega \) = Fundamental Frequency [rad/s]
- \( E \) = Young’s Modulus [psi]
- \( I \) = Moment of Inertia [in^4]
- \( M \) = Mass per unit length [lbf*s^2*in^{-2}]
- \( L \) = Beam Length [in]

Also, the beam’s mounting configuration was designed to be compatible with a piezoelectric shaker in Figure 22 that could be used to verify the true fundamental frequency as compared to the theoretical frequency (See Appendix D).
As a source for comparison, our group decided to also design and manufacture an aluminum cantilever beam, seen in Figure 23. This beam was constructed using a 1/8” thick by 1” wide segment of aluminum that was compressed between two base blocks. Each base block contained a 1” wide and .006” deep channel so the beam would function very similar to a one piece assembly (See Appendix B). The natural frequency of this beam was chosen to be 50 Hz since it would require much less driving force to produce larger amplitudes of acceleration.
Both of the beams were designed to be driven by a shaker that would be connected below the beam and attached directly to it via a flexible coupling, which consists of two threaded ends joined by steel cable (See Appendix B). A coupling of this nature was designed to be rigid to compressive and tensional loads while flexible to bending moments that would place unnecessary strain on the shaker. The shaker was mounted to an adapter plate that mated the 1” x 1” spacing of the bread board holes to the 1.25” x 1.25” spacing of the shaker mount.
3.3.2 Design of the Cantilever Beam Support and Driving System

The next component of the mechanical system was the vertical support column which the cantilever beam was attached to. This column was assembled using two segments of 1.5” x 3” extruded railing. The railing was placed vertically and held together by three square braces that were designed with slotted holes to allow for adjustable alignment on the column. Once mounted to the column, these braces were screwed directly to the 1” x 1” spaced bread board to create a rigid structure for the beam to be attached to (See Appendix B).

The next step was to assemble the necessary components to drive the shaker (See Appendix D for shaker specifications). For this task, we chose to use a Tektronix AFG3102 function generator to create a sinusoidal output signal that would serve as the heart of the system. The signal generator in Figure 24 was capable of producing an output signal of 12 volts, but was unable to drive the shaker and beam at large enough amplitudes to study (i.e. < 1 mm). To boost the power of the signal, our group connected a Crown D-45 amplifier to the output of the function generator which was then directed to the shaker.
Once the driving portion of the mechanical validation system was completed, our group tested both beams to determine which would be the best candidate to evaluate. Our major limitation was the output force of the shaker, which was a mere 4 lbf. The polycarbonate beam, while capable of being driven at resonance, did not provide use with a wide range of frequencies to study that would still produce displacements of over 1 mm. On the contrary, our aluminum beam was designed to resonate at 50Hz which was lower than the average speaking frequency of the average human male. The major advantage of the aluminum beam was that it could be driven well by the shaker anywhere between 1 and 300 Hz without using resonance. Therefore, we decided that this flexibility would be more useful than a resonance frequency at 140 Hz so the aluminum beam was chosen for the final testing.
3.3.3 Development of the signal input and the stroboscopic light source

The major goal of the mechanical validation system was to prove that a signal from an accelerometer could be used to strobe a light and freeze the motions of a vibrating cantilever. In order to accomplish this, our group needed to mount an accelerometer on the beam that would generate a signal to be read by our LabView peak-tracking program. For the final design, our group chose to use an Analog Devices ADXL 203EB accelerometer that was affixed to the base of the beam where accelerations were minimal (See appendix D for accelerometer specifications). This particular model was chosen because of the high sensitivity it offered and because it was already soldered to a conditioned evaluation board.

The signal from the accelerometer was wired directly to an NI SCXI-1322 card which was connected to an NI SCXI-1122 pin-out card on an SCXI-1000 chassis. From here, the signal was analyzed in our LabView peak-tracking program to determine the fundamental frequency at which the beam was oscillating. Simultaneously, a digital output pulse of the same frequency was generated within LabView and output through an NI SCXI-1180 feed-through panel which was directly connected to a ThorLabs ITC-502 laser diode driver. Finally, the driver strobed a laser diode that was aimed directly at the side of the beam, as in Figure 25. See Appendix D for information about the NI equipment.
The last step to capturing the necessary information to validate the theory of stroboscopy was to use a camera to record video footage of the frozen beam. Our group chose to use the PixeLINK PL-A741 regular-speed camera to take videos. The camera (shown in Figure 26) was connected directly to the same computer running our LabView program via FireWire, so that any adjustments made to LabView could be correlated with what was viewed by the camera.
3.4 Capture Frozen Images of the System

The ultimate purpose of the cantilever test bed was to prove that images of vibrations could be frozen. As stated before, this is a necessary requirement of the laser fringe projection method that will ultimately be used in the future for this application. The human eye is incapable of keeping up with a vibration that is as small in magnitude and high in frequency as what the vocal chords produce regularly. As a result, what we see is a “ghosting” effect of the object moving. For example, when a guitar string is plucked, the human eye sees what seem to be multiple strings. It is, in fact, only the parts of the cycle that eye can pick up on, such as the extremes of the vibration.

For laser fringe projection to work, the object must be completely still, as quantitative data will be taken from it. If the fringes are blurry, the measurements from the CAD software will be incorrect. Since there is no way to clamp down a moving object without removing the pertinent vibrational data, another method must be chosen.

It was mentioned in preceding sections of this report that the eye cannot keep up with all parts of a vibration if it is moving too fast. One way to remedy this is to reduce the amount of data the eyes have to process so that it can keep up. Strobing a light will reduce the portion of the vibration that the eyes see. For this method to work however, the light source must be strobed at the same frequency as the vibration that is being measured. Our VI accomplished this (see section 4), so the final step here is to record the data.

The PixeLINK program allowed us to view frozen images of the cantilever by changing the amount of light that was able to enter the aperture of the camera, and how long the lens was
open per shot. Furthermore, the duty cycle of the laser was set to 8% so that just enough light was shown for a short period of time to illuminate a small part of the vibration cycle. By reducing the duty cycle to this number it was possible to bring the ghosting of the beam to a minimum, and combined with the correct strobing frequency, it was possible to freeze the motions of the beam.

To collect these images, it was as simple as recording the videos of the frozen beam with the video camera and the PixeLINK program. These videos could then be viewed at a later date for reference. With further developments in the project, the videos would be used to show back to a patient and to read data into the CAD software to obtain quantitative data.

3.5 Adapt MEMS Device to Mount on the Throat

Once we had validated the vibration data from the shaker setup, the next course of action was to test a neck apparatus to see if the results we obtained could be replicated by the human voice. To accomplish this, the accelerometer had to be enclosed in a casing to prevent damage to the device, to align the axis of excitation normal to the neck, and to ensure that the wiring was not compromised during measurements.

