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DEVELOPMENT OF A VIBRATION CONTROL SYSTEM FOR TESTING RADAR AND LASER SPEED-MEASUREMENT DEVICES

presented by

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# DEVELOPMENT OF A VIBRATION CONTROL SYSTEM FOR TESTING RADAR AND LASER SPEED-MEASUREMENT DEVICES

By

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ABSTRACT

DEVELOPMENT OF A VIBRATION CONTROL SYSTEM FOR TESTING RADAR AND LASER SPEED MEASUREMENT DEVICES

By

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Speed-measurement devices used to enforce speed laws on our nations highways must be accurate under a wide variety of operating conditions. To help achieve this goal, NHTSA has published a set of performance specifications and testing protocols for these devices, one of which tests the accuracy when the device is mechanically shaken.

In the past at Michigan State University, there was no automatic control system to perform these vibration tests; so, the tests were conducted manually. This dissertation project developed a computer-controlled vibration system.

The result of this dissertation project was the development of an automatic control system for performing the NHTSA vibration testing protocols which was accurate to within 0.06 g's. This control system is currently being used to test the operation of radar and laser speed-measurement devices and has replaced the old method of manually controlling the equipment.

Dedicated to my parents for their continued love and support.

## ACKNOWLEDGMENTS

This thesis project would not have been possible without all assistance and guidance of Dr. Fisher. I would also like to thank the following people for their help: Dr. Haddow for his early help in the beginning of the project and for the use of the vibration equipment; Brian Wright and the Electrical Engineering Hardware Shop for constructing a null-modem cable and two mounting devices; Christopher Hause for helping me understand all my questions dealing with accelerometers and vibration; and, finally, Rebecca Gregg for helping assist in performing the experiments and tests.

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# Chapter 1

# INTRODUCTION

Radar speed measurement devices are required to pass a series of tests before they can be approved to be used by police departments. One of the operational tests, which needs to be performed on radar speed-measurement devices, is to test the accuracy of the device under vibration. These tests simulate the operation of the device in a moving vehicle. While the radar device is being subjected to vibration, measurements are taken to determine its accuracy.

Previously, at Michigan State University, there was no automatic control system to perform these tests. The tests were performed manually, which was a difficult and tedious process to do accurately. These vibration tests require changing the frequency of vibration while keeping the amplitude of vibration constant.

The vibration equipment which was used in this thesis project was a Ling Dynamic Systems (LDS) Model 726 Vibrator [1] connected to a Ling Dynamic Systems DPA 4 Modular Power Amplifier [2]. For the remainder of this thesis, the vibration equipment will be simply referred to as the vibration machine.

To perform these tests, not only does the frequency need to be changed but the voltage into the vibration machine needs to be updated. For one person to change the frequency, update the voltage, and perform the radar measurements is impossible. Not only is it impossible but very difficult and tedious to be done accurately, even with multiple people, because of the difficultly in changing the frequency at a constant rate manually. Thus there is need for an automated control system.

## 1.1 Objectives

The overall goal of this thesis project was to develop a control system that is capable of performing the vibration tests on radar speed measurement devices. But besides just designing a system to perform these tests, another objective was to develop a system that could be easily modified to perform other similar vibration tests.

In addition to developing a control system to perform vibration tests, we also wanted to provide students and faculty in the future with documentation that would help them with similar research and development projects. The most important documentation that would be developed, would be the setup and running procedures for performing the vibration tests. This documentation will be used by others to aide them in performing these vibration tests on radar and laser speed-measurement devices.

Besides just creating documentation on how to setup the equipment and running the experiment, we also wanted to create documentation that explains and teaches certain aspects of the control system needed to run the existing tests or to modify the hardware/ software to run other similar types of tests. This will help shorten the learning curve for those who follow.

## 1.2 Organization

This thesis is organized into a series of major chapters, the first being this introduction. The next chapter provides the background behind the control system which was developed. The third chapter describes the major steps in the developmental process and the fourth chapter describes the actual control system. Chapter five examines the performance and results of the control system. The conclusions and summary can be found in chapter six along with recommendations for future work. The appendix contains additional instructions on running the vibration tests.

# Chapter 2

# BACKGROUND

## 2.1 Problem

The National Highway Traffic Safety Administration (NHTSA) developed a series of performance tests which they believe police radar devices should meet, and they are published in the document: "Model Minimum Performance Specifications for Police Traffic Radar Devices" [3]. Included in the Environmental Testing Section (§1221.74) are two tests used to evaluate the radar device operation undergoing vibration. These vibration tests are based on work done by the National Institute of Standards and Technology (NIST) to simulate the motion of a moving vehicle. The steps in the vibration testing process are as follows:

(1) Fasten the radar device to the vibration tester using a rigid mounting fixture. Perform a two-part test for a total of 30 minutes in each of three directions, namely, the directions parallel to both axis of the mounting and perpendicular to the plane of the mounting.

(2) First subject the radar device to three 5 minute cycles of simple harmonic motion having an amplitude of 0.38 mm (0.015 in) [total excursion of 0.76 mm (0.03 in)] applied initially at a frequency of 10 Hz and increased at a uniform rate to 30 Hz in 2.5 minutes, then decreased at a uniform rate to 10 Hz in 2.5 minutes. Conduct the appropriate radar device tuning fork test (§1221.72) during the last 5 minute cycle.

(3) Then subject the radar device to three 5 minute cycles of simple harmonic motion having an amplitude of 0.19 mm (0.0075 in) [total

excursion of 0.38 mm (0.015 in)] applied initially at a frequency of 30 Hz and increased at a uniform rate to 60 Hz in 2.5 minutes, then decreased at a uniform rate to 30 Hz in 2.5 minutes. Conduct the appropriate radar device tuning fork test (§1221.72) during the last 5 minute cycle.

(4) Repeat this procedure for each of the other two directions.

To help explain the two vibration tests, Figure 2.1 represents these vibration-test protocols graphically. The plots illustrate how the frequency of vibration is swept as a function of time for each of the tests.

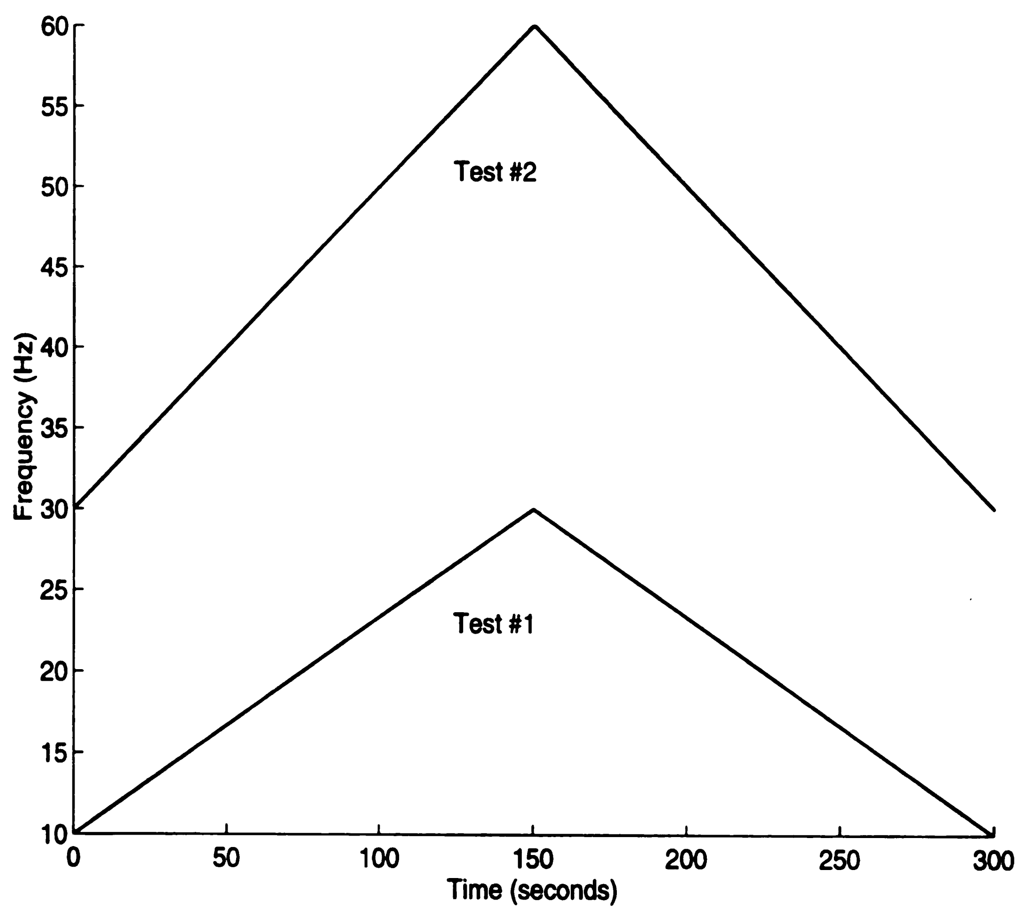


**Figure 2.1: Vibration tests - frequency vs. time.**

In practice, the amplitude of the vibration is not measured, but rather the acceleration. Figure 2.2 summarizes the key relationships among the parameters acceleration, amplitude, and frequency for the two test protocols. This figure also includes the equation used to calculate the accelerations used in this project as well as the constant for 1 g. Also listed are the key accelerations for both vibration tests (starting and peak frequencies).

## 2.2 The Vibration Control System

### 2.2.1 Overview

To begin developing the control system, the first item that needed to be considered was the possible methods that could be used and the equipment that would be required before starting. Figure 2.3 shows a basic block diagram of the control system that was to be implemented.

$$\text{Acceleration (g's)} = \frac{(2\pi)^2 \times (\text{frequency in Hertz})^2 \times (\text{amplitude in inches})}{1g}$$

$$1\text{ g} = 385.8\text{ in/s}^2$$

Test 1 (amplitude = 0.015 in, frequency = 10 Hz to 30 Hz)
at 10 Hz, acceleration = 0.15 g's
at 30 Hz, acceleration = 1.38 g's

Test 2 (amplitude = 0.0075 in, frequency = 30 Hz to 60 Hz)
at 30 Hz, acceleration = 0.69 g's
at 60 Hz, acceleration = 2.76 g's

**Figure 2.2: Acceleration equation and key accelerations.**

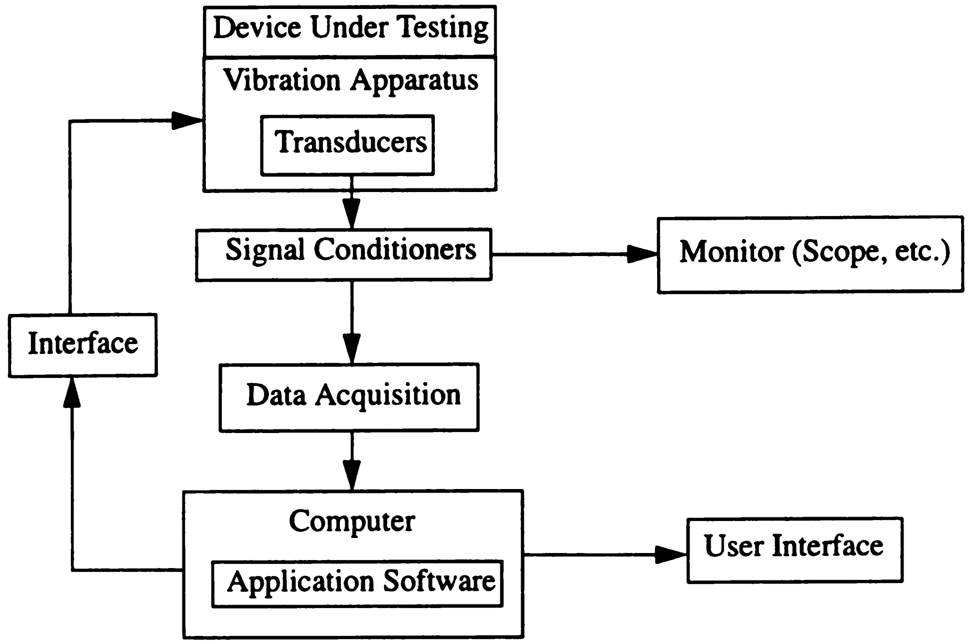


**Figure 2.3: Block diagram of control system.**

In the diagram above, the device that is undergoing testing is attached to the vibration apparatus along with transducers which are used to measure the acceleration of the vibration. The output of the transducers is then forwarded on to signal conditioners which send the signals to some sort of data acquisition equipment attached to a computer. The user interface is made up of the computer, software, and person performing the experiment. The computer controls and corrects the motion of the vibration apparatus by sending signals to an interface which is connected to the vibration apparatus. Other instruments can be connected to measure various intermediate signals.

### 2.2.2 Computer

One of the first decisions that needed to be made was the type of computer that would be used in implementing the control system. A decision needed to be made to select either a desktop computer or a laptop computer. Both types of machines were already available but one needed to be chosen because it would have an impact on the other types of equipment that would be required. The deciding factor on the type of computer was the location of the vibration machine. The vibration machine was located in a lab on the other side of the engineering building and the lab and vibration machine are used by other students. The laptop was chosen so that it could be used in performing the tests as well as be used during development in another part of the building. Besides the laptop, a desktop PC was also selected to be used during the development of the control system. The laptop that was used was an IBM ThinkPad 750C [4] running Windows 3.1. The desktop computer was a Gateway2000 4DX2-66V [5] with 32Mb RAM running Windows95. The amount of disk space required for the installation of LabVIEW and the control system program used was just under 17 Mb on the laptop.

### 2.2.3 Application Software

After selecting the type of computer that was going to be used, the software needed to be selected. The two routes that could have been used seemed to be using a high-level software package or writing a program from scratch. The programming language C++ was first considered and then the software package, LabVIEW (version 4.0) [6] was examined. Upon further investigation into what LabVIEW was capable of doing, it became the logical choice. LabVIEW contains many built in functions and sample programs which accomplished many of the tasks needed. Writing these functions from scratch would be difficult and very time consuming. Plus LabVIEW makes it very easy to design a user interface with graphics. An additional reason why LabVIEW was selected was that it too, was also already available.

