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STUDY OF BUILDING VIBRATIONS CAUSED BY MACHINERY

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CAUSED BY MACHINERY

by

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BACHELOR'S DEGREE IN CIVIL ENGINEERING
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THESIS

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DEDICATION

To my grandparents Hira Kaji Shrestha and Krishna Kumari Shrestha, and my parents Bisho Dev Shrestha and Sarita Shrestha. Thank you for all the sacrifices you have made for me and your belief in me.

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ABSTRACT

This thesis studies the vibration of structures caused by machinery. Machines exhibit unique vibrational characteristics. This thesis focuses on detection of these unique vibrational characteristics through the study of structural vibration caused by machines. The study extends from simple laboratory structures to a real existing building called the Ford Utility Building. The vibrational readings on the roof of the Ford Utility Building are studied to capture signals that can be attributed to machines running inside the building. This thesis supports the research in remote detection and identification of concealed machinery through SAR vibrometry.

A study of human perception of vibration is included. Human beings have very efficient sensory organs that detect external stimuli. Also, humans have very good ability to recognize patterns. As a mechanical sensor, human senses can detect vibration and may also be able to quantitatively estimate vibration. Several experiments have been conducted to explore the level of perception of vibration through the human senses.

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1 Introduction

1.1 Motivation

Vibration is the oscillation of a structure about an equilibrium point. Machines operate with unique characteristics and cause vibration in structures. In this thesis, we seek to capture these vibration signals from structures to determine the characteristics of the vibrating machines. With appropriate sensors, we acquire vibrational signals near an operating machine and by exploiting the appropriate tools of vibration analysis, information about the machine is extracted.

Our current research focuses on remote detection and recognition of vibrating machines concealed within buildings or other structures by capturing their unique signatures. With an appropriate pattern recognition and characterization database, information about the machines concealed can be deduced. This capability will allow concerned authorities to monitor suspicious nuclear activity. Nuclear proliferation is a threat to humanity. To monitor and prevent malicious activities, this remote detection ability will be helpful. Advanced radar technologies have been able to image and characterize vibration of ground objects by capturing reflected signals from an airplane. The question is: “Will it be possible to recognize signals from the machines running inside a building?” For the radar to capture signals, the building envelope must transmit the vibrational characteristics of the machines. Also, the transmitted signals should be at a magnitude detectable by the radar system.

Synthetic-aperture radar (SAR) has been used for the remote detection of mechanical vibrations. A real building located at the University of New Mexico called the

Ford Utility Building, which is the power generating plant of the university, was selected as the target building to study the remote detection of concealed machinery. A flight test over the Ford Utility Building was conducted to capture the vibrations on the roof of the building. Fig. 1.1(a) shows the satellite image of the roof of Ford Utility Building whereas Fig. 1.1 (b) is the SAR image of the roof.

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Figure 1.1: a) Google image of the roof of Ford Utility Building. b) SAR image of the roof of the Ford Utility Building

Vibrations of each pixel in the scene are estimated by studying the Doppler shift in the returned signals. Using the SAR based vibration estimation technique in conjunction with the SAR image, the aim is to develop a pattern recognition system to identify activities in nuclear facilities.

1.2 Scope of Thesis

Research in the past by Ghimire (2017) and Mareddy (2006) had shown that building envelopes do carry the signals of machinery. Experiments were conducted with laboratory structures to study their response to vibration due to machinery. Ghimire (2017) used a laboratory structure called the “doghouse” to study the vibrational response of structures. The design of the doghouse is fully documented in Ghimire (2017). The doghouse is a simple structure made of steel plates, shown in Fig. 1.2. It was used to represent a building envelope. It has been further used in this thesis.

Figure 1.2: Doghouse

The study was extended to the Ford Utility Building. Vibration readings were taken on the roof of the building at different locations using accelerometers. Through vibration analysis of these signals on the roof of the building a correlation between a frequency of vibration seen in the signal and a machine running inside the building during the data collection was established.

This thesis furthers the research in the detection of structural vibrations caused by machinery in the Ford Utility Building. We continue to study the vibrations on the roof of the building using accelerometers with the goal of detecting and identifying unique characteristics of the machines running underneath it. These observations serve as baseline data for comparison with the remotely sensed signals. The data collected in the past by Ghimire (2017) on the roof of Ford Utility Building were very noisy. They contained a wide range of frequencies that could not be attributed to a particular machine running inside it. Although some conclusions were drawn considering a few selected frequencies seen in the magnitude spectrum, the information contained in data was not fully understood.