Several designs were discussed, including an epoxy casing in the shape of a cylinder. These methods usually included two actions that resulted in malfunctioning accelerometers; heating and hand-melding. Depending on the outer shell of the MEMS device, it can be very sensitive to temperature. Applying low-temperature hot glue to an LGA-8 chip without a circuit
board or casing would damage it. Even a protected LGA-16 chip might be damaged when exposed to slightly higher than normal temperatures. Hand-melded epoxy was also used to create a bullet-like design for insertion into the collar. Although the shell would harden after drying, shaping it would break some of the solder points connecting the wires to the chip. Both of these methods would result in extra noise over the power spectrum or no signal at all.

The method that was used in the final product was a mechanical design. A small cylinder, shown in Figure 27 and Figure 28, consisting of two parts that fit together would encase the MEMS device and prevent any damage. Since the casing is rigid, damping of the vibrations from the throat will not pose a significant problem. The chip is also partially protected from overextension of the wire due to included strain relief in the design of the casing (See Appendix C).

Figure 27: Compression "Bullet" Mount
When this was fashioned, the “bullet” was placed in a pouch on a neck collar obtained from a local pharmacy. While it is far from a final product that can be used in a medical practice, the collar provides excellent placement of the accelerometer and adequate pressure against the neck to pick up readings from the vocal chords. Figure 29 shows the collar being worn during a series of measurements.
3.6 Validate Throat-Mounted Device against a Microphone

The last step towards completing the goal was verifying that the accelerometer on the neck was reading the correct frequency. This was done using a microphone, which was assumed to yield the correct frequency of the voice when it collected data.

The VI was set up on two different workstations within a short distance of each other, since the SCXI equipment in the labs cannot obtain sufficient data while using two channels at
once. On one chassis we used a microphone to collect data, and on the other we set up our collar. The VI’s on both computers were started as close together in time as was possible. Since the program displays and writes data to a file at roughly 1 second intervals, it was possible to let it run for a few seconds (producing noise signals) before phonating. This made it easy to tell when the actual data set began. Based on the output from this experiment, we could tell whether or not the collar was picking up the correct frequencies.
4 Results

4.1 Frequency Response of the VI

In previous sections of the paper, our group discussed the importance of tracking the fundamental frequency of the voice to the highest resolution possible: the more that the tracked frequency deviates from the frequency of the vocal chords, the more the image of the vocal folds will shift when they are supposedly frozen. Many current systems track the frequency of the vocal chords within ± 5Hz of their true oscillation frequency (Dr. Franco, 2007). We discovered, through our experimentation with a vibrating cantilever beam, that truly frozen images require the frequency to be tracked to within .1 Hz of the true value. Therefore, our VI needed to be capable of consistently achieving a resolution of less than .1 Hz.

The first step of validating the resolution of our VI involved the use of a Hewlett Packard 3314A Function Generator that was connected directly to the input channel of our peak tracking VI. This allowed us to vary the frequency of the signal being generated in increments of .1 Hz to study how our Virtual Instrument tracked the fundamental peak. The first sets of measurements were taken over a wide, random range of frequencies within the natural speaking limits. We recorded the frequency output of the signal generator and compared these values with the fundamental peak that our VI was tracking. Figure 30 shows the results of this experiment.
The results of Figure 30 prove that our VI was capable of following the correct frequency of the signal generator over the range of natural speaking frequencies that we were concerned with in our study. At all of the frequency points studied, the resolution of our VI was within .1 Hz of the signal generator.

Once our group was convinced that the VI could effectively track the fundamental peak over a wide range of frequency values, we decided to determine how high the resolution of the program would be in a specific range of interest. For the second experiment, we studied the frequency range between 140.0 and 141.0 Hz. Similarly to experiment 1, we recorded the frequency of the signal generator and plotted it against the fundamental peak reading obtained from our program.
Figure 31 shows the results of experiment 2 and the resolution that was obtainable by our VI. It is clear that in all of the ranges between 140.0 and 141.0 Hz, our VI can track the fundamental peak to within less than .1 Hz of the actual value if we assume that the signal generator is 100% accurate. According to Figure 31, the resolution of the majority of the readings is actually much less than .05 Hz. In reality, there is uncertainty of .05 Hz in the function generator signal which means that our program could have a true resolution of .1 to .01 Hz. Since, on average, our VI is capable of resolutions less than .1 Hz, our group concluded that the VI could effectively track and freeze the motions of the vocal chords.

Figure 31: VI Frequency Response between 140.0 and 141.0 Hz
The next step to test the VI’s ability to track a signal involved using the input from an actual MEMS accelerometer rather than from a signal generator. Since the final throat apparatus would only be receiving a signal from a MEMS device, the following two experiments were performed using only accelerometer signals. Both sets of measurements were taken from the MEMS device located on the base of our cantilever beam. We chose to use our mechanical system to verify the correct tracking since we would know the frequency at which the beam was being driven.

The first accelerometer-tracking experiment was executed in a similar manner to validation with the signal generator. In this experiment, our group recorded the frequency at which the beam was driven and compared the data to the peak tracked by our VI. These readings were taken in .1 Hz increments between the frequencies of 91.0 and 93.0 Hz and plotted in Figure 32.

The results of Figure 32 demonstrate that the VI tracks the input signal of an accelerometer to within .1 Hz or (in many cases) considerably better. This signifies that the VI will consistently track the correct peak to .1 Hz resolution regardless of what device is being used to provide the signal. Moreover, we can be confident that the signal tracked by the VI in the throat apparatus represents the frequency at which the vocal chords are oscillating.
The last experiment that was conducted to validate the tracking capabilities of the VI used our mechanical system and the ADXL 203EB accelerometer just as in the previous example. However, in this experiment we changed the frequencies by increments of only .01 Hz. Figure 33 shows the plot of the generated signal vs. the VI fundamental frequency between 90.00 and 90.10 Hz.

The results verify that, in many cases, the actual resolution of the VI is on the order of a few hundredths of a Hertz. It can also be observed in Figure 33 that there is an oscillating nature to the VI’s FFT data which is due to the resolution of our 16-bit DAQ system. To eliminate this oscillation, we added an optional rounding function to the virtual instrument that stabilized the frequency readings of the VI for .1 Hz tracking capabilities. This function would allow a user of
our project to negate the effects of oscillations in the hundredths of Hertz if a resolution of .1 Hz was sufficient for freezing the vocal chords.

Figure 33: VI Frequency Response to .01 Hz Increments on Driven Beam
4.2 Captured Frozen Images of the System

From the data above it can be seen that the VI correctly tracks the frequency of the vibrating cantilever beam with a resolution on the order of .01 Hz. Using the laser driver and diode, a strobing light can illuminate the side of the beam and allow for data to be recorded via video. Figure 34 shows what the beam looks like when the laser is strobed correctly.

![Figure 34: Frozen Cantilever Beam](image)

This still image yielded from the recorded video shows that the frozen images are completely still. The laser is able to show every imperfection on the beam’s side surface and show a very accurate model of the vibrating object. As mentioned before, at this point the phase of the output signal can be changed to show the different frames of vibration. By adjusting the phase, one can move the frozen image from the bottom of the vibration cycle to the top with ease, allowing the user to see an entire cycle.
To obtain a result like the one above, we had to work around the imperfect vibrations of our beam system. The harmonics on the power spectrum become apparent when trying to take data from the system, as the midpoint in the vibration would be slightly blurry when driven at the first mode of fundamental vibration (on the order of 50 Hz). However, we ran several experiments and discovered that by choosing different frequencies at which to run the system we obtained a different amount of blur during the vibration cycle. Figure 35 shows a power spectrum with the setup vibrating at 50 Hz.