### 2.2.4 Transducers and Signal Conditioners

An accelerometer was selected to be the device to read in the current acceleration being generated by the vibration machine. Actually two accelerometers were needed, as will be explained later, with one serving as a safety precaution. An accelerometer was needed that would be able to operate in the frequency and acceleration ranges of the two tests for which the control system was being developed. For the two tests, the frequency range is 10 Hz - 60 Hz, which corresponds to an acceleration range of 0.15 g's to 2.76 g's. Dr. Haddow [7], from the Mechanical Engineering Department at Michigan State University, recommended PCB Piezotronics brand accelerometers [8, pp. 41-44]. The two accelerometers which were considered were ICP (Integrated Circuit Piezoelectric) low cost accelerometers, general purpose (338B34) and high sensitivity (338B35). The high sensitivity accelerometer was selected because of its sensitivity, 100 mV/g compared to the general purpose accelerometer which only had a sensitivity of 10 mV/g. Both accelerometers were capable of operating in the 1 to 2,000 Hz frequency range which included the frequency range of the two tests. They both also operated within the acceleration range, the general purpose accelerometer had an amplitude range of 500 g and the high sensitivity accelerometer had an amplitude range of 50 g.

In addition to ordering the two accelerometers, 4 mounting studs and two coaxial cables were ordered. The mounting studs (081B05) [8, p. 43] were the best option for mounting the accelerometers to the platform on the vibration machine because they could be removed easily. Four studs were ordered so that there were two extra studs as replacements, since the mounting studs are very small and could easily get lost. The two coaxial cables (M002A002C) [8, pp. 78-81] that were selected were 2 meters in length and had a coaxial plug at one end and a BNC plug at the other end. The coaxial plug attached to the accelerometer and the BNC plug attached to the signal conditioner which was the power source for the accelerometer.

Two signal conditioners were also ordered along with the accelerometers. The purpose of the signal conditioners is to supply the power to operate the accelerometers and also condition and then transmit the acceleration reading to the computer's data acquisition system. The signal conditioners selected also were from PCB Piezotronics [9, pp. 8-11]. Two basic line-powered signal conditioners for use with ICP sensors were selected to operate the two accelerometers. Two signal conditioners were needed because the model selected, 482A06 [10], only had one channel. These signal conditioners had BNC connectors for its input/output and that is why the coaxial cables were selected with BNC plugs.

### 2.2.5 Data Acquisition Selection

The accelerometer maps acceleration into a voltage, and the laptop needed a way to read these voltages. A data acquisition card connected to the laptop was selected to read in the values so additional hardware did not have to be constructed.

One of the first data acquisition cards considered was the DAQPad-1200 [11, pp. 3.100-3.103] from National Instruments. The main reason this device was considered was the possibility of being connected to a laptop or a desktop computer via the parallel port on the computer. After examining the specifications of the DAQPad-1200 further, it was realized that this device required a special parallel port and the use of the parallel port limits accessing the data to slower speeds.

Since the DAQPad-1200 failed to work for our needs, a data acquisition card that used the PCMCIA slot on the laptop was chosen. Two cards which meet all the specifications which we needed were the DAQCard-700 [11, pp. 3.82-3.84] and the DAQCard-1200 [11, pp. 3.77-3.81; 12]. The major differences in the two cards were that the DAQCard-1200 has a larger ADC buffer, the gain can be set (possible gains: 1, 2, 5, 10, 20, 50, 100), and has 8 more digital I/O lines. The DAQCard-700 does have 8 more single-ended channels, but only two channels are needed for our control system. Both cards had a maximum sampling rate of 100 kS/s and a 12-bit ADC. The DAQCard-1200 was selected over the DAQCard-700 based on its additional features which may be needed if this equipment is used for other projects in the future.

Along with selecting the DAQCard-1200, a few other parts to go along with the card were needed. A BNC adapter board, BNC-2081 [11, p. 3.244; 13], was selected to be connected between the DAQCard-1200 and the signal conditioners. The BNC adapter board was ordered with a 1 meter NB1 cable which was to connect to the DAQCard-1200. After receiving the DAQCard-1200 and the NB1 cable [11, p. 3.250], an additional cable was needed to connect the NB1 cable with the DAQCard-1200, so a PR50-50M [11, p. 3.251] cable was ordered. BNC cables are used to connect the signal conditioners with the BNC adapter board and were already readily available in the labs.

### 2.2.6 Signal Generator Control Method

The last item to consider in selection of the hardware equipment was the method of controlling the vibration machine. Both the frequency and a voltage amplitude needed to be sent to the vibration machine to control the vibration. One choice was to do this directly from the laptop which would have required designing and building a hardware device to convert the output from the laptop into the correct signal for the vibration machine amplifier. Another choice was to use a function generator, such as the Hewlett Packard HP33120A [14], which would be controlled by the laptop. This second method was chosen because the function generator was available and this was the device that was normally used to control the vibration machine manually in the past, although this control was strictly manual.

The method in which to control the function generator then needed to be selected. According to the function generator manual, the two possible approaches of controlling it from another device is either by using the HP-IB port or the RS-232 port on the back of the function generator. In order to use the HP-IB port, additional hardware (HP-IB card) would be required for the laptop. The simplest, yet sufficient, method was to use the RS-232 port connected to the laptop serial port via a null-modem cable. To control the function generator the laptop only needed to output ASCII text to the serial port.

# Chapter 3

# CONTROL SYSTEM DEVELOPMENT

## 3.1 Introduction

This chapter describes the early testing and learning that went into the development of the vibration control system algorithm. Before developing the control system algorithm, the individual parts of the control system needed to be developed separately. This included tasks like controlling the vibration machine from the laptop, reading in the acceleration from the accelerometers with the laptop, and performing various functions in the software.

To be able to perform all these tasks individually, certain configurations needed to be made in software as well as to the individual hardware components, the accelerometers needed to be calibrated, and the operation of the various hardware and software components needed to be learned.

## 3.2 Learning LabVIEW

The first task where a large majority of time was spent was used becoming more familiar to programming in LabVIEW. This was done by working with the LabVIEW Tutorial [15] and examining the various demonstration programs that were included with LabVIEW. The tutorial was helpful in that it contained many exercises to help the beginner learn, identify, and study useful demonstration programs. LabVIEW was very easy to learn because it was somewhat similar to other programming languages, the only major difference is that the programming was done by graphically drawing the program instead of typing code. Once comfortable with programming in LabVIEW, programs were constructed that tested the individual tasks used in the development of the control system. Many of these early programs, as well as the end control system, incorporated modified demonstration programs. This was an advantage because LabVIEW came with many sample programs which performed many of the needed tasks and only needed to be modified slightly.

While learning how to use LabVIEW, another job that needed to be performed was the installation of LabVIEW on the laptop. The minimum installation of LabVIEW was selected, except anything related to data acquisition was also installed. The process involved copying the files off of the cd-rom and onto floppy disks using the desktop computer. The files were organized on the cd-rom in directories (disk1, disk2,...) which could easily fit onto a 1.44 Mb floppy disk. The files then were transferred from the desktop computer to the laptop one disk at a time. Once all the files were transferred to the laptop, the setup program was executed and LabVIEW was installed. The version which was installed on the laptop required just over 16 Mb of disk space.

### 3.3 Configuration of Data Acquisition Card with LabVIEW

Since one of the major functions of the control system was to read values into the computer, one of the first tasks was configuring the DAQCard-1200 to be used with LabVIEW. Once the DAQCard-1200 was configured, it then needed to be tested so that values could be read into LabVIEW.

One of the requirements for the DAQCard-1200 is that it must be connected to a computer which has Card & Socket Services 2.1 or higher. The laptop which was being used did not meet these standards so a newer version of these PCMCIA drivers was required. These drivers where downloaded from the IBM web site [17].

Once receiving the DAQCard-1200, BNC Board, and cables from National Instruments and attempting to connect them to the laptop, it was discovered that an additional cable needed to be ordered. This cable, PR50-50M, connected the DAQCard to the NB1 cable which was connected to the BNC Board.

LabVIEW uses a program called WDAQCONF [6] in Windows 3.1 to work with the PCMCIA slots on laptops. This program needed to be configured before the DAQCard could be used with LabVIEW. The WDAQCONF program allows LabVIEW to communicate with a device by associating the device to a device number which is used within LabVIEW. The DAQCard-1200 was configured for device 1 for use with LabVIEW. To do this, WDAQCONF [16, pp. 2.6 - 2.14] was opened and Device 1 was selected which brought up the device configuration window. From the Device pull-down menu, under DAQ Cards, the DAQCard-1200 was selected. After selecting the device, the PCMCIA socket needed to be selected. To select the socket number, the socket button was selected and socket 0 was chosen. As will be explained below, this originally was configured incorrectly. Both the base address and IRQ were set up for Auto Assign by placing an X in their respective Auto Assign boxes. These settings passed the configuration test with the DAQCard-1200 connected to the laptop. After passing the configuration test, certain hardware configurations could and were configured. From the Hardware pull-down menu the polarity/range, analog input mode, and accessory were selected. The polarity/range was selected to be -5 V to +5 V, the analog input mode was selected to non-referenced single ended (NRSE), and none was selected as the accessory option.

Originally after attempting to configure WDAQCONF for use with the DAQCard-1200, the configuration test indicated that a bad base address was being used. National Instruments suggested installing a program called CardWare [18], which would aide in the configuration of the DAQCard. This program was available from the National Instruments FTP site (ftp.natinst.com), but is no longer available from National Instruments. After installing the files which came with CardWare and running the PC Card Control for Windows version 2.00 program, the correct setup parameters for WDAQCONF were determined. It turned out that the correct base address was being used, but the wrong socket number was being used. Once the configuration of the DAQCard was changed to use PCMCIA socket 0 the configuration test was successful.

### 3.4 Controlling Function Generator with LabVIEW

The HP 33120A function generator / arbitrary waveform generator was selected as the device that was to be used to control the vibration machine because it could continuously output a sine waveform to operate the vibration machine. If the laptop was used instead to control the vibration machine, it would have to continuously send each point of the waveform out to the vibration machine. This would require too much from the software which was needed to perform other tasks. With the function generator, the laptop only needed to communicate with the function generator only when a change was needed in the waveform, say once a second.

The function generator could be controlled via the RS-232 port by simply outputting commands in ASCII text from the laptop through the serial port (COM1). To be able to connect the laptop from the serial port to the RS-232 port on the function generator a null-modem cable [14, pp. 196-197] was constructed. The test LabVIEW program which was used to test communication between the laptop and function generator was very simple. It used the built in Serial Port Write VI (Virtual Instrument) [6] and was placed in a loop that wrote a string from an array of strings once a second to port 0 (COM1).

Once connected to the laptop via the null-modem cable, an attempt was made to place the function generator in remote mode. When the remote mode command, "SYST:REM", was sent from the laptop, nothing appeared to happen to the function generator. It was determined that the function generator was configured for HP-IB and that is the reason that it didn't receive the command over the RS-232 port. After configuring the function generator for Remote Interface Selection [14, p. 115], errors started occurring on the function generators display.

In trying to determine what was causing the errors, the function generator was then connected to the desktop computer and the LabVIEW program was executed, which correctly put the function generator in remote mode without errors. Since it worked on the desktop computer and not on the laptop computer, the error was determined to be the way in which the laptop was configured.

After comparing the com1 port settings on the desktop computer to those on the laptop, it was noticed that the flow control setting on the laptop was incorrect for com1. It was set to 'none' when the correct setting was supposed to be 'Xon/Xoff'. Once making this change on the laptop, the program worked correctly. The port settings can be configured under Windows 3.1 by selecting ports from the Control Panel. The table below shows the port settings which were used for the com1 port on the laptop.

**Table 3.1: Windows 3.1 com1 port settings.**

| | |
|---|---|
| Baud Rate | 9600 |
| Data Bits | 8 |
| Parity | N |
| Stop Bits | 1 |
| Flow Control | Xon/Xoff |

**Table 3.2: LabVIEW ASCII commands.**

| Command Description | ASCII Command |
|---|---|
| Remote Mode | SYST:REM\n |
| Reset | *RST\n |
| Initiate Sine Wave | APPL:SIN\s(frequency),\s(amplitude)mV\n |
| Update Amplitude | VOLTS\s(amplitude)mVPP\n |
| Update Frequency | FREQ\s(frequency)\n |

The ASCII commands which are used to communicate with the function generator are listed in Table 3.2. In these commands, the word in parentheses represents a number which belongs in that location without the parentheses. The first three commands are used during the setup of the function generator and the last two commands are used during the update of the amplitude and frequency of the vibration. The units for frequency were omitted in the commands because the default is Hertz and this was what was used.

Other errors occurred because of special characters which are used to communicate with the function generator. Without including these in the ASCII commands, errors occurred on the function generator because it had trouble understanding the commands. The \s represents a space in the command and \n represents a carriage return in the command. LabVIEW can be setup to display these characters on the screen, otherwise they are not shown.

### 3.5 Testing Vibration Machine Operation

Early on in this thesis project, the procedure for operating the vibration machine needed to be learned. This was done with assistance from Dr. Alan Haddow and using the start-up and shut-down procedures for the vibration machine (see Appendix A). This was a very important process because of how expensive the equipment was, we needed to be careful so that no damage would occur to the equipment during the project. Once understanding how to operate the equipment, permission was given to be able to operate the vibration machine on our own and whenever it was needed.

After understanding how to operate the vibration machine, the output range of the function generator needed to be determined. The amplitude values of the sine wave which was generated needed to be determined so that the correct acceleration was being outputted via the accelerometers.