The Ford Utility Building houses numerous machines including turbines, generators, and coolers running at various frequencies. It has been difficult to differentiate noise from the signals. Therefore we conducted several experiments in a more controlled laboratory setting using simple structures. We simplified the doghouse and conducted further experiments on it. Even simpler experiments were conducted using a cantilever beam. A yardstick, shown in Fig. 1.3 was used as to represent the cantilever beam, which acted as a single degree of freedom structure.

We also broaden the scope of our research to include a study of human perception of vibration. We observed that many machines on the roof of the Ford Utility Building vibrated at high frequencies but with very small displacement amplitude. There was also noise caused by the machines. To the naked eye, the vibrations were not visible yet they were easily felt through the fingers. One could detect vibrations by listening to the sound as well. This was a motivation for us to study the perception of vibration with the human senses. Human beings have senses of touch, sight, and hearing which allow us to identify a vibrating object. In fact, these senses might work as well as a mechanical sensor like an accelerometer in the qualitative assessment of vibration. We were curious to understand the human perception of vibrational signals. We performed several laboratory experiments to explore this question.

Figure 1.3: Yardstick

1.3 Outline of Thesis

This section describes the content of this thesis. The chapters included in this thesis are outlined with a brief introduction. This thesis includes 9 chapters.

Chapter 1 is a general introduction to the research and it presents the reader with the motivation and scope of this thesis.

Chapter 2 provides a literature review. The research work done in the past including work done by former University of New Mexico graduate students relevant to this research is included in this section.

Chapter 3 introduces the reader to the data acquisition system used in this research. The data collection process and the equipment used are explained. In addition, signal processing tools used in the data analysis are explained.

Chapter 4 describes the vibration study of the Ford Utility Building. Observations of the roof of the building are presented.

A simple prototype is studied in Chapter 5, which discusses the vibrational study of a vibrating cantilever beam. Free and forced vibrations of the cantilever beam are studied.

Chapter 6 discusses a vibrational study with the doghouse. DC gear motors were used as the source of the vibration and the response of the doghouse to these motors was studied.

Chapter 7 continues the vibrational study conducted with the doghouse using a speaker as the source of vibration.

Chapter 8 introduces the reader to the human perception of vibration. Experiments conducted to measure the threshold of perception of structural vibration by human fingers are presented.

Chapter 9 provides a summary of this thesis and draws conclusions. It highlights some of the limitations of this research and provides several suggestions for future research.

2 Literature Review

2.1 Introduction

This chapter presents a summary of some of the research relevant to this thesis conducted in the field of structural vibrations. Structures subjected to dynamic loads such as wind, earthquake, vehicles, and machinery vibrate in response to these loads. The vibrational response carries information about the structure and the forcing objects. Therefore, vibrational analysis has been the key technique for damage detection and structural health monitoring (Craig and Kurdila 2006). In addition, the well-being of the occupants of the structure is directly affected by some types of vibrations.

There has been a substantial amount of research in the area of machine vibrations, especially vibrations of rotating machinery (Chen and Mechefske 2001). From a purely mechanical point of view, the operation and condition monitoring of machines is a matter of interest, whereas civil engineers are more concerned with the effects of the machines on the well-being of the occupants. Some literature in vibration analysis of rotating machinery that is applicable to this research is presented here. It is possible to estimate the vibration of objects using radar vibrometry to remotely detect and identify concealed machinery (Pérez et al. 2016). This thesis supports this broader research project.

2.2 Vibration due to Machinery and Structural Health Monitoring

The ability to detect damage or a fault at an early stage is of great value. In fields like civil and mechanical engineering, this information about damage and defects helps to prevent a catastrophic collapse of the structure. Vibration signals are also good indicators for diagnostic testing of machines. Condition monitoring of machines can be carried out by studying the vibrations of the machines. A considerable amount of research has focused on machine signature analysis using spectral analysis (Chen and Mechefske 2001). Especially in the monitoring of rotating machinery, vibration-based analysis has been widely used.

It is, however, important to acknowledge that the effectiveness of damage detection and elimination depends upon the availability of good data from models of the structure or data from the undamaged structure which serves as the baseline data (Doebling et.al 1996). The choice of sensors, the data acquisition system and the signal processing and analysis tools used in the collection and interpretation of data is very important.