![Power Spectrum at 50 Hz](image)

Our group decided on running the system in the range of 95-105 Hz (denoted by the red arrow) to reduce the effects of harmonics in the system on our results. This range yields the frozen beam in Figure 34. Other ranges that could also yield this result are at 150-160 Hz and 180-200 Hz. If frequencies other than this are used, the beam may begin to vibrate at one of its
other modes of fundamental vibration, or at one of its harmonics. This will produce less-than-ideal results.

To show how meaningful results like this are to the success of the project, consider Figure 36. This shows what the beam would look like if viewed by the camera when the strobing is incorrect. Note the white reflection (the small white circle) in Figure 34. There is only one in that figure as compared to the three that can be seen in Figure 36.

![Figure 36: Incorrectly Strobed Cantilever Beam](image)

Data like Figure 36 would occur when we either adjust our VI to show the incorrect frequency, or if the laser is not on. To a lesser extent, this phenomenon occurs when the beam is vibrated by the shaker at a frequency close to one of its fundamental modes.
4.3 Data from Throat Apparatus

Based on the background research performed at the beginning of the project, our group determined that it would be essential to design a MEMS throat apparatus that would track the correct fundamental frequency of the voice without deviating during measurements. Moreover, we concluded that it would not be necessary to model the decay of the vibrational amplitude as sound passed through the neck as long as the MEMS system could achieve high signal-to-noise (S-N) ratios. It was this requirement that dictated our selection of MEMS to be used in the final throat apparatus design.

The accelerometer chosen for the final design was the Analog Devices ADXL 276 accelerometer. Interestingly, this accelerometer provided the lowest amount of noise during measurements even though its sensitivity was much lower than that of other models such as the ADXL 203EB.

In initial tests, the ADXL 276 would occasionally deviate from the fundamental frequency it was tracking when a noise peak in the FFT would become larger than the accelerometer’s input signal. This would cause our VI to track the noise peak over the true frequency since it was more powerful than the signal. In order to decrease the probability of incorrect peak tracking, our group chose to construct a low-pass filter with an optional amplifier to increase the sensitivity of the accelerometer while decreasing the power of the noise in the FFT. Figure 37 shows Analog Device’s low-pass filter schematic that was used in the final design (analog.com, 2008).
Subsequent tests of this accelerometer and low pass filter revealed that the signal-to-noise ratio of the throat apparatus could be significantly increased. At this point, the ADXL 276, located in the “bullet” and collar, would effectively track the fundamental frequency even when the sound level of phonation was barely audible. Based on this result, our group took some additional data to confirm that this device could be used with confidence.

The initial sets of measurements were gathered to demonstrate how much difference existed among several volumes of phonation when compared to the noise signal. The experiment took four separate data readings with the final collar and accelerometer design. The first measurements were taken when the collar was placed on a table without being excited by any source of phonation. The second, third, and fourth data collection sets were taken while the speaker produced a vowel sound. The second reading was performed at the lowest possible volume that the speaker could achieve before the noise overpowered the fundamental. The third set was performed at a medium volume and the fourth set was completed as loud as comfortably possible. Figure 38 shows the results.
Figure 38 is a comparison of the adjusted voltage output of the accelerometer’s time domain signal. “Adjusted” in this case implies that the DC voltage excitation was removed to yield only voltage changes in response to noise or excitation. It can be deduced from Figure 38 that all of the phonation signals are significantly above the amplitudes produced by noise. Likewise, it demonstrates that the collar will effectively track accelerations on the order of 0.5 g’s of acceleration even when it is only 1.4 % of the ADXL 276’s range.

As an alternate, non-dimensional method to interpret the data in Figure 38, the signal-to-noise ratio of the time domain can be plotted against the reading number. Figure 39 shows the signal-to-noise ratios for each of the three volumes used in the experiment. For the most part,
the ratio of the low volume input is approximately 3 while the ratios for the medium and loud volumes are about 3.5 and 4 respectively. These are not excessive, but confirm that the vibrational signal would need to be at 1/3 of the strength of a “low” volume signal before noise would overpower the accelerometer. It should be noted that the large dips in the S-N curves (around reading 18) represent a reading number where the speaker was taking a breath.

![Figure 39: Signal-to-Noise Ratio for Varying Voice Volumes](image)

The second set of measurements conducted was designed to account for the ratio of signal-to-noise power within the FFT. This data is more important than the time domain signal-to-noise ratio since it is the Fourier Transform that determines which frequency is being tracked, and therefore what frequency is driving the strobe. This experiment was performed identically to
the time domain measurements with the exception that the power of the highest peak of the FFT was recorded. Figure 40 displays the FFT maximum peak power for the collar with no response (noise), and with low, medium, and loud levels of phonation.

Figure 40 shows that the volume has a profound effect on the power of the FFT peak with the low and high volumes differing by a factor of 6. The figure also demonstrates that even the lowest volume level is at least twice as powerful as the largest noise peak. Alternatively, the results of Figure 40 may be interpreted in ratio form as shown in Figure 41. This result shows that the signal-to-noise ratio of the lowest signal is approximately 2 while the medium and high volume readings have ratios of approximately 5 and 10 respectively. This result is promising,
since the S-N ratios of the medium and high volume signals are nearly twice as large as the ratios taken from the time domain. Ultimately, Figure 41 signifies that a comfortable volume of phonation (medium) will have to be 5 times less powerful than it is before noise becomes an issue.

![Figure 41: Voice Signal to FFT Noise Ratio](image)

Upon studying the results of this section, our group concluded that our collar assembly with an ADXL 276 accelerometer would be likely to track the fundamental frequency of the voice efficiently without interference from noise. If vibration damping is a function of the distance from the vocal chords to the exterior of the neck, then our apparatus will have a safety factor ranging from 2-10 where the correct frequency will remain more powerful than the noise;
thus producing a stroboscopic light source of the correct frequency. Future studies conducted on multiple subjects could determine if more sensitivity would be needed for the release of a commercialized product. In either circumstance, accelerometer sensitivity could always be used to overcome the need for detailed analysis of vibration amplitude decay.

4.4 Validation of Throat-Mounted Data versus a Microphone

The final set of results that follows describes the data obtained from validating the collar versus a microphone. Two sets of data were taken: one using Joshua’s voice and the other using Marc’s. In the first case, the reader will recognize that the two forms of vibration acquisition are nearly the same, which validates our accelerometer setup if the microphone is assumed to be calibrated.
Figure 42: Microphone-Accelerometer Validation (One-to-One Signal)

From Figure 42 it can be seen that the signals from both sources are very close to each other. There are small variations in the data from point to point, mostly because the two programs could not be started at exactly the same time, and LabView records the absolute measurement time in thousandths of a second.