### 3.5.1 Selection of an Attenuator

Based on early experiments with the vibration equipment and accelerometers, the function generator appeared to be unable to produce a low enough output voltage to achieve the desired accelerations. The function generator which was being used in this experiment was limited to a minimum output voltage of 50 mV [14, p. 298] and a lower voltage appeared to be required. This was the reason an attenuator was needed, so that voltages less than 50 mV could be sent to the vibration power amplifier. The attenuator which was selected was a Tektronix (11-059) 10X attenuator [19], which allowed the function generator output to be reduced by a factor of ten. The final control system actually used voltages which were greater than the 50 mV limit for the two vibration tests, but just barely over. The attenuator adds flexibility in case other tests are used that may not operate above the 50 mV limit.

### 3.5.2 Discharging the Capacitors in the Signal Conditioners

It was also discovered that a modification was needed to the signal conditioners in order to discharge their capacitors. When testing the accelerometers under vibration, it was discovered that the output from the signal conditioners, when observed on an oscilloscope, appeared to float. When starting the vibration it took some time for the signals to settle and when they did settle, they settled at different points. Resistors (1 kΩ) were connected across the output of both signal conditioners to discharge these capacitors. After connecting the resistors, the output of the signal conditioners centered around 0 V and then settled almost immediately.

### 3.5.3 Mounting Method for Accelerometers

A method for mounting the accelerometers to the platform on top of the vibration machine was needed because the accelerometers came with mounting studs which were much to small to screw into the holes that already existed on the platform. Two mounting devices were developed which had a hole at one end in which the accelerometers could be attached using the mounting studs. The other end of these devices contained threads which were capable of screwing into the mounting platform. The accelerometers then could be easily attached to the vibration equipment during setup and also could be removed easily so they did not need to be permanently attached. This was an advantage during early development of the control system because the accelerometers could be used both in the vibration lab as well as to be used in the lab where most of the control system development took place.

## 3.6 Reading From Accelerometers with LabVIEW

Once the data acquisition equipment was correctly configured and working, the next objective was to be able to read in values from the accelerometers using the DAQCard-1200 attached to the laptop. A LabVIEW demonstration program, Acquire N Scans.VI, was initially used to test reading in the accelerometer values. A Brüel & Kjær [20] Mini-Shaker type 4810 was used to demonstrate reading from the accelerometers before the vibration machine was used. This was done, because the Mini-Shaker was portable and could be used in the lab where most of the development took place. The demonstration VI was eventually modified to work the way it would be needed to by the final control system. The modified version, AI_READ3.VI, included the option of writing the values of each sample to a file, calculating the maximum and minimum values from the accelerometers, calculating the filtered maximum and minimum values, and allowing for the coupling, input configuration, and input limits to be set.

### 3.7 Calibration of Accelerometers

The accelerometers which were used came calibrated from the factory along with the voltage sensitivity engraved on each accelerometer. During the initial testing of the vibration equipment with the accelerometers it was noticed that different readings were being obtained from each of the accelerometers. The reason was that the accelerometers where calibrated in the frequency domain, and this experiment uses the laptop to read the values in the time domain. Before calculating the acceleration that the accelerometers were measuring, the accelerometers needed to be calibrated operating with the other equipment which was being used. To do this a Brüel & Kjær calibration exciter type 4249 [20] was used to calibrate the accelerometers.

Before the accelerometers could be calibrated, the calibration exciter needed to be calibrated itself. To do this, a brand new accelerometer from PCB was used which had been calibrated at 101.9 mV/g. Performing two readings with the calibration exciter resulted in values of 108.265 and 108.335 on a signal analyzer. Calculating the acceleration of the exciter using these values and taking the average resulted in an acceleration of 10.43 $m/s^2$ which is about 1.06 g's. The calibration exciter's marked acceleration was listed as 10 $m/s^2$, this is only a difference of less than 5%.

Using the newly calculated acceleration for the calibration exciter, two readings for each of the two accelerometers being used in this project were taken. Their voltage sensitivities were calculated and averaged and the results were 94.95 mV/g and 97.04 mV/g which is very close to their marked values of 94 mV/g and 97 mV/g.

At the time of calibration, the two accelerometers, two signal conditioners, and two coaxial cables were labeled A & B respectively so that the same components were always connected together. This was done during calibration and again when performing the vibration tests. Accelerometer A was the one which was marked with the calibration reading of 94 mV/g and accelerometer B was marked at 97 mV/g. These calibrations were done in the frequency domain and would not work for the control system being developed. That brought about the need to calibrate the accelerometers using the laptop and the other equipment which would be part of the final system.

Before performing the actual calibrations, the equipment was assembled and an oscilloscope was connected to the signal conditioners to get an idea of what the calibrated values would be. The actual calibration was performed using the AI_READ3.VI (mentioned in section 3.6) which would be used in the final control system. This was done so that the accelerometers were calibrated in regards to the values LabVIEW would read.

Once the accelerometers were being excited, 800 samples over one cycle of the waveform were made and the maximum voltage after passing through a digital filter was taken. The design of the digital filter is discussed in the next section. Five readings for each accelerometer were taken and an average over the five readings for each accelerometer was computed. Five readings were taken for each accelerometer so that an average could be taken for each accelerometer. There was no other special reason why five readings were selected other than to have a few different readings in which to compute an average. The readings and the averages for both accelerometers are shown in the Table 3.3.

Since the recorded values were not being read at 1 g, the voltage sensitivities needed to be calculated at 1 g. This was done by dividing the averaged voltage of each accelerometer by 1.06 g resulting in 136 mV/g for accelerometer A and 141 mV/g for accelerometer B. These values were then used by LabVIEW for each accelerometer as the voltage sensitivity for the accelerometer (mV/g).

**Table 3.3: Accelerometer calibration.**

| Reading # | Accelerometer A at 1.06 g | Accelerometer B at 1.06 g |
|---|---|---|
| 1 | 143 mV | 149 mV |
| 2 | 143 mV | 148 mV |
| 3 | 144 mV | 149 mV |
| 4 | 144 mV | 149 mV |
| 5 | 145 mV | 149 mV |
| Average | 144 mV | 149 mV |

Since the voltage sensitivities were input parameters in the final control system, it made it possible to re-calibrate the accelerometers and use the new values or even use different accelerometers as long as their voltage sensitivities were known.

These voltage sensitivities were considered to be linear over the frequency range used in this project. The accelerometer calibrations for this project were only taken at a frequency of 159.2 Hz which is the frequency that the calibration exciter operates. The voltage sensitivity curve could have been created for the accelerometers using a NIST standard accelerometer and plotting the values over the frequency range of the two experiments. This wasn't done for two reasons. The first reason was that these results were only as accurate as the equipment being used to perform the calibrations and the second reason is that PCB accelerometers have fairly linear voltage sensitivities according to their specification sheets over the ranges we were using.

### 3.8 Digital Filter Design

By observing the waveform that was produced by the accelerometers, it was noticed that these waveforms contained noise. These waveforms were further examined with a Hewlett-Packard Dynamic Signal Analyzer [21] and the noise occurred at high frequencies. This noise could cause unwanted side effects if it wasn't reduced. This is what brought about the need for a low-pass digital filter [22]. A low-pass filter was desired to filter out the high-frequency noise and keep only the part of the signal in the lower frequencies. The operational range of frequency for the vibration tests is between 10 Hz and 60 Hz; so, any signals above this range were not desired. A digital filter was used in which the average value was calculated over a sub-region of a handful of samples. Figure 3.1 illustrates the presence of this noise. The information used in the figure was taken from the third reading for accelerometer A during calibration.

The originally proposed method was to divide the sample range, one cycle of a sine wave, into 16 regions and then compute the average over this region. Only breaking the waveform into 16 regions didn't seem like a very strong method for a digital filter because the regions contained too many samples. With fewer regions, too much of the curve will be represented and taking an average over these regions would not be very accurate.

The new proposed method was to break the range into 50 regions with 32 samples per region. When testing this out for two channels an error occurred, which indicated an attempt to sample at a faster rate than the maximum sampling rate of 100,000 S/sec. For two channels, the maximum sampling rate for each channel turns out to be 50,000 S/sec. At the maximum frequency of the two tests of 60 Hz, the maximum number of samples which could be taken would be 833 because this is a sampling rate of just under 40,000 S/sec per channel. For the filter, 800 samples per cycle was selected which is a sampling rate of 48,000 S/sec. per channel, or 96,000 S/sec for both channels at 60 Hz. This turns out to be 16 samples per region which is half of what was proposed in the second method.

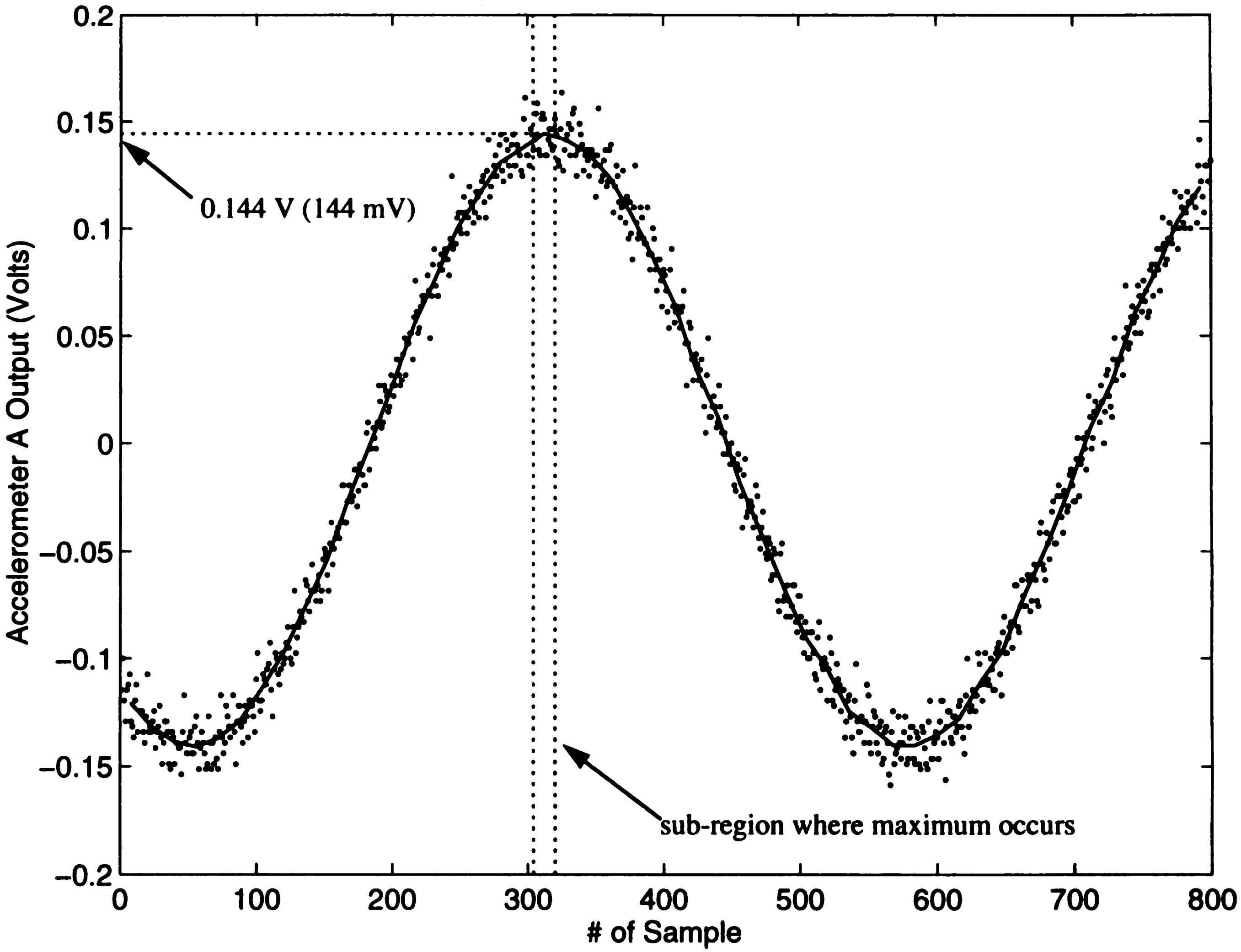


**Figure 3.1: Digital Filter on Calibration Data of Accelerometer A (sample #3).**

The filter, as implemented in LabVIEW, first collects the values of all the samples and then calculates the average value within each of the 50 subregions. The maximum value of these averages is used as the current acceleration. Figure 3.1 shows the use of the digital filter during the calibration of the accelerometer A. The dots represent the readings from the accelerometer, and the solid line is the plot of the filtered values. The region where the maximum value occurs is marked in the figure along with the maximum value. The maximum value for this calibration was 0.144 V (144 mV), this is the value that was recorded in Table 3.3.

# Chapter 4

# CONTROL SYSTEM DESCRIPTION

## 4.1 Introduction

After developing the individual components which performed the tasks which the final control system would need to perform, it was time to put everything together in one system. Once everything was put together, the system could be used to examine how well it performed the vibration tests and what changes, if any, were needed. Certain features were also added to the individual components to help improve the overall performance of the final control system, one of which was additional safety precautions were implemented to ensure the proper operation of the vibration equipment.

## 4.2 Hardware Description

Tying all the hardware equipment together in the final system was very simple. It didn't require any additional improvements over what was developed during the design of the individual components. All of the equipment was capable of being connected together without any conflicts, the only additional parts may have been the need for a power cord and a power strip in which to plug all the equipment into so that they could be supplied with power. Figure 4.1 shows a diagram of how all the hardware equipment was connected to execute the actual testing protocols. The oscilloscope was used to provide an independent way to monitor the actual acceleration.