Collection of vibration data using sensors and employing various signal processing tools to extract information about the structure is a very common practice in the field of structural health monitoring. Mascareñas et al. (2014) state that “In many cases, expert judgment is superior to automated classification.” Some of the research suggests novel approaches to combine the human sensory system with the network of physical sensors placed in structures to enable a robust damage detection technique. Mascareñas studied the effectiveness of a vibro-haptic sensation to classify different damage conditions in a structure. Real vibration data from a laboratory structure measured using an accelerometer was converted to vibrotactile stimulus and fed to human subjects for them to classify damage levels in the structure.

It is common to observe vibrations of some sort in almost all buildings. It is not just in factories or laboratories but also in our homes and at times even in libraries that we feel structural vibrations, although the magnitudes and frequencies vary. These vibrations are usually generated from machines inside the building. For instance, most houses have heating and cooling systems, or a generator or a pump. These machines run at specific frequencies and produce specific levels of vibration as well as sound. Unless isolated from the building structure, these vibrations transmit through the structure and thus can be felt even at a distance from the running machine. However, mechanical sources within the structures are not the only cause of vibrations. Structures are also affected by the vibrations due to heavy vehicles operating nearby, such as trains and heavy construction equipment. Another main source of vibration in a tall structure is wind. The comfort of occupants and their daily activities can seriously be affected by vibration induced by wind in tall buildings (Kwok, Hitchcock, and Burton 2009). Burton et al. (2006) studied human response to wind-induced vibration in the range of 0.1Hz to 1.2Hz among 500 participants through laboratory experiments using a dual axis simulator.

2.3 Detection and Identification of Concealed Machinery with Vibration Analysis

Wang et al. (2011) and Perez et al. (2016) studied the feasibility of using synthetic aperture radar (SAR) image to remotely capture the vibration signatures of concealed machinery. Using SAR, signals reflected back from a ground object remotely from an aircraft are processed. They exploited the Doppler shift in the returned radar signals to estimate the vibration of the target object. They were able to recover an estimate of instantaneous acceleration and frequency spectrum though discrete fractional Fourier transform (DFrFT) and distinguish several vibrating structures.

Ghimire (2017) furthered this research in the identification of concealed machinery through vibrometry in his thesis. He studied the vibrations on the roof of a real building to detect machines running inside the building. He was able to conclude that the operating status of a machine inside a building can be determined by studying the vibrations on the roof of the building. Further, he studied the nonlinear behavior of a laboratory structure to show that the frequency response of a structure, in reality, differs from results from a linear finite element analysis. It was shown that by considering the nonlinear behavior of structure, a result closer to the experimental observation was possible through finite element analysis.

2.4 Perception of Vibration

The properties of the vibrating source have a lot to do with the effects they produce. A vibration signal can be defined by its characteristics such as amplitude, frequency, and duration. Clearly, the influence of the vibration signal depends upon these characteristics. Sound is another important aspect associated with vibration. Griffin (1990) performed experiments to study the effect of simultaneous sound and mechanical vibration on discomfort caused by passing trains. However, a particular method to determine the combined effect of sound and vibration has not been devised (Schiavi, Rossi, and Ruatta 2016).

The annoyance to inhabitants caused by the vibrations to the inhabitants depends not only on the vibrating source but also on the observer as well. Schiavi, Rossi, and Ruatta (2016) state that “It is not possible to define accurately the boundary of comfort without performing a subjective analysis”. “Comfort” and “discomfort” are broad terms that encompass physiological, psychological and behavioral aspects. Building design codes restrict vibration to standard limits, nevertheless, inhabitants may feel discomfort in buildings well within these limits. The interaction of sound and vibration is a complex phenomenon and thus quantifying a combined effect is a challenge. Griffin (1990) performed a statistical study to come up with a subjective equality condition of noise and vibration.

There are international and national standards such as ISO 2631 that incorporate vibration perception in buildings detailing the methods to evaluate whole-body vibration (Griffin 2012). A significant amount of research has been conducted over the years to quantify human perception of wind-induced vibration and determine the tolerance and acceptability threshold levels to develop universally accepted serviceability criteria for a design standard.