Several measurements were taken like the one shown above in Figure 42. However, results like these are not always obtained. For several of the measurements, we switched the person who was phonating during the experiment to see if the results were 100% repeatable, and to check the effect of different frequency ranges on the setup. The results from one of these measurements are shown in Figure 43.
Figure 43: Microphone-Accelerometer Validation (Harmonics)

seen here is the data from a different test run using a different voice than in Figure 42: Microphone-Accelerometer Validation (One-to-One Signal). For a majority of the data points, the signals are approximately 1:1. At other points however, there is a significant deviation in the frequency recorded by the program using the microphone. When this person phonated, the power of the harmonics in their voice approached the power of the fundamental frequency. The high peaks seen in the microphone data are when the harmonic overpowered the fundamental. This happened several times during the 40 second measurement, while the accelerometer continued to pick up the fundamental frequency of the person singing. The large peak seen at the 27-second data point is when the singer was asked to change the vowel sound they were using from “e” to “o”. From this we can gather that the same vowel sound should be used throughout the entire test if a voice is being examined.
5 Conclusions & Recommendations

From the results outlined in the previous section we can draw several conclusions. First is that LabView is capable of tracking frequency peaks with a resolution of less than 1 Hz. Using the interpolation algorithm in our VI, it is possible to achieve a resolution of 0.1 to 0.01 Hz. This will allow peaks to be tracked much closer to their true value and permit a light source to strobe in a fashion that will freeze the motions of a vibrating body.

Secondly, by having increased the resolution of our measurements, the idea of capturing frozen images using stroboscopic illumination becomes viable, and has been validated by our mechanical system. Without this fact there would be no basis into researching an en-vivo approach to laser projection. By freezing the cantilever beam we have opened the door to subsequent investigation by the WPI community as to how to take this product to the next level of development.

As a result of our testing, we have also confirmed that the human voice can be tracked correctly using an accelerometer and our VI. Knowing this, we can also strobe a light at the same frequency as the vocal chords if they are kept at a semi-constant frequency. Since most laryngologists only need a few seconds of data when examining the vocal chords, this should not be a problem for most patients. During that time, it should be relatively easy to keep the voice steady enough to obtain measurements.

Since frozen images of the vocal chords can be obtained based from the conclusions above and the data obtained from their respective tests (see section 4), further development of fringe projection technology can be justified. Using this method it will be possible to take 3D
images of the vocal chords. For this to happen; however, a number of areas in the project must be improved upon in the future.

First, several improvements need to be made to the VI. It would be much easier to obtain visual data if the controls for the video camera were integrated into the VI. This would allow for on-the-fly changing of the shutter interval and brightness settings. Changing these preferences to automatic processes would make the program easier to use and reduce the time it would take the examiner to obtain viable data. To further enhance the program, it would be useful if it did not require LabView to be present to function. This would cut down on costs for buying the system in the long run, while removing one more link in the chain between the laryngologist and the data he wants to retrieve.

Another enhancement that could be made to the system is consolidating some of the equipment. Currently, the laser setup fills the top of a medium-sized table. When a computer, monitor, and National Instruments equipment are added to this, there will probably be some confusion about the total setup, as well as a space problem (See appendix D). If an examination room is small, it is likely that the entire system as it is now would not be able to fit in the room comfortably. Miniaturizing and reorganizing the equipment would aid in the effort to make the system a reasonably sized console that has the ability to be moved from exam room to exam room.

Another recommendation for future work is to test the dynamic capabilities of the system. We have run experiments with fairly constant signals. While the patient will be encouraged to keep their voice steady during an exam, it may not be possible. Until further developments are made, the program and camera (until the controls are automatic) might not be able to keep up
with a rapidly changing voice. It is crucial that situations like this be considered so an easy-to-use and effective product can be created.

Finally, an inner throat mechanism capable of projecting fringes on the vocal chords must be designed. The current setup is not suitable to be used en vivo, and must be meshed with the current model of endoscope as part of the laser-fringe projection system. When the laser, camera and endoscope can be integrated successfully, frozen images of the vocal chords will be obtainable, leading to 3D quantitative models.
6 References


Franco, Dr. Ramon. Personal interview. 14 November 2007.


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7 Appendices

7.1 Appendix A: Description of the VI

This section of the appendix will serve as a detailed guide to the use and development of the Virtual Instrument designed for this project. We will discuss the components of the front panel and the steps one would need to be familiar with if he/she was to use our VI for measurements. We will also discuss each of the components and algorithms in detail so the VI can be re-created or modified for future work.
7.1.1 General Layout and Description of the VI

Figure 44: Front Panel of the VI

Figure 44 is the front panel from our VI where all of its functions can be controlled during measurements. The explanation of its functions will be broken into three parts. The first part will discuss the plots. The second section will discuss the left-side buttons and file paths while the third section will discuss the right-handed windows.
The first graph on the VI, Figure 45, is the waveform graph that displays the time domain of the voltage signal read into the program. This graph tells the user the magnitude and direction of the acceleration readings over time. The x-axis can be adjusted to allow for any period of time to be studied. The VI in the image above is set to 10 ms so that the number of peaks can be counted and multiplied by 10 to achieve an estimate of the frequency being generated.

Figure 46: Power Spectrum
The bottom graph on the VI, Figure 46, provides the user with a plot of the Fast Fourier Transform (FFT) Power Spectrum. The x-axis of the plot can be set to any frequency range that is no more than ½ of the sampling rate. The y-axis is the power of any given component of the signal in dB. Each of the peaks corresponds to any one frequency’s (x-axis) level of predominance within the signal. In simplest form, the largest peak on the graph is the dominant frequency is the signal. This is also known as the fundamental frequency and is the component that our VI tracks.

The next section of the VI is the control panel shown in Figure 47. This section allows the user to switch certain functions of the VI on and off. The buttons in the upper corner controls the number of FFT samples (number of samples), the sampling rate (rate) and value of the source voltage. This upper area also contains a control to stop the VI as well as a rate adjustment control which is used to correct the peak tracking capabilities if the number of samples is changed to a value different that 1024. Since the entire VI was built around the practical sampling rate of 1024 samples per second, the adjustment is needed for the occasional times when other rates need to be used.
Figure 47: Left Side of Front Panel

Moving down the panel, one would encounter three text boxes that are used to enter a file path when the user would like to write data to a file. These boxes correspond to the buttons below the text boxes that control the write-to-file commands. The first button, *Write Waveform to File*, will write the time domain data of the first plot to file. This file will display the timestamp in the first column and voltage readings in subsequent columns. Next, there is a button to *Write FFT to File*. This button will record the number of FFT samples specified in the (number of samples) control along with the timestamp during which each FFT plot was generated. The output file will consist of a timestamp column and as many columns as the
number of samples where each row corresponds to one FFT graph. Lastly, there is a button, Write True Frequency to File, which will record the highest peak value and the corresponding timestamp to a spreadsheet.