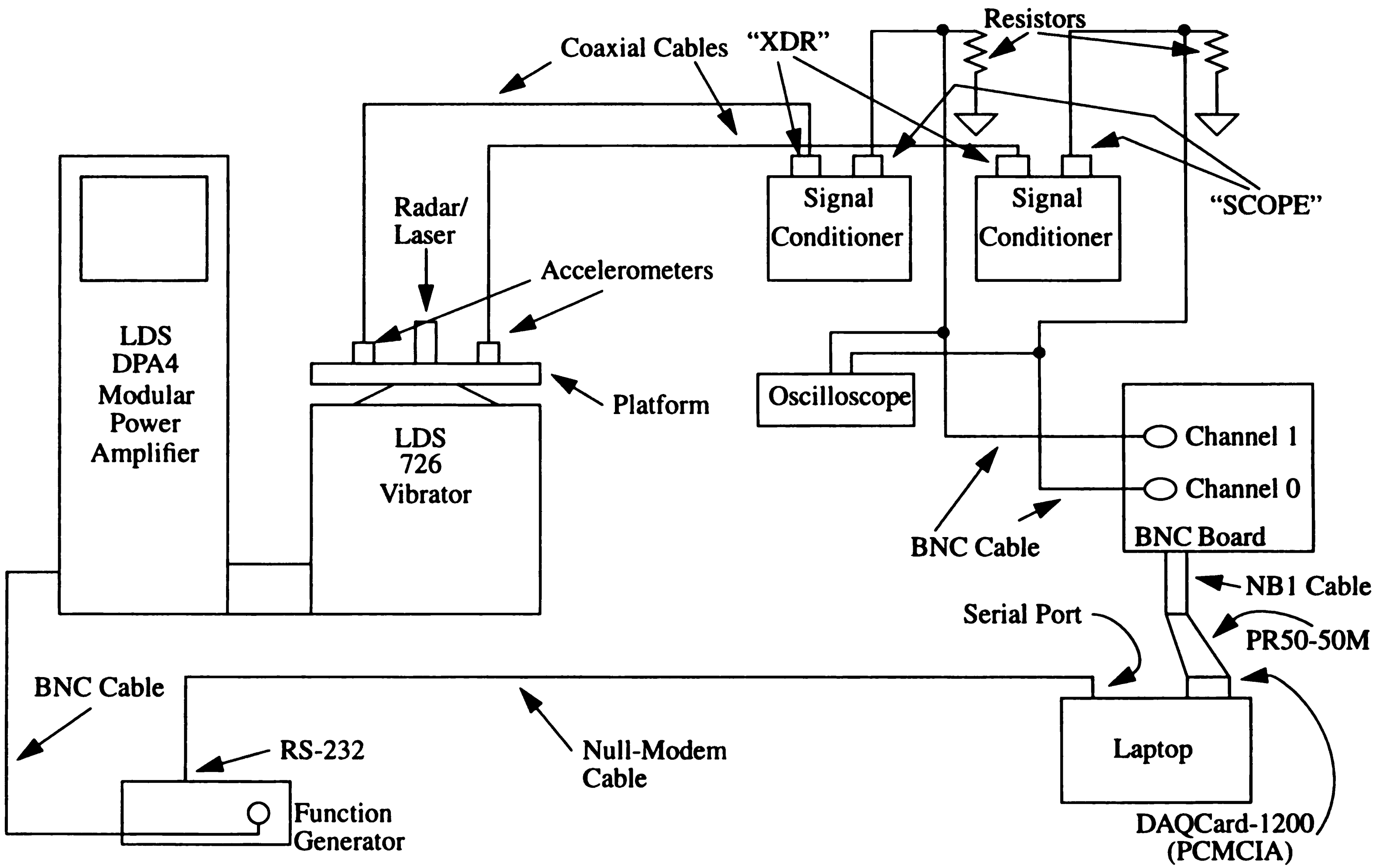


**Figure 4.1: Hardware setup diagram.**

#### 4.2.1 Platform Installation

Since the vibration machine was available for use by other students and faculty, the platform which was mounted on top of the vibrator itself needed to be removed or installed. Early on in this project, another student had a steering-column mounted on the vibrator which needed to be removed and replaced with the platform which we needed mounted in its place. With the proper wrenches and screwdrivers available, the current device mounted on the vibrator could be removed and replaced with our platform in about 20 minutes.

#### 4.2.2 Accelerometer Setup

With the correct platform mounted on the vibrator, the accelerometers were next installed. The first step in mounting these to the platform is to attach their mounting devices to the platform. These could be screwed into the platform by hand and were placed on opposite sides of where the device undergoing the testing was to be placed. The accelerometers could then be attached to these devices by hand using their mounting studs.

#### 4.2.3 Signal Conditioner Setup

The signal conditioners needed to be positioned relatively close to the accelerometers because the cable which connected them together was only two meters in length. A resistor was connected to the "SCOPE" plug on each signal conditioner in order to discharge its capacitors as was explained earlier (section 3.5.2). Each resistor was connected between the signal lead and ground, as illustrated in Figure 4.1. The coaxial cable could then be attached from the accelerometer to the signal conditioner at the "XDR" output. This connection of equipment was always done connecting to the same pieces of equipment together based on how they were labeled. A BNC cable could also be connected from the "SCOPE" output on the signal conditioner to the BNC board.

accelerometer A was connected to Channel 1 on the board and accelerometer B was connected to Channel 0. The "SCOPE" output could also be connected to an oscilloscope.

### 4.2.4 Data Acquisition Card Setup

While the laptop is off, the NB1 cable would be attached to the J1 connector on the BNC board and to the 50 pin connector on the PR50-50M connector. The other end (smaller end) of the PR50-50M connector would be attached to the DAQCard-1200. The DAQCard could then be inserted into the top PCMCIA slot (socket 0) on the laptop. After these pieces of equipment have been connected, the laptop would be turned on and while the laptop is booting, the red light on the BNC board should light up, which is an indication that the DAQCard and BNC board were properly connected.

### 4.2.5 Function Generator Setup

The function generator also needs to be plugged into the power strip before it could be turned on. The attenuator is connected to the output terminal on the front of the function generator and a BNC cable is attached to the attenuator but will not be connected to the modular power amplifier until told to do so by the LabVIEW program. A double-ended BNC male connector may be needed if the one attached to the BNC cable connected to the modular power amplifier is missing.

The laptop also needs to be attached to the function generator and this is done using the null-modem cable. The null-modem cable connects from the RS-232 port on the back of the function generator to the serial port on the back of the laptop. The null-modem cable has the capability of being firmly attached with the use of a small regular screwdriver.

When the function generator is powered-up, special attention needs to be paid to the remote mode that it is configured to. This control system requires that the function generator be set to RS-232 mode and not in HP-IB mode. Originally the function generator was set to HP-IB and needed to be configured to RS-232 mode [14, p. 115].

### 4.2.6 Mounting of Device Undergoing Testing

The radar or laser speed-measurement device also needs to be mounted on the platform which is attached to the vibrator. This is done using various parts which when put together, act as a clamping mechanism. These parts include threaded rods which can screw into the threaded holes which are spaced evenly over the mounting platform, wing-nuts which are attached to the rods, and wooden boards with a hole at each end which the rods can be inserted through. The wooden board is placed on top of the device which is being mounted and a rod is inserted through both holes and screwed into a hole on the mounting platform. A wing-nut is then tightened on both rods pushing the board down against the device to act as a clamp.

### 4.2.7 Laptop Setup

The laptop needs to be positioned fairly close (1-2 meters) to the signal conditioners and the BNC board due to the length of the cables. The laptop power adapter needs to be attached to the back of the laptop and to the power strip. The DAQCard-1200 also needs to be inserted as explained in section 4.2.4 and the null-modem cable is attached as explained in section 4.2.5. Once the laptop has been connected, it can be turned on and windows can be started. Once windows is loaded, the WDAQCONF program needs to be started as well as LabVIEW. The name of the control system which was developed is VIBRATION.VI and this program needs to be loaded to start the vibration testing.

### 4.2.8 Vibration Equipment Setup

Nothing else needs to be done to the vibration equipment hardware unless the mounting platform needs to be attached. The platform mounting procedure was explained in section 4.2.1. The modular power amplifier needs to be turned on and this can be done following the instructions in Appendix A.

### 4.2.9 Additional Hardware Setup

The only additional equipment which may need to be setup includes extra cables and power cords. Depending on the location of wall outlets, an extension cord may be needed and attached to the power strip. A power strip is needed to plug in the two signal conditioners, the laptop computer, the function generator, and additional instruments.

## 4.3 Software Description

Once the initial testing and configurations were formed, the control system would be ready for final assembly, verification, and use. In the early development of the control system, individual programs were created which now needed to be combined into one functioning program. These programs performed the major tasks like controlling the function generator, reading from the accelerometers, and implementing the digital filter. Besides combining these programs, additional items needed to be added into the software, one of which was to prompt the user for the correct information to perform the vibration test.

The following sections describe how the final control system was put together. The order in which the control system is described next was not the exact order in which it developed but an easier way to explain the control system.

### 4.3.1 Experiment Input

When pressing the run button for the control system program, a separate window pops up prompting the user to select certain operating parameters. This was done to allow the two vibration tests to be performed as well as to perform other similar tests. On this screen the user is prompted for the major experiment parameters, which include: the "start frequency", "peak frequency", "test period", and "amplitude" of vibration in inches. Additional parameters which can be modified include the voltage sensitivities of both accelerometers ("mV/g A", "mV/g B"), "channel difference range", starting amplitude of function generator ("start"), and the amount of change in determining starting amplitude ("change"). Once the user has selected all the parameters, the "Click to Start" button can be pressed to continue on with program. After the "Click to Start" button has been selected, the program initializes the function generator using the starting amplitude as well as the starting frequency.

Safety checks were also built into the program so that the program will not allow to high of a voltage or frequency to be used. The maximum frequency which is allowed was set to be 100 Hz, which is well above the highest frequency which was needed for the two vibration tests. The maximum voltage which was allowed to be outputted by the function generator was selected as 1.8 V, which is reduced by the attenuator by 10 times before entering the amplifier. During initial testing with the vibration machine, it was noticed that 1.8 V was well above the voltage needed for both vibration tests.

Figure 4.2 is the window that is displayed when prompted to enter the experiment input values. Once the values have been entered, the "Click to Start" button can be pressed.

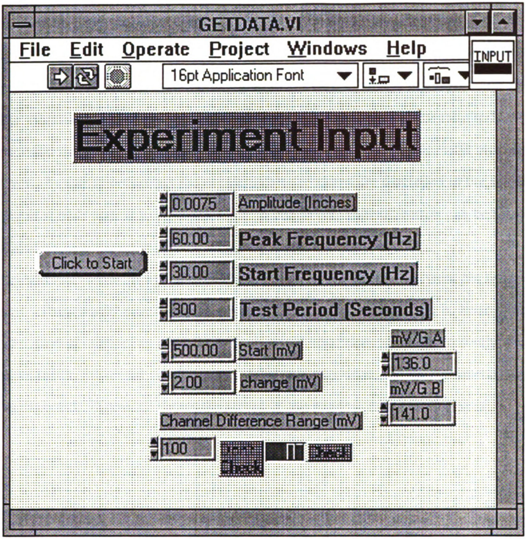


**Figure 4.2: Experiment input screen.**

### 4.3.2 Channel Verification

Once the function generator has been initialized another pop up window is displayed and directs the user at this point to connect the output from the function generator to the power amplifier. This must be done using an attenuator, otherwise damage could occur with the vibration equipment. As soon as the connection is made between the function generator and the vibration machine, the platform on top of the vibrator starts moving up and down. As this is occurring, the accelerometer readings are displayed in the window. Once these signals appear to be correct, the "Click When Settled" button can be selected to continue on with the program.

During initial testing, it was noticed that the accelerometer readings were not what was expected. They would even produce negative numbers at times. This is what brought about the need of connecting resistors to each signal conditioner in order to discharge the capacitors inside the signal conditioners. After this was done, the accelerometer values were as expected. Figure 4.3 shows the screen of the window which is displayed.

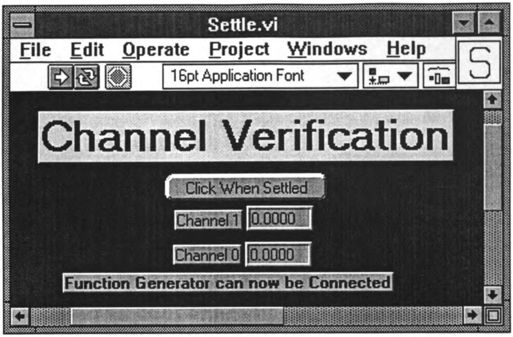


**Figure 4.3: Channel verification screen.**

### 4.3.3 Finding Starting Amplitude

Before the tests can be performed, the starting amplitude which the function generator sends to the vibration machine needs to be calculated. This is done by continuously increasing the starting amplitude by the amount selected by the user, amount of change, until the desired starting acceleration is received from the accelerometers. Both the starting amplitude and amount of change are selectable by the user and are represented in Figure 4.2 as the "start" and "change" inputs respectively. The starting acceleration is computed using the voltage sensitivity of accelerometer A. Once the starting amplitude has been achieved the experiment is ready to begin, and a pop up window indicating that everything is ready. Once the "OK" button has been selected the experiment is started. Figure 4.4 illustrates the window which is displayed when the experiment is ready to be run.


**Figure 4.4: Status-menu screen.**

### 4.3.4 Main Program

The main program handles the performance of the actual experiment. This involves sending out the commands to control the vibration machine and reading in the current acceleration and making any corrections that are necessary. When the run button is selected, the main program first executes the GETDATA.VI to receive the experiment input variables which are to be used. Once the data is received, the initialization can be performed on the function generator and it can be placed in remote mode. After receiving the input and initializing the function generator, the SETTLE.VI is executed instructing the user to connect the function generator to the modular power amplifier after the accelerometer outputs look reasonable. The starting amplitude for the function generator is then calculated and once determined, a pop up window indicating that the experiment is ready to begin.

Once the main loop of the experiment has begun, certain tasks occur once a second in the following order: calculation of current frequency, update of frequency, read values from accelerometers, update amplitude, write data to file, and check to see if the "STOP" button has been used or the accelerometer readings differ by more than what is allowed.

Figure 4.5 on the next page is the screen display that is used during the execution of the main program. This display includes the current readings of the frequency, time, channel 1, and channel 0, as well as displays the current plot of frequency vs. time. The correction amount is also displayed on this screen and can be selected before the run button is pressed to either none (0), half (0.5), or full (1.0).