3 Data Acquisition and Signal Processing

3.1 Introduction

Structures are subjected to static as well as to dynamic loads. A dynamic load is characterized by its change in magnitude, direction, or location of application with respect to time (Craig and Kurdila 2006). In other words, the load is a function of time. Seismic loads and wind loads are classic examples of dynamic load on buildings. As with static loads, the structure responds to dynamic loads. The response, however, is dynamic. Dynamic analysis studies the response of structures to dynamic loading to ensure the sustainability and performance of the structures to such dynamic loads. Dynamic analysis comes into play during the design process and also during health monitoring of structures to determine their adequacy.

Modern data acquisition is the process of collecting vibration signals from structures under dynamic excitation and converting these signals into digital data. The signal is usually in the form of acceleration, velocity or displacement. Fig 3.1 shows the components of a typical data acquisition system. The data acquisition process starts with physically capturing analog signals from the vibrating system. These analog signals are then converted into digital signals that are recognized by computers. The data acquisition system consists of software and hardware components that perform the task of digitizing analog signals.

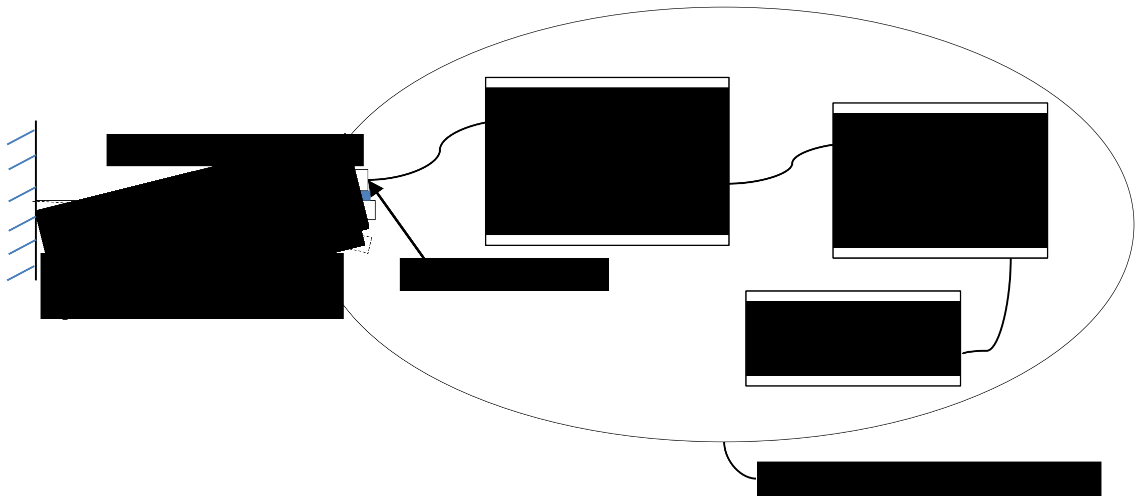

Figure 3.1: Schematic of data acquisition process

3.2 Components of Data Acquisition System

The main components of the data acquisition system used for this research are briefly described below.

3.2.1 Sensor

A sensor is a device that detects and responds to a physical stimulus. It is a transducer that produces an output signal in the form of an electrical voltage that is proportional to the sensed physical motion. There are many sensors that measure different physical quantities. For instance, a vibrometer or linear variable differential transformer (LVDT) measures displacement, and a velocity pickup measures the velocity of motion. In this research, we use an accelerometer as our sensor. An accelerometer is a transducer that produces electrical signals proportional to the input acceleration. Accelerometers are the most commonly used transducers to measure vibration response (Craig and Kurdila 2006).

There are different types of accelerometers available that have different working mechanisms. Piezoelectric accelerometers have an arrangement where a small mass is mounted on a piezoelectric crystal. The crystal acts as a stiff spring and also generates an electric charge when deformed. Therefore, when the body of the accelerometer is subjected to vibration, an inertial force is transmitted by the mass that compresses and stretches the piezoelectric crystal which consequently generates an electric charge proportional to the acceleration induced on the sensor. We used two Model 353B52 Piezoelectric ICP accelerometers: SN 102082 and SN 211610 for the data recording. The sensitivity values of the accelerometers are 488 mV/g and 498 mV/g respectively.

3.2.2 DAQ Hardware

The data acquisition (DAQ) used in this research was National Instruments Data Acquisition System (NI DAQ), Model 9178. The NI DAQ is an interface between the sensor and a computer. The NI DAQ converts the