The final portion of the left front panel contains two buttons. The first button provides the user with the option to turn the FFT power spectrum on or off. The final button, Remove DC Offset, will eliminate the steady DC reading from the FFT graph so that the true fundamental peak will not be overpowered by the DC peak.

The last portion of the front panel is the lower right corner shown in Figure 48. This area of the VI displays the True Frequency or the frequency that corresponds to the highest power in the FFT. The only other window of concern is the Round To control that is located in the lower right corner. This control allows the user to remove some of the oscillations associated with peak tracking in the tenths, hundredths, and thousandths of Hertz regions. For example, a user concerned with tracking the peak to ± .1 Hz would set Round To as a value of 10 in order to round to the tenths place.
7.1.2 Detailed Description of VI Block Diagram and Construction

This section of the appendix will discuss the detail of the block diagram including a description of how the interpolation algorithm functions. Figure 49 is a shot of the entire block diagram that will be split from left to right in this section of the paper.

Figure 49: Block Panel of the VI
The first section of the block diagram to consider is the signal input corner shown in Figure 50. Here, the DAQ Assistant is used to set up a physical channel within LabView that can be used to take continuous samples. The DAQ Assistant also contains the controls for Rate and Number of Samples so they can be changed from the front panel. Next, the signal is split and run into the Time Domain plot and into the conditional loop that controls the FFT Power Spectrum. Within this loop there is the Spectral Measurements sub VI that controls the settings of the FFT. By entering this sub VI, the user can control the window, averaging, and plot settings of the FFT. From here, the signal is directed to the Power Spectrum Plot.

The last two components of Figure 50 are the Elapsed Time and the Source Voltage control. The Elapsed Time keeps track of the total time since the VI was started. The Source Voltage control adjusts the input voltage displayed in the Time Domain so that the values
inputted to a spreadsheet are the true accelerations. In effect, this control removes the DC component of the accelerometer.

Figure 51 shows the section of the block diagram that removes the DC component of the signal and writes the waveform to file. To remove the DC component, we inserted a conditional loop and used the *Replace Array Subset* option within LabView. This function takes a specified index of the array and replaces it with a specified value. Replacing the first two components of the array with a value of 0 will remove the DC component of the signal and will not affect the ability of our VI to track the frequency of the human voice since the frequency range of concern is well above 2 Hz.
The next section of Figure 51 writes the waveform to file. This example of writing to a file was used throughout the VI so it will only be discussed here. In order to write to file, we used a conditional loop and the Write to Spreadsheet option within the Measurement I/O. We also added constants to enable the VI to append to file or to transpose the data as we saw necessary. Lastly, we added the option to enter the Time Domain File Path.

Figure 52: Peak Tracking Algorithm

The most important aspect of our program was its ability to track the peak of the FFT. Figure 52 is the section of the VI that makes this possible. The way the program works is by searching for the maximum value of the FFT array and returning the index number and value in that cell. Next, our VI looks for the value of the index just ahead of the maximum index and returns its value. The left side of Figure 52 shows how the Array Max & Min function is able to obtain this information from the Power Spectrum.
Once the maximum index (index or MI), maximum value (MV), and cutoff value (CV) are known, then an interpolation algorithm within our VI tracks the fundamental frequency. This can be demonstrated in Figure 53. All of the calculations take place inside the formula node to the right of Figure 52 where input variables appear light and output variables have thick borders. Directly from the formula node, the true frequency is passed through the Round To function and to the front panel of the VI where the true frequency value is displayed.

![Interpolation Algorithm](image)

**Figure 53: Interpolation Algorithm**

<table>
<thead>
<tr>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rs=Resolution [Hz]</td>
</tr>
<tr>
<td>MV= Peak Power Value</td>
</tr>
<tr>
<td>IV = Power Value Adjacent to peak</td>
</tr>
<tr>
<td>MVmax = Power when slope (G) = maximum</td>
</tr>
<tr>
<td>IVmin = Power when slope (G) =0</td>
</tr>
<tr>
<td>G = Slope of Ln(Power) Vs Resolution</td>
</tr>
<tr>
<td>Z = Slope of G Vs True Frequency</td>
</tr>
<tr>
<td>LL = Lower frequency cutoff [Hz]</td>
</tr>
<tr>
<td>UL = Upper frequency cutoff [Hz]</td>
</tr>
<tr>
<td>Tf = True Frequency [Hz]</td>
</tr>
<tr>
<td>Rf = Frequency read by VI (limited by resolution)</td>
</tr>
<tr>
<td>MI = Index number of array corresponding to the maximum values</td>
</tr>
<tr>
<td>OA= Frequency offset constant</td>
</tr>
</tbody>
</table>

**Figure 54: Interpolation Variables**
The last important function of our VI was to create a digital pulse signal that could be used to drive a stroboscopic illumination source. In order to achieve this goal, our group created a channel that read the frequency that our VI was tracking. Next, the channel would create a pulse signal of the same frequency and would direct the signal through the DAQ card of our computer. Figure 55 shows the upper portion of the block diagram that contains the components to achieve a pulse signal.

Figure 55: Pulse Channel

The right side of Figure 55 can be seen in greater detail in Figure 56 where the duty cycle, output channel, and phase of the pulse signal can be controlled. These settings are transferred into the VI where they are received by the pulse channel shown in Figure 57. The orange line entering the bottom of Figure 57 is the true frequency from the peak tracking algorithm. The last required component of the pulse channel, as seen in Figure 58, stops the task upon termination of the VI.

Figure 56: Control Block for Pulse Signal
Figure 57: Pulse Channel

Figure 58: Pulse Stop
7.2 Appendix B: Schematics of the Mechanical System

7.2.1 Aluminum Beam

Figure 59: Beam Mount

Figure 59 is a drawing of the clamping base that was designed and manufactured to create an effective one piece cantilever beam with predictable boundary conditions. The groove on the beam was machined to a depth of less than one half of the beam’s thickness in order to
provide a compressive force to the base of the beam to eliminate vibrations that may have caused the effective length to deviate from the length of beam protruding from the base. The 1.25” x 1.25” holes were spaced close to the beam in order to create tight compression. These holes were reduced in diameter on the second beam and threaded to ¼ -20 UNC so the two halves could be joined. The 1.5” spaced holes were through holes on both halves of the mount where machine screws were used to mount the entire assembly to the base of the cantilever beam support.

Figure 60: Cantilever Beam
Figure 60 is the complete beam assembly that consists of a 12” aluminum beam and two compression beam mounts shown above. The entire beam assembly was designed to screw directly to the cantilever support column. The three holes located in the beam are places 1” apart and were created to provide a location for the shaker to be coupled to. The three locations provide three different locations from which to drive the beam.