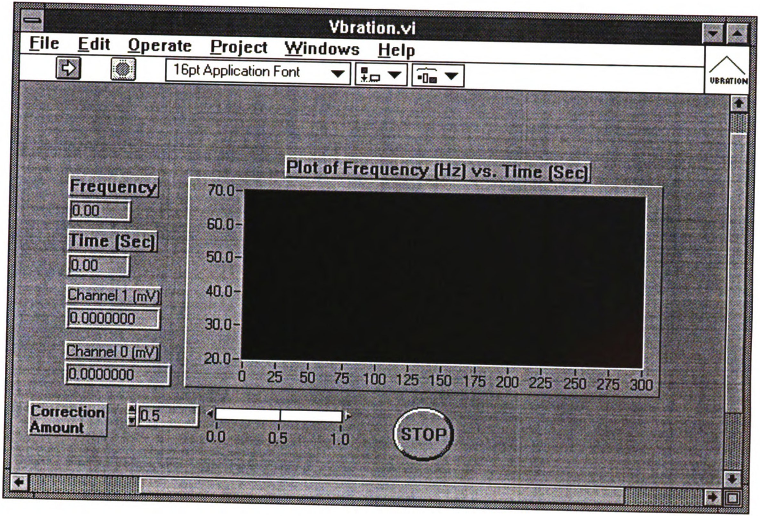


**Figure 4.5: Main-menu screen.**

#### 4.3.4.1 Calculation of Current Frequency

Based on the current time, starting frequency, peak frequency, and test time period, the current frequency can be calculated. The frequency is calculated using one of two different equations. The first equation calculates the frequency before the midpoint of the experiment is reached and the second equation calculates after the midpoint has been reached. These equations are listed in Figure 4.6 below.

Once the frequency is calculated for the current time, the calculated value is used to update the plot of the current frequency vs. the current time on the Main-menu screen. This indicates to the user the progress of the current experiment.

#### 4.3.4.2 Update of Frequency

This section of the program takes the frequency which was calculated, as the current frequency, and compares it to the maximum frequency allowed and writes the smaller of the two frequencies to the serial port. The following string "FREQ\s(frequency)\n" is the command which is used to update the frequency on the function generator. The value of the new frequency is placed in the string for (frequency). The function generator will receive this command and update the frequency accordingly.

$i < (\text{time}/2)$ $$\frac{(peak + start) \times i}{(\text{time}/2)} + start$$

$i \geq (\text{time}/2)$ $$\frac{(peak - start) \times i}{(\text{time}/2)} + (2 \times peak) - start$$

<u>Equation Variables</u>

*peak* - Peak Frequency
*start* - Starting Frequency
time - Test Time Period
*i* - Current Time

**Figure 4.6: Calculation of frequency equations.**

#### 4.3.4.3 Read Values from Accelerometers

The AIREAD3.VI is used to read the values from the accelerometers. These values are then converted from Volts to mV and displayed on the Main-menu screen. The difference of the two readings is calculated and if it is larger than the allowed amount specified with the GETDATA.VI then a signal is sent to the Check Stop Button routine to abort execution of the program.

#### 4.3.4.4 Update Amplitude

This routine compares the readings from the accelerometers to their desired values and calculates a new amplitude for the function generator to try and correct any errors. Different ways of performing the correction were examined. The first method was to use the same amplitude for the update over the entire time period (zero-correction). The next three methods would calculate the amount of amplitude change that was required every second and multiple this number by 0.0 for no correction, 0.5 for half correction, or by 1.0 for full correction of amplitude.

The first attempt at adjusting the amplitude used by the function generator was to calculate the amount of change needed based on the starting amplitude used. This was done by taking the starting amplitude which was found and dividing it by the starting frequency to determine the amount of amplitude per hertz. The frequency was updated at a constant rate, so an attempt was made at updating the amplitude at a rate which was equal to the change in frequency per second times the amount of amplitude per hertz. As can be seen in Figure 4.7, this method isn't very accurate and at the peak frequency, the actual acceleration is much greater than the desired acceleration.

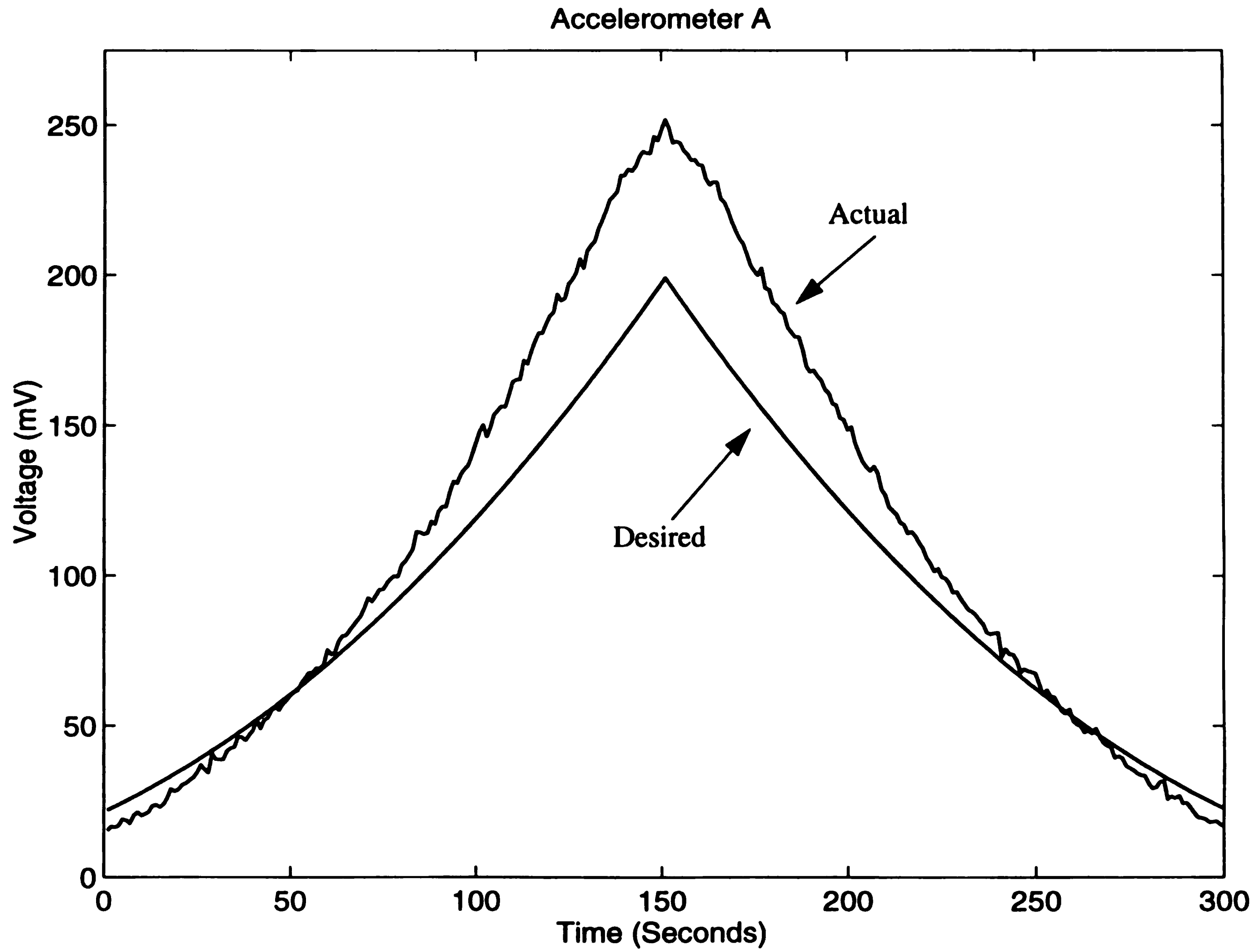


**Figure 4.7: Accelerometer A, Test #1, with constant amplitude adjustment.**

The first method for updating the amplitude wasn't very successful, so another method was needed. The next three methods all used the same idea, but made corrections at different rates. These methods try and determine the correction which is needed and then update the amplitude on some percentage of this correction, either none, half, or full. Once the values are read from the accelerometers, accelerometer A's actual value is compared to its desired value. The correction amount is calculated by subtracting the desired value from the measured value (error value) and multiplying this value by the previous amplitude divided by the measured value. This correction amount is then multiplied by either 0.0, 0.5, or 1.0 for no correction, half correction, or full correction and added to the previous amplitude.

The block diagram of the correction method is illustrated in Figure 4.8. The vibration apparatus shakes the sensors which output a voltage indicating the acceleration. This actual acceleration is compared with the desired acceleration and a correction is made. The correction is sent to the function generator once a second which corrects the waveform used for vibration.

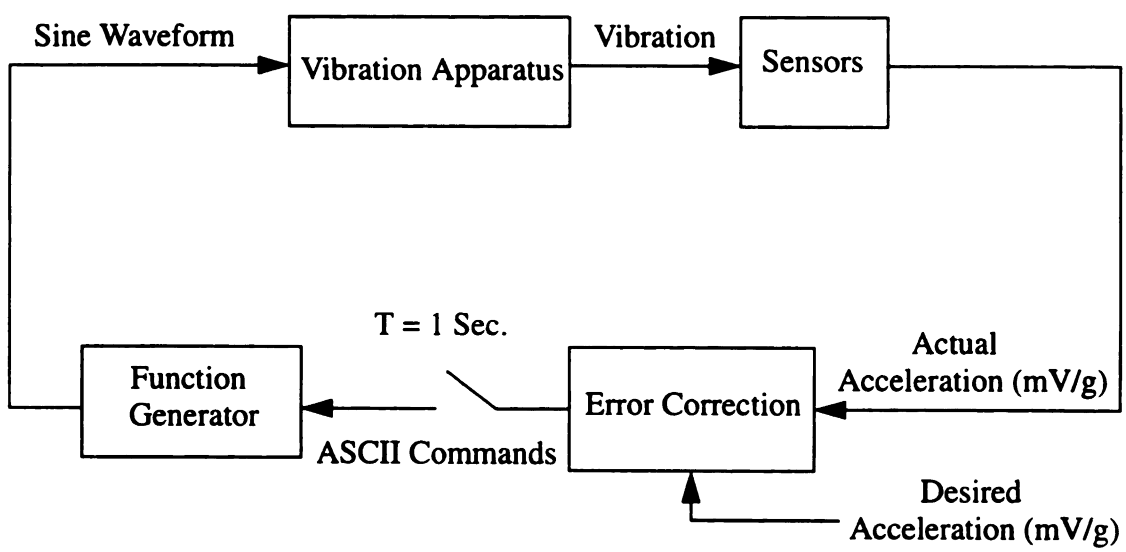


**Figure 4.8: Block diagram of correction method.**

This procedure can be used because it was determined that the amplitude vs. acceleration is linear. These results were obtained by performing three tests at 30 Hz, 45 Hz, and 60 Hz and plotting the amplitude values vs. the acceleration readings. The results of these three tests are shown in Figure 4.9. It can be seen that these plots are fairly linear.

The method of no correction wasn't a very effective way to update the amplitude for the function generator. Once the starting amplitude was determined, this amplitude was the value that was always used because after calculating the correction amount needed, this value was multiplied by zero. The result was that the actual values received from the accelerometers were always less than the desired values. As the frequency is increased, the amplitude must also be increased to be able to achieve the desired results, this method was immediately discarded and the half and full correction methods were examined next.

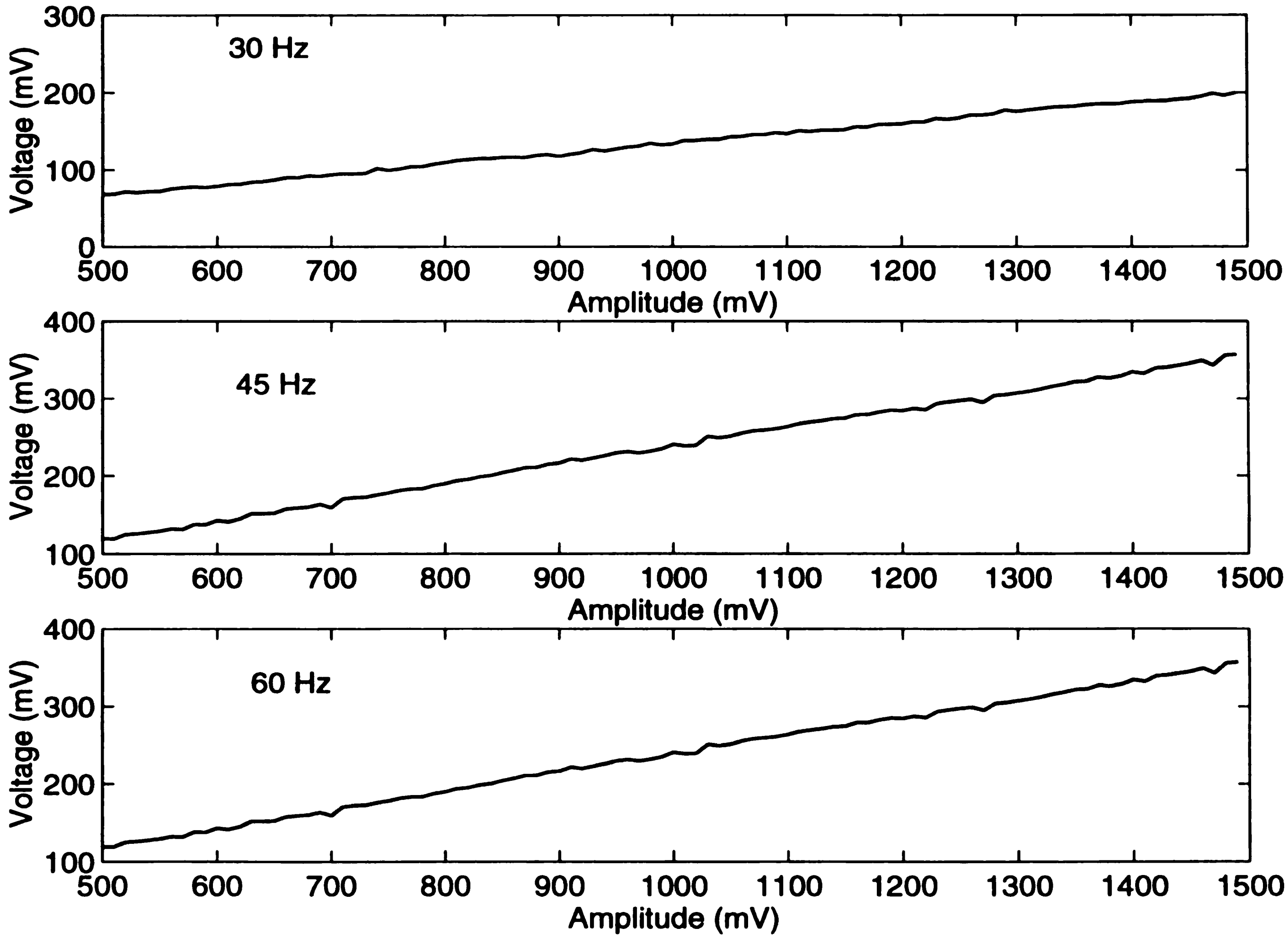


**Figure 4.9: Amplitude vs. accelerometer acceleration.**

The half correction method calculates the change in amplitude needed based on the difference between the actual value and desired value. Only half of this change in amplitude is sent to the function generator. The results of the half correction method are displayed in Figure 4.10 for vibration test #1 and Figure 4.11 for vibration test #2.

The full correction method is exactly the same as the half correction method, except the entire correction is applied to the function generator. The results of the full correction method are listed in Figure 4.12 for vibration test #1 and in Figure 4.13 for vibration test #2.

In the next four figures the desired values occur on the straight line and the actual values are located on the lines which are not perfectly straight. On these figures, it can be seen that the results are fairly accurate which makes it difficult to distinguish the actual values from the desired values. The plots of the two lie on top of each other.

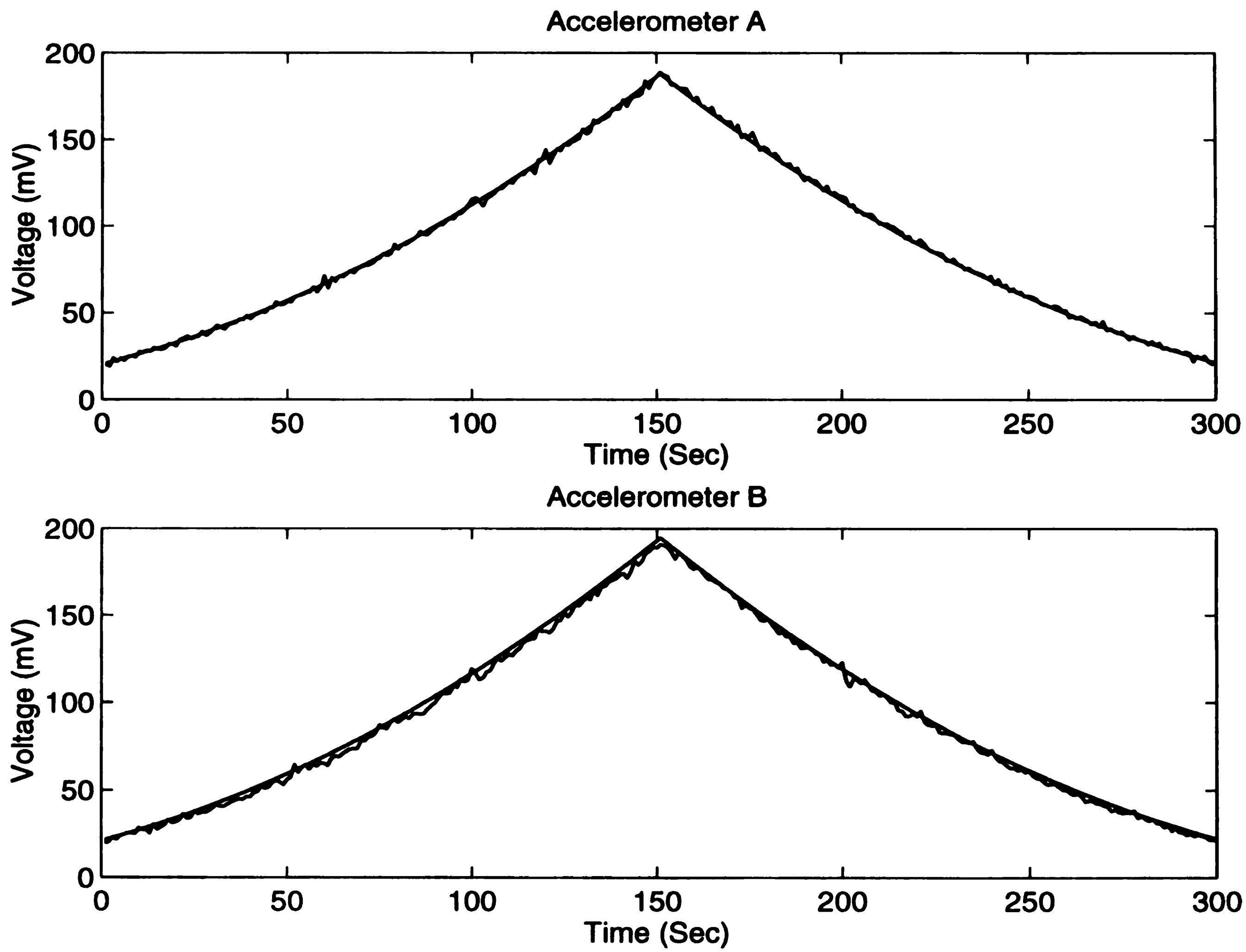


**Figure 4.10: Test #1, half correction**

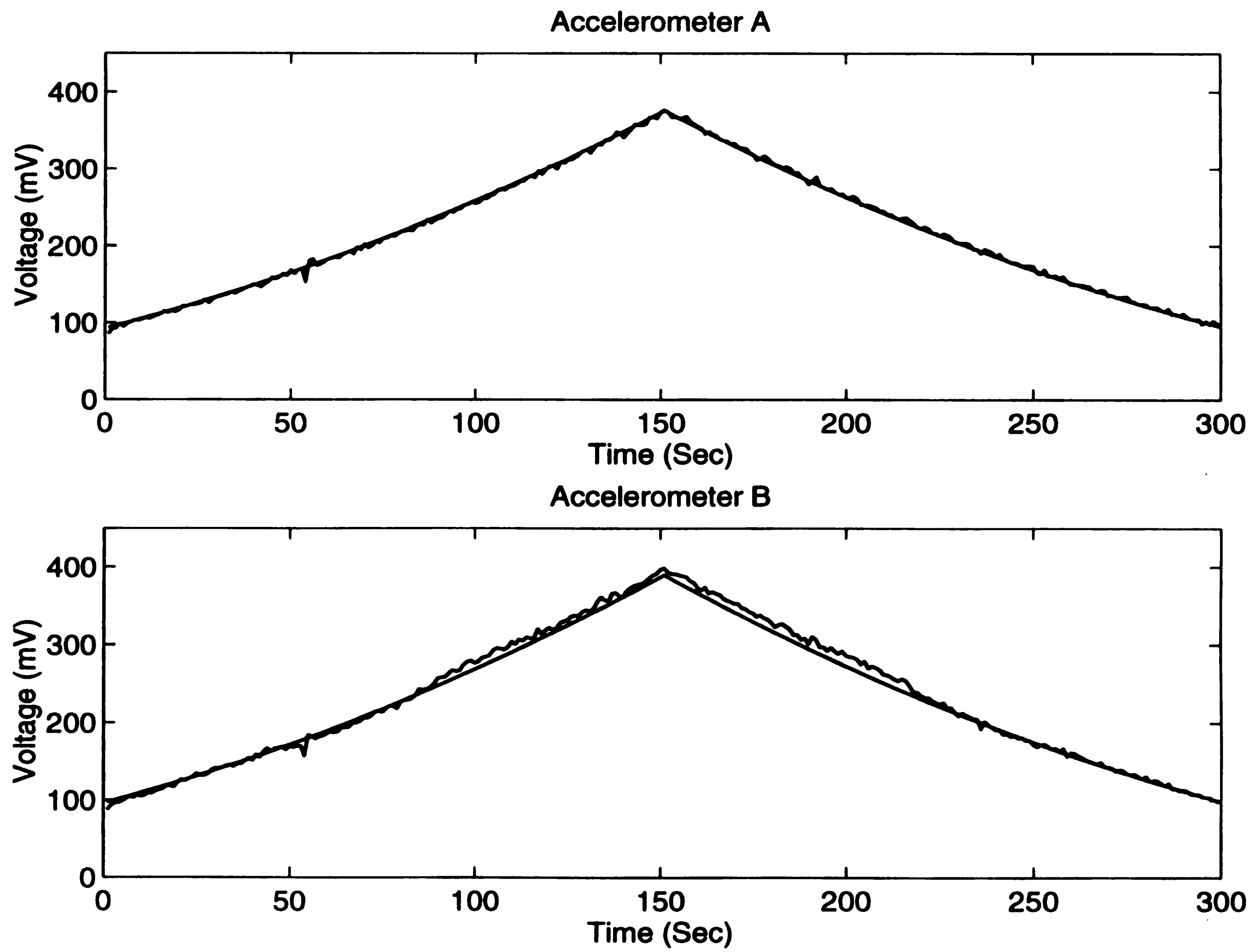


**Figure 4.11: Test #2, half correction.**

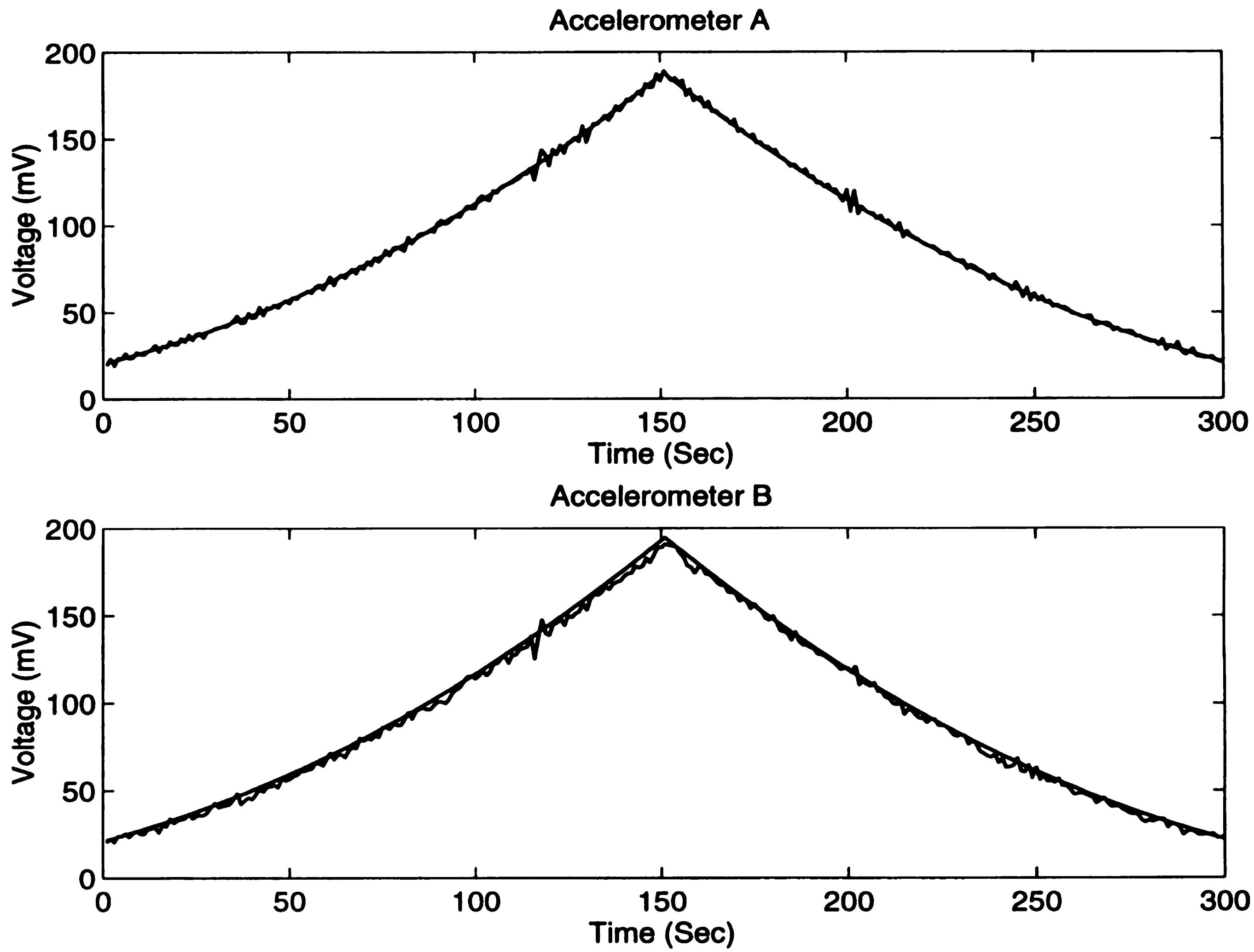


**Figure 4.12: Test #1, full correction.**

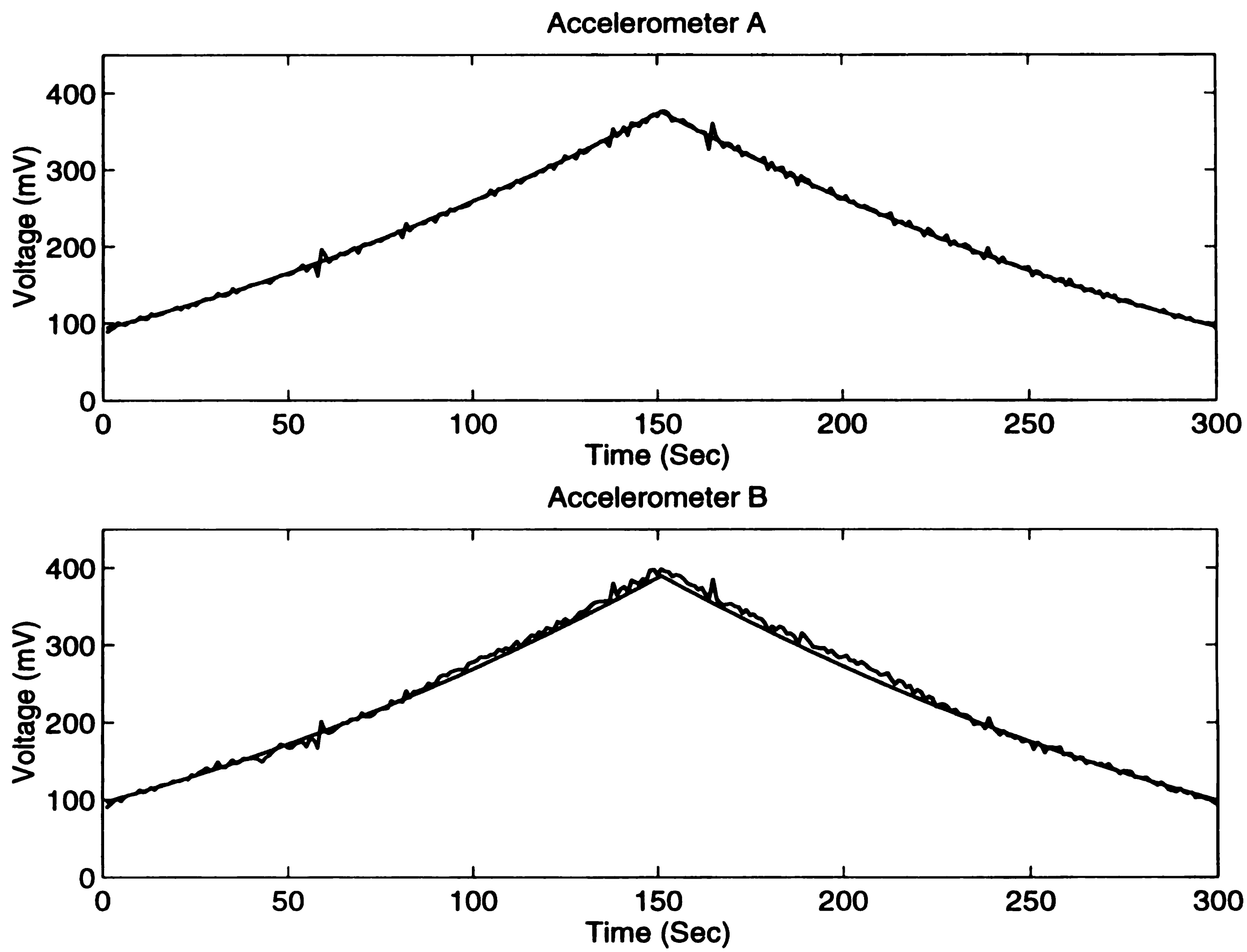


**Figure 4.13: Test #2, full correction.**

Both the half and full correction methods only use the values of accelerometer A in calculating the correction. It can be noticed from Figures 4.10 - 4.13 that the results of accelerometer B are close to its desired values too, even though it wasn't included in the correction method. After examining the data files created from both the half and full correction methods, it appears that the half correction method is slightly better at updating the amplitude than the full correction method. The reason for this is that the full correction method may be more likely to overshot the desired value during correction compared to the half correction method.

Once the new amplitude is calculated, it is inserted into a string command which is sent to the function generator. The string command which is used is of the format "VOLTS\s(amplitude)mVPP\n", where (amplitude) is replaced by the new amplitude value. Once the function generator receives the command, it updates the amplitude to the new value. There is a check to make sure that no voltages greater than 1.8 V are sent out to the function generator. This value was greater than the amplitudes which needed to be sent out for both vibration tests. Depending on the load which is undergoing testing, this value may need to be changed in the future.

#### 4.3.4.5 Write Data to File

The data is not actually written to a file once a second, but rather stored in an array which will be written to a file upon completion of the program. The information which is stored on each line of the file includes the frequency, acceleration, channel 1 actual reading, channel 1 desired reading, channel 0 actual reading, and channel 0 desired reading. When the program is finished executing, the user is prompted for the name of the file in which data is to be stored.

#### 4.3.4.6 Check Stop Button

The program, when it reaches this section, checks to see if the stop button has been pressed, indicating that the user would like to end the program. If the stop button has been pressed, the program is aborted, otherwise the program continues. Before the program aborts, it applies a sine wave with an amplitude of 50 mV at a frequency of 10.0 Hz as a precautionary measure.

This routine also checks to see if a signal has been received from the section of the program which reads in the values from the accelerometers. If the difference between the two accelerometer readings is larger than what was selected by the user, then the program is aborted. The difference range can be selected along with the other experiment inputs with the GETDATA.VI function.

# Chapter 5

# ANALYSIS AND EVALUATION

## 5.1 Introduction

Once the final control system was designed, it needed to be tested. As explained in the previous section, experiments were conducted in order to determine the most efficient amplitude correction method which was to be used. From these tests it was determined that the half correction method was the most accurate method. Upon completion of testing, the accuracy of the developed control system needed to be examined.