7.2.2 Fundamental Frequencies

Below is a list of expected fundamental frequencies calculated using equation 6.1.

\[
\omega = 3.516 \cdot \sqrt{\frac{E \cdot I}{M \cdot L^4}}
\]  

(6.1)

Where:

\( \omega \) = Fundamental Frequency [rad/s]

E=Young’s Modulus [psi]

I=Moment of Inertial [in^4]

M=Mass per unit length [lbf*s^2*in^-2]

L=Beam Length [in]
### Table 4: Calculated Fundamental Frequencies

<table>
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<tr>
<th>Material Name</th>
<th>Density (lbm/in³³)</th>
<th>Young's Modulus (psi)</th>
<th>Natural Frequency (Hz)</th>
<th>Length (in)</th>
<th>Thickness (in)</th>
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<td>3.00E+07</td>
<td>140</td>
<td>6</td>
<td>0.154</td>
</tr>
<tr>
<td>Steel 1020</td>
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<td>3.00E+07</td>
<td>140</td>
<td>5</td>
<td>0.107</td>
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<tr>
<td>PVC</td>
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<td>5.00E+05</td>
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<td>12</td>
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<td>10</td>
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<td>0.502</td>
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<td>4</td>
<td>0.223</td>
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<td>1.57E+05</td>
<td>140</td>
<td>12</td>
<td>2.955</td>
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<td>10</td>
<td>2.052</td>
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<td>1.57E+05</td>
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<td>8</td>
<td>1.313</td>
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<tr>
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<td>1.57E+05</td>
<td>140</td>
<td>6</td>
<td>0.739</td>
</tr>
</tbody>
</table>
7.2.3 Polycarbonate Beam

Figure 61: Polycarbonate Beam

Figure 61 is the drawing for the one-piece polycarbonate beam that was designed to vibrate at 140 Hz. The spacing of the holes on the base of the beam is compatible with the piezoelectric shaker that was going to be used to verify that the fundamental frequency was 140 Hz. The four holes in the beam itself were used to attach the coupling of the shaker.
7.2.4 Adapter Plates

Figure 62: Shaker Base Mount

Figure 62 is the shaker mounting plate that was used to adapt the 3.125” spacing of the shaker to the 1” spacing of the bread board.
Figure 63: Support Mount

Figure 63 is the support used to attach our cantilever support to the bread board. Three of these mounts were placed on the support as seen in the picture below.
Figure 64: Mount Locations
7.2.5 Flexible Shaker Coupling

Figure 65: Flexible Shaker Coupling

Figure 65 is the flexible coupling used in the final mechanical design to connect the shaker to the beam. The threaded steel rod and cable were connected by drilling a 1/8” hole in the steel rod, inserting the steel cable, and then clamping the ends closed.
7.3 Appendix C: Design of Throat Mounted Accelerometer Mount

Figure 66: Accelerometer Compression Mount Outer Shell

Figure 66 is the outer shell of the two-piece compression mount or “bullet” that was used to house the accelerometer. The outer shell was machined out of polycarbonate to create a rigid yet smooth outer surface as compared to metal. The .08” notch in the inner wall of the mount provides strain relief for the wires attached to the accelerometer.
Figure 67: Accelerometer Compression Mount Inner Shell

Figure 67 is the drawing for the inner piece of the compression mount assembly. The ADXL 276 accelerometer can be affixed inside the flat cut inside of the part and the wires can be fed out the slot in the side of the cylinder. Next, the slots of the inner and outer shell are aligned and the entire assembly is pressed together to create the finished accelerometer mount. Figure 68 shows the complete assembly of the mount with the ADXL 276.
Figure 68: Model of Compression Mount
7.4 Appendix D: List of Equipment Used in this Experiment

7.4.1 National Instruments (NI) Hardware and Software

7.4.1.1 LabView 8.5

Our group used LabView 8.5 (Figure 69) to program the peak-tracking software used in the project. See section 7.1 for information about how the program was made. LabView is a visually based programming language that uses “blocks” to assign functions and values to parts of a program (NI.com, 2008).
7.4.1.2 SCXI-1000

The SCXI-1000 shown in Figure 70 can house up to 4 modules. It is normally connected to the computer via a proprietary cable and PCI card. For our project we used a USB variation to obtain a connection to the PC (see section below). The device can also be hooked in a chain formation for applications requiring large numbers of channels (NI.com, 2008).

Figure 70: SCXI-1000 Chassis
The card shown by Figure 71 in the red box is the SCXI-1600. This is a 16-bit data acquisition card that is capable of acquiring data at 200 kS/sec. To connect to a PC it uses a standard USB cable (NI.com, 2008).

Figure 71: SCXI-1600 DAQ Card
7.4.1.4 SCXI-1122

The SCXI-1122 card in Figure 72 works in conjunction with the SCXI-1600 to acquire data and feed it to a PC. It can accept voltages ranging from a few millivolts to 250 Volts, as well as currents from 0-20 milliamps; in other words well within the needs of this project (NI.com, 2008).

Figure 72: SCXI-1122 DAQ Card
7.4.1.5 *SCXI-1322*

The SCXI-1322 screw terminal in Figure 73 interfaces with the 1122 shown in the above section. It has 16 channels as well as voltage and current supply pins. The accelerometers used in this project are wired to this card (NI.com, 2008).

![SCXI-1322 Pinout Card](image-url)

*Figure 73: SCXI-1322 Pinout Card*
7.4.1.6 SCXI-1180

The SCXI-1180 card shown in Figure 74 is a feed through panel that will allow an unconditioned signal to be input or output from a slot of the SCXI-1000 chassis. The cable from the rear of this module will be directly interfaced with the PCI card in the computer (NI.com, 2008).

Figure 74: SCXI-1180 Feed Through Panel
7.4.1.7 SCXI-1302

The SCXI-1302 screw terminal in Figure 75 interfaces with the SCXI-1180 in the above section (NI.com, 2008). For the purposes of this project, the pulse signal was output to the laser driver using this card.

Figure 75: SCXI-1302 Pinout Card
7.4.1.8 **PCI-MI0-16E-4**

The PCI-MI0-16E-4 DAQ card (Figure 76) in the PC is a 16-bit device that allows 250 kS/sec to be taken (NI.com, 2008). Since the card can only do input or output at any given time, we used the SCXI-1600 to take input and this card to do output.

![Figure 76: PCI-MI0-16E-4](image)
7.4.2 Specifications of Accelerometers

7.4.2.1 ADXL 203EB

Figure 77: ADXL 203EB

Table 5: ADXL 203EB Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Scale Range (±g)</td>
<td>1.7</td>
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<tr>
<td>Sensitivity (mV/g)</td>
<td>960 – 1040</td>
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<td>Input Voltage (V)</td>
<td>3 – 6</td>
</tr>
<tr>
<td>Size (in)</td>
<td>.8 x .8 x .42</td>
</tr>
</tbody>
</table>

7.4.2.2 ADXL 276

Figure 78: ADXL 276

Table 6: ADXL 276 Specifications

<table>
<thead>
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<th>Value</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
<td>Sensitivity (mV/g)</td>
<td>55</td>
</tr>
<tr>
<td>Input Voltage (V)</td>
<td>4.75 – 5.25</td>
</tr>
<tr>
<td>Size (in)</td>
<td>.38 x .29 x .15</td>
</tr>
</tbody>
</table>
7.4.2.3 ADXL 250EB