## 5.2 Accuracy of System

The accuracy of the final control system needed to be calculated to determine the reliability of the vibration test results. The data collected during the tests was used in determining the accuracy. The data from the vibration experiments contained both the actual and desired values of the accelerometers at each step during the experiment. Using this data, the accuracy for the system could be determined. For each set of data points the difference between the actual and desired values were calculated. Because tuning-fork tests take a few seconds to perform, the differences were averaged over three second time intervals. Finding the maximum average difference over a three second time interval would indicate the largest amount the control system was off the desired value. For the two trial tests, the largest error was just over 7 mV for test #2 with full correction, which is an error of less than 0.06 g's. Using half correction for both tests turned out slightly better results.

An interesting set of tests were performed to determine the accuracy of the vibration equipment over time when applied with a constant signal. These tests were performed by supplying a constant signal without making any corrections to the signal being applied. Two tests were performed, the first test had the function generator apply a sine wave with an amplitude of 800 mV (80 mV after passing through attenuator) at a frequency of 30 Hz to the power amplifier. The results of this test are plotted in Figure 5.1 and they show that even when a constant signal is applied on a function generator the accelerometer readings are not constant. The acceleration readings were averaged over 3 seconds and showed that the accelerations ranged from about 0.786 g's to 0.831 g's which is about a difference of 0.045 g's.

Figure 5.2 contains the results of the same test that produced Figure 5.1 but this test was operated at a frequency of 60 Hz and at a function generator amplitude of 700 mV (70 mV after passing through the attenuator). Again the results are not a perfectly straight line. The range of accelerations averaged over 3 seconds for this test was from 1.603 g's to 1.650 g's which is about a difference of 0.047 g's. These results illustrate that there is some error due to the accuracy of all the hardware components. These tests used a function generator connected to the vibration apparatus which read the acceleration from two accelerometers mounted on the vibrator. The values were read through the data acquisition card attached to the laptop. The combination of all these pieces of equipment can lead to the variances in results obtained.

These results are what was expected. During initial testing it was noticed that the function generator output would vary even though a constant signal was being used. It is also easy to understand that the accelerometer readings as well as the motion of the vibrator can vary with a constant signal.

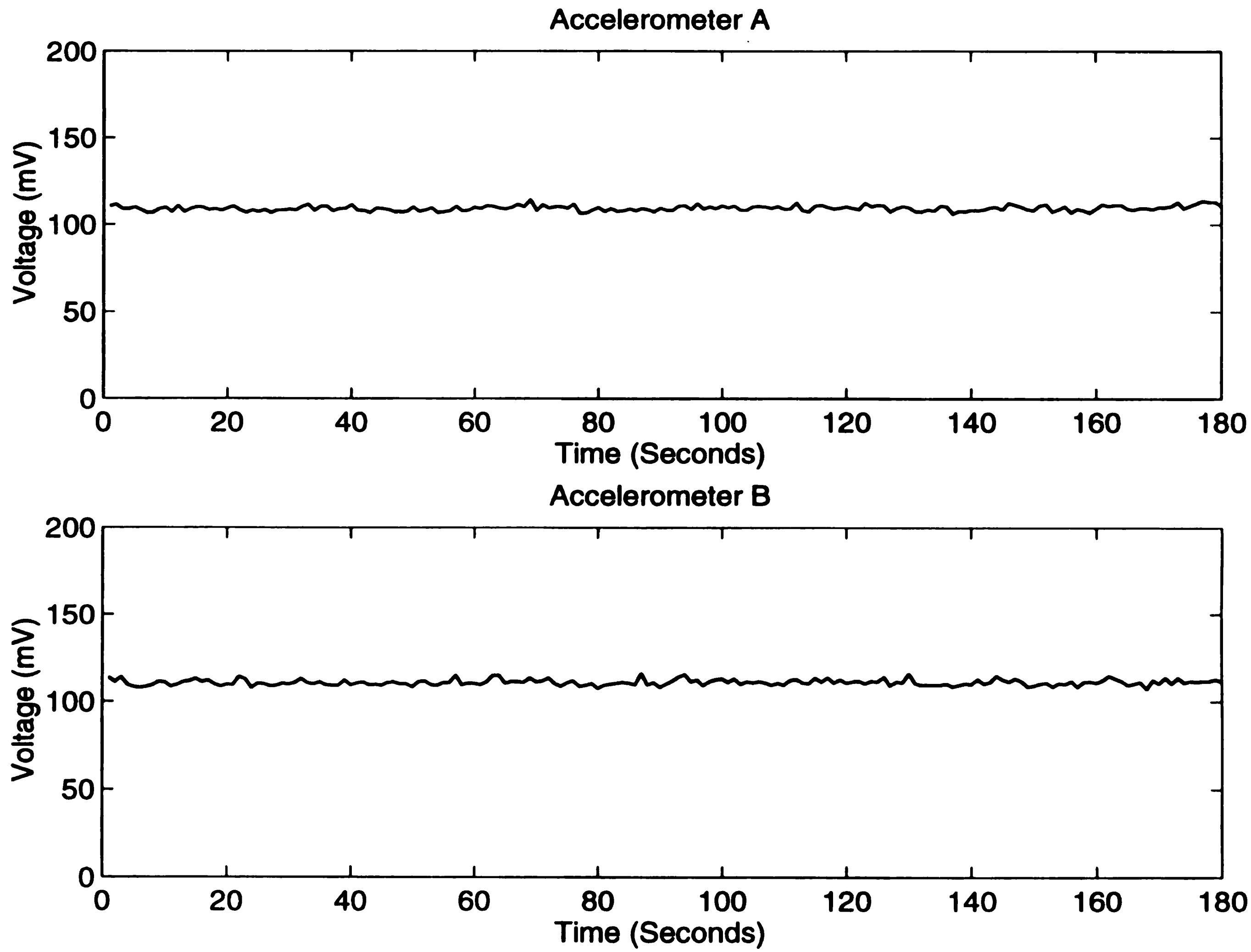


**Figure 5.1: Constant vibration at 30 Hz with an amplitude of 800 mV.**

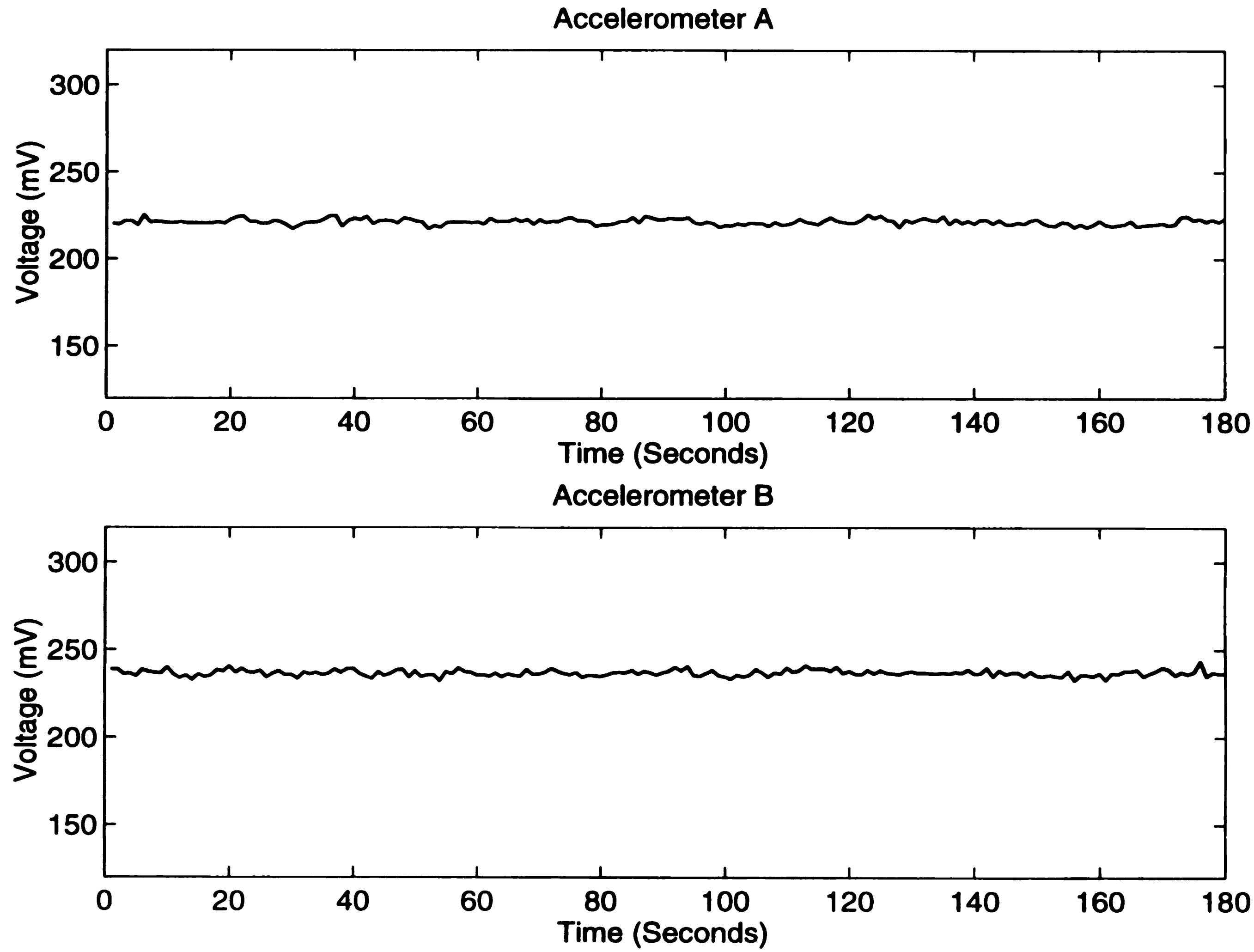


**Figure 5.2: Constant vibration at 60 Hz with an amplitude of 700 mV.**

There are many different areas in this control system which could be the cause the errors that are being seen, as was described in the previous paragraphs. The operation of the various pieces of equipment may not be operating consistently. This includes the vibration apparatus, function generator, data acquisition equipment, laptop, accelerometers, signal conditioners and any other equipment used. Even though this vibration control system isn't 100% accurate, its accuracy is a giant improvement over the manual operation of these vibration tests.

# Chapter 6

# SUMMARY AND CONCLUSIONS

## 6.1 Purpose of Project

The main purpose of this project was to develop an automated vibration control system capable of performing the recommended vibration tests on radar and laser speed-measurement devices. These vibration tests are used to simulate the operation of the device in a moving vehicle. An automated control system was desired to provide testing methods which were more accurate and reliable than the old manual method of testing. In addition to developing the control system, documentation needed to be created to instruct others on how to setup and perform these experiments. This information can be found in both Appendix A and B.

## 6.2 Summary of Results and Contributions

The major contribution of this project was the development of a working automated vibration control system for performing vibration tests. As was explained in the last section, this system is quite accurate and is a major improvement over the previous method of performing the required vibration-test protocols. The amount of disk space required for the LabVIEW programs in the final control system is about 1 Mb.

Other contributions included the ability to record data from experiment runs, documentation on how to perform the experiments, the ability to change experiment parameters, and built in safety checks.

### 6.3 Problems Encountered

As with any project, certain problems and obstacles occur which need to be resolved. In the development of the control system, only minor problems occurred which were easily solved. Most of these problems occurred as the result of improperly configuring the hardware devices used in the experiments.

The DAQCard-1200 was one of these devices which caused problems during its initial configuration. Once determining the correct settings and parameters, this data acquisition card worked perfectly (section 3.3).

The function generator was another device which also slowed down the development of the system. Originally the function generator was configured to the wrong remote mode (HP-IB vs. RS-232) and the serial port settings were improperly set on the laptop. Besides the configurations for the function generator, the original commands which were sent to the function generator were in the wrong format. After correcting the configurations on both the laptop and function generator and using commands in the correct format, the function generator also functioned correctly (section 3.4).

One of the biggest problems which was encountered also had an easy solution. While performing some of the initial tests, it was discovered that the signals from the accelerometers tended to float and not settle as quickly as was desired. This was easily solved by attaching a 1 kΩ resistor to the "SCOPE" connector on the back of each signal conditioner. The resistor helped discharge the capacitors in the signal conditioners, creating signals which could be read using the laptop (section 3.5.2).

These were just some of the larger problems which occurred. Other more smaller problems resulted which were easily fixed. These included problems like making simple mistakes in LabVIEW programming. Problems like the ones listed here caused setbacks in the development of the system. The goal was to avoid these types of problems, but not all problems can be avoided.

### 6.4 Future Recommendations

This automated control system for performing vibration tests was a large improvement over the existing manual method, but it also could be improved further. The developed control system based updating the amplitude for the function generator only on one of the accelerometers (accelerometer A connected to Channel 1). One way at improving the accuracy of the system might occur if both accelerometer readings were considered in the update process. Currently the only function of accelerometer B is to ensure that both accelerometers were receiving readings within a range which was selected by the user. Otherwise the system would quit if the difference between the two accelerometers was larger than what the user selected.

This control system also uses a number of various pieces of equipment and this can reduce the accuracy of the system. Examining the accuracy of each individual hardware component and its effect on the system is another suggestion for improvement. Another way in which the control system could be improved may be to examine if increasing the frequency and amplitude at a faster rate than once a second would be more accurate.

### 6.5 What Was Learned

This project was very beneficial in that it illustrated what steps are required in the development of a system of this degree of complexity. These steps included the initial decision process, selecting the hardware and software to use, initial testing, creation of the actual system, and evaluation of the system which was built.

The initial decision process included deciding on the possible approaches and selecting the method which was to be used. The selection of the hardware and software required selecting and ordering the components which meet our desired needs. Once receiving the equipment, various individual parts of the control system could be developed and tested. The development of the final control system involved using some of the initial developed parts and tying everything together, plus adding any other required or desired features. Once the final control system was developed it needed to be evaluated for its accuracy.

### 6.6 Conclusion

With the development of an automated vibration control system, radar and laser speed-measurement devices can now be more accurately tested at Michigan State University. This new control system is currently being used as the method to perform the desired vibration tests on these devices.

APPENDIX A

# APPENDIX A

## VIBRATION MACHINE OPERATION

### Model DPA4 Power Amplifier Power Up Process

1) Turn key clockwise from 12:00 position to 3:00 position.

2) Turn on signal generator, but keep output disconnected from power amplifier.

3) Turn "Amplifier Standby" On.

4) Turn "Amplifier Signal" On.

5) Signal generator may be connected to power amplifier when told to by program. (Caution: make certain that both frequency and amplitude are properly adjusted before activating on the output).

### Power Down Process

1) Signal generator may be turned off and disconnected.

2) Turn "Amplifier Signal" off.

3) Turn "Amplifier Standby" off.

4) Turn key counter-clockwise from 3:00 position to 12:00 position.

# APPENDIX B

# APPENDIX B

## VIBRATION TESTING PROTOCOL

### EQUIPMENT

Laptop computer with Windows 3.1 and LabVIEW software.
2 Signal conditioners.
2 Accelerometers (already calibrated).
2 Resistors for signal conditioners (1 kΩ).
1 DAQCard-1200.
1 NB1 cable.
1 PR-50M cable.
1 BNC board.
2 Coaxial cables for accelerometers/signal conditioners.
Powercord / powerstrip.
10X attenuator.
5 BNC Cables (or more).
1 Null-modem cable.
1 Function generator.
1 Oscilloscope.
2 BNC T connectors (to connect oscilloscope).

Device undergoing testing.
Device mounting equipment (boards, rods, wing-nuts).

## SETUP

### Laptop

- Plug power adapter into laptop.
- Connect null-modem cable from laptop to function generator.
- Plug DAQCard-1200 into top PCMCIA slot (Slot #0).
  - Insert card with DAQCard-1200 label facing down.
  - Before plugging in card, connect PR-50M cable.
- Connect NB-1 cable to BNC board connector J1.
- Connect other end of NB-1 cable to PR-50M cable.
- Power up laptop (notice red light on BNC Board lights up).
- Start up Windows (type win at DOS prompt).
- Start up DAQCONF and minimize (This sets the device number for LabVIEW).
- Start up LabVIEW and load program.
  - Program Directory: **C:\2.MPS\THESIS**
  - Program Name: **VBRATION.VI**

### Function Generator

- Connect to null-modem cable from laptop.
- Connect 10X attenuator to output.
- Do not connect to vibration power amplifier yet (will be told to by program).
- Power on and set waveform to sine wave, 10Hz, 50mV VPP (precaution method).

### Accelerometers

- Screw accelerometer mounting devices onto specially designed platform.
- Attach accelerometers to mounting devices.
- Plug in both signal conditioners into power strip.
- Attach coaxial cable from "XDR" on signal conditioner to accelerometer (corresponding letters: original accelerometer A marked 94 mV/g, original accelerometer B marked 97mV/g).
- Attach resister to "SCOPE" output of signal conditioner (corresponding letters).
- Connect BNC cable from channel 1 on BNC board to resistor on signal conditioner A.
- Connect BNC cable from channel 0 on BNC board to resistor on signal conditioner B.
- Power on signal conditioners.

### Vibration Machine (Power-Up)

- Turn key clockwise from 12:00 position to 3:00 position.
- Turn on "Amplifier Standby".
- Turn on "Amplifier Signal".
- Do not connect to function generator until told so by program.

### Mounting Testing Device

- Center device in middle of platform.
- Use mounting boards, threaded rods, and wing-nuts to clamp device down.

**Table B.1: Vibration testing protocol parameters.**

| Test # | Starting Frequency | Peak Frequency | Time (Seconds) | Amplitude |
|---|---|---|---|---|
| 1 | 10 Hz | 30 Hz | 300 | 0.015 in |
| 2 | 30 Hz | 60 Hz | 300 | 0.0075 in |

**Oscilloscope**

- Place BNC T connectors on BNC board (Channel 1 and 0).
- Connect BNC cable from T connector to oscilloscope input.
- Connect BNC cable from T connector to "SCOPE" output on signal conditioner.

<u>RUNNING PROGRAM</u> (vbration.vi)

1) Follow power amplifier power up process (Appendix A).
2) Press run button.
3) Enter desired values (see above table), click "Click to Start" button.
4) When told to, connect vibration machine to function generator.
5) Select "Click When Settled" button when values appear to be correct.
6) After starting amplitude has been reached, select "OK" in pop-up menu to start experiment.
7) After experiment completes, a pop-up window will appear to enter filename to save data to. Disconnect vibration machine at this time and enter filename.

<u>SHUT DOWN PROCEDURE</u>

- Power down vibration machine in reverse order than setup.
- Close all Windows programs and turn-off laptop.
- Turn off signal conditioners and function generator.
- Pack up all equipment.

## APPENDIX C

# APPENDIX C

## PHOTOS OF CONTROL SYSTEM EQUIPMENT

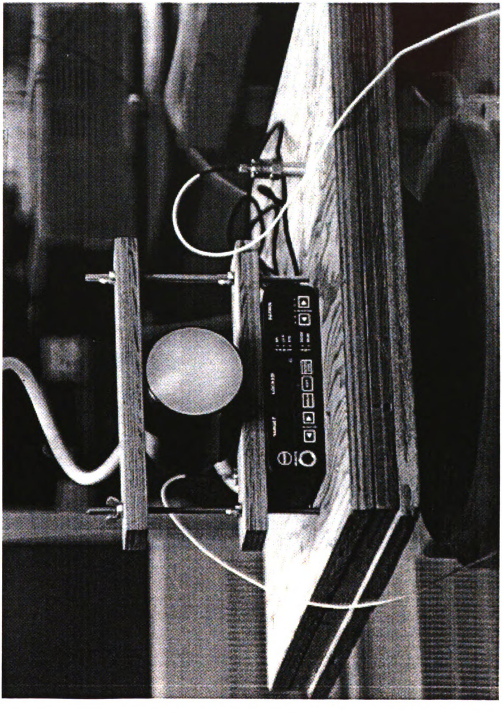

**Figure C.1: Vibration platform (mounted radar device and accelerometers).**

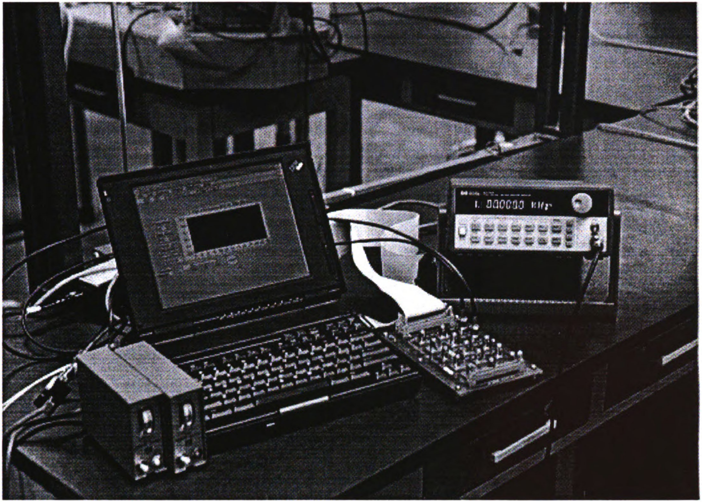

**Figure C.2: Control system equipment (signal conditioners, laptop, BNC board, function generator).**

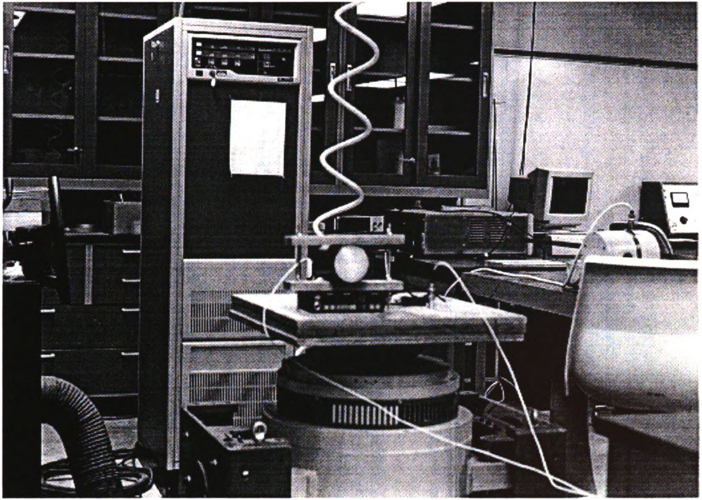

Figure C.3: Ling Dynamic Systems vibrator and modular power amplifier.

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