![ADXL 250EB Image]

Figure 79: ADXL 250EB

Table 7: ADXL 250EB Specifications

<table>
<thead>
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<th>Specification</th>
<th>Value</th>
</tr>
</thead>
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<td>Full Scale Range (g)</td>
<td>40 - 50</td>
</tr>
<tr>
<td>Sensitivity (mV/g)</td>
<td>33 - 43</td>
</tr>
<tr>
<td>Input Voltage (V)</td>
<td>4 - 6</td>
</tr>
<tr>
<td>Size (in)</td>
<td>1 x 1 x .225</td>
</tr>
</tbody>
</table>

7.4.2.4 ADXL 311JE

![ADXL 311JE Image]

Figure 80: ADXL 311JE

Table 8: ADXL 311JE Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Full Scale Range (g)</td>
<td>2</td>
</tr>
<tr>
<td>Sensitivity (mV/g)</td>
<td>140 - 195</td>
</tr>
<tr>
<td>Input Voltage (V)</td>
<td>2.7 – 5.25</td>
</tr>
<tr>
<td>Size (in)</td>
<td>.2 x .2 x .1</td>
</tr>
</tbody>
</table>
Specifications for all of these accelerometers can be found on the Analog Devices website (analog.com, 2008).

7.4.3 Neck Brace

We used the Futuro neck brace (Figure 81) as a collar-based mount for the accelerometer. In the future something less bulky will be preferable for clinical use. This model was ideal because it had a small cavity in which we stored the accelerometer during measurements (cvs.com, 2008).

Figure 81: Neck Brace
7.4.4 Low-Pass Filter

7.4.4.1 Circuit Board

A standard circuit board (Figure 82) was used for this project. A model similar to this can be found at a local electronics shop or bought from a supplier. Another option is to have an integrated circuit (IC) built to fulfill this purpose (radioshack.com, 2008). See section 4.3 for a description of the circuit.

Figure 82: Circuit Board
7.4.4.2 Enclosure

To ensure that no damage was done to the circuit, we purchased a project enclosure (Figure 83). Wires were simply fed in and out through a small hole cut into the lid (radioshack.com, 2008).

Figure 83: Circuit Board Enclosure
7.4.5 Test Bed Materials

Any test bed materials and equipment that have not been mentioned above are described in the following section. Each offers a basic description of the equipment. For links to the manufacturer websites, see our References section.

7.4.5.1 ThorLabs Breadboard

To support our test bed (Figure 84) we needed a secure table to put it on. This metallic table was equipped with many ¼-20 holes so that we could secure various parts of our setup to it (thorlabs.com, 2008). For our purposes we used a 2’ x 4’ piece.

Figure 84: Breadboard
7.4.5.2 *Tektronix AFG3102 Function Generator*

The signal generator we used to produce the sine vibrations in our cantilever was the AFG3102 (Figure 85). It is capable of outputting two signals at once, and changing the phase, amplitude, frequency, and duty cycle of its signals (tek.com, 2008).

![Figure 85: TekTronix Signal Generator](image)

7.4.5.3 *Crown D-45 Amplifier*

The Crown D-45 Amplifier (Figure 86) was used to amplify the signal to the shaker, as the voltage from the signal generator was not enough to produce the vibrational amplitudes we needed for the experiment (sweetwater.com, 2008).
To use the laser on the beam, we needed an ITC-502 laser driver (Figure 87) to provide the correct voltage, current, and frequency to the diode. This device accomplishes these things, letting us choose how much power to supply to the laser diode (thorlabs.com, 2008).
7.4.5.5 *ThorLabs TCLDM9 Laser Cooler*

The laser must be kept within a certain temperature range to keep it in operating condition. To do this, we used the TCLDM9 Laser Cooler (Figure 88) (thorlabs.com, 2008).

![Figure 88: ThorLabs Laser Cooler](image-url)
7.4.5.6 *ThorLabs Laser Mount*

The diode is a very instrument, so a mount is needed to secure it in place for measurements. We obtained a mount in Figure 89 from our advisor’s lab and used it to focus the laser on the beam (thorlabs.com, 2008).

![ThorLabs Laser Mount](image)

*Figure 89: ThorLabs Laser Mount*
7.4.5.7 Thorlabs LPS-660-FC Laser Diode

The diode used for this project was the LPS-660-FC from ThorLabs (Figure 90). It has a 660 nm wavelength and runs on an average of 75 mW of power (Thorlabs.com, 2008).

Figure 90: ThorLabs Laser Diode
7.4.5.8 *PixeLINK A-741 Video Camera*

The camera we used for capturing the frozen beam was the PixeLINK A-741 in Figure 91. It is capable of taking monochrome video at 33 fps at standard resolution, or 105 fps at 640x480 resolution (avsupply.com).

![Figure 91: PixeLINK Video Camera](image-url)
7.4.5.9  **Ling Dynamic Systems 200 Series Shaker**

Our mechanical system was driven by a 200 series shaker (Figure 92) produced by Ling Dynamic Systems (LDS). Since this model is no longer in production and was manufactured more than 30 years ago, we thought it would be pertinent to include some of the user manual in this appendix. For information on new shakers that have a similar function to this one, see the LDS entry in our references section (lds-group.com, 2008).

![LDS 4lbf Shaker](image)

Figure 92: LDS 4lbf Shaker

-115-
INSTALLATION
COMMISSIONING
& OPERATING
VIBRATOR MODEL 200 SERIES

PART No. 892071

USER MANUAL
LING DYNAMIC SYSTEMS LTD.
Section 1 - INTRODUCTION

The Ling Dynamic Systems 200 Series Vibrators are miniature units for use in small scale vibration testing or as non-seismic pick-ups. They are also widely used by Technical Institutes for educational purposes.

The description and operation of the Types 201, 202 and 203 Vibrators are identical, the only structural difference being the thread provided in the vibrator header assembly. All three vibrators are therefore dealt with in this manual under the description 200 Series.

The 200 Series Vibrators can be driven by any suitable Oscillator/Amplifier combination but in particular the Ling Dynamic Systems Model TPO 25 is recommended for this purpose; full details are obtainable upon application to the plant or accredited distributor.

A lightweight armature construction (an epoxy resin bonded coil wound on a laminated former), top and bottom laminated spiders, vibrator body and a trunnion mounting where required, form the main parts of the Model 200 Series Vibrator.

An auxiliary suspension is available at extra cost for use when the weight of the test package exceeds the table suspension rating.

Being of the permanent magnet design the 200 Series Vibrators do not require a field power supply.

Cooling is not normally required although provision is made for the easy connection of a forced air supply. This is only required when the input power is expected to exceed the specified figures.
Section 2 - REFERENCE DATA

VIBRATOR
Maximum Thrust (Natural Cooling) 17.8N (4.01bf)
Maximum Thrust (Forced Air Cooling) 26.7N (6.01bf)
Fundamental Armature Resonance Above 10kHz
Frequency Range D.C. to 13kHz
Maximum Displacement +/- 2.5mm (0.11in)
Maximum Acceleration (Base Table) 136g

MOVING COIL ASSEMBLY
Maximum Current (Natural Cooling) 2.5A r.m.s.
Maximum Current (Forced Air Cooling) 3.75A r.m.s
Resistance d.c. at 20°C 1.5 OHM.Nominal
Effective Armature Mass 20g (.0441lb)
Suspension Stiffness 3.5N/mm (20lbf/in)

LOAD ATTACHMENT
V201 M4 x 0.7 Metric Thread
V202 2 BA Thread
V203 8-32 U.N.C. Thread

FIELD
Permanent Magnet

COOLING
Forced Air Cooling (See Notes On Operation) 9.4 x 10^-4 m^3/sec
(2.0 ft^3/min)

DIMENSIONS AND FIXING DETAILS
See Figure. 3

WEIGHT (BODY AND TRUNKION)
See Figure. 3
Section 3 - GENERAL DESCRIPTION

A single section Columax permanent magnet and pole tip, armature and no coil assembly, front plate and vibrator body form the major parts of the vibrator and are assembled as shown in Fig. 1. The magnet and pole tip assembled within the body so that an annular gap exists between the pole and the central bore in the front plate. The magnet and pole tip are secured with an epoxy adhesive. The complete magnet and pole tip assembly are secured to the base plate of the vibrator body in a similar manner.

The moving coil assembly (Fig. 1) is accurately located in the annular gap between the pole tip and the front plate by screws and distance pieces through the front plate and the upper and lower flexible suspensions of assembly. The armature is attached to the upper part of the coil and passing through a flexible seal in the top cover. The top cover is secured to the front plate by four screws.

Electrical connection to the vibrator is made via two screw-down/plug-in terminals located on the side of the vibrator. For use when forced air an air hose connection may be made via the trunnion mounting hole whilst air exhaust is located between the two electrical terminals. (See Fig.

The support screw is in this case removed and replaced by an air connect adaptor Type 320300.

The vibrator depends for its operation on the interaction between the st magnetic field, produced by the permanent magnet, (concentrated in the the gap formed between the pole tip and the central bore in the front plate) and an oscillating current flowing in the moving coil. In such circumstances force is generated at right angles to the lines of flux and to the conductor carrying the current.

This force is proportional to the product of the instantaneous current and magnetic flux density.

The drive current for the vibrator is derived from the amplified output of an oscillator. The frequency of the movement of the moving coil is the same as the frequency of the oscillator signal. A test load mounted on the arm can, therefore, be vibrated at any fixed frequency pre-set on the oscillator or swept through a range of frequencies under manual or motorized control.

In addition to the electrical characteristics of the equipment, mechanical limitations must also be considered when assessing the performance of the vibrator. The construction of the moving assembly is such as to give the maximum possible strength compatible with the lowest possible weight. Th most important to the efficiency of the vibrator since the total weight to be vibrated necessarily means the weight of the moving assembly plus the weight of the test package. Therefore, the greater the weight of the moving system the less force is available to vibrate the test package. It should also be realised that, at the lower frequencies, the vibrator amplitude limitation will restrict the theoretically available acceleration. For sinusoidal motion this is governed by the standard formula:

\[ a = \frac{0.002f^2d}{g} \]

where

- \( a \) = acceleration in g,
- \( d \) = displacement in mm (peak to peak)
- \( f \) = frequency in Hz.

See also Section 4...
Section 4 - OPERATION

The operating procedure for the Series 200 Vibrator is relatively simple, however it is necessary to take certain precautions to prevent overloading the vibrator and subsequent electrical or mechanical damage.

For vertical operation the weight of the test load and subsequent deflection of the suspension system must be considered when calculating the available displacement.

If necessary an auxiliary suspension system can be supplied which will increase the load carrying capacity as shown below.

Alternatively a low stiffness spring, such as rubber shock cords, can be used to support the load at the mean working height.

Available displacement \( D = \frac{2 (2.5 - \frac{M}{K})}{K} \)

Where
\( D = \) Max. available displacement peak to peak in mm
\( M = \) Load (specimen and fixture) in kg.
\( K = \) Suspension stiffness 0.356kg/mm Basic Vibrator
\( K = \) Suspension stiffness 1.25kg/mm with Auxiliary Suspension.

The maximum permitted current is shown in Section 2. Should it be necessary to force air cool the vibrator the following paragraphs describe a practical method of controlling the air flow in order to prevent overheating of the moving coil.

If a high pressure factory line is to be used the pressure should first be reduced to approximately 0.3 bar (4 p.s.i.) by means of a pressure regulator. The flow through the vibrator body should then be controlled with a needle valve and reduced to a level with neither lifts the armature or causes leaks around the rubber diaphragm seal.

The vibrator operating procedure is as follows:

1. Mechanically connect the pay-load to the vibrator by means of a suitable screw ensuring that the maximum load attachment thread is fully utilized. Do not over-tighten the attachment screw and always hold the drive spindle in position by means of the spanner supplied which fits over the two flats on the drive spindle head to prevent damage to the internal suspension. Similar care should be taken if a thread adaptor is fitted.

2. Check that the oscillator amplitude control is at the zero position before switching on the oscillator and amplifier.

3. When the oscillator and amplifier are both operating select a suitable frequency and amplitude and check that the driving spindle commences to vibrate.

4. Carry out the test programme.
1. Trunnion
2. Body
3. Centre Pole Magnet
4. Terminals
5. Air Vent
6. Top Access Cover
7. Top Suspension Spacer and Securing Screw (2 off)
8. Moving Coil and Suspension Assembly
9. Package Mounting Hole: 201 M4 0.751 Metric Thread
   202 2BA Thread
   203 8-32 UNC Thread
10. Top Cover Securing Screw (4 off)
11. Top Suspension Spider
12. Front Plate Securing Screw (3 off)
13. Moving Coil
14. Front Plate
15. Bottom Suspension Spider
16. Trunnion Clamp Bolt
17. Support Screw.

Figure 1 - SECTIONAL VIEW OF VIBRATOR
Typical characteristics of vibrator Model 200 Series (natural cooling) with amplifier Model TPO 25.

Data plotted for a thrust of 17.8N (12.8kg 41bf) vector with displacement limit 5mm (0.2in) Peak to Peak.

Figure 2 - TYPICAL PERFORMANCE CHARACTERISTICS
Weight:  
Vibrator 1.8Kg (4.0 lb)  
Trunnion 1.4Kg (3.1 lb)

Figure 3 - DIMENSIONS AND FIXING DETAILS
VECTOR THRUST 17-8
SHAKER TYPE 201
TRANSFORMER TAPPING DIRECT COUPLED
EFFECTIVE ARMATURE MASS 20gm (0.044 lbs)
RANDOM RATING N.r.m.s. (lb t.r.m.s.)

Example: Given Frequency = 20Hz and Displacement = 25mm P-P then, Acceleration = 20g (vector) and Velocity = 1.6m sec. (vector)
1 lb = 0.454kg 1g = 9.81m sec. 1 lb f. = 4.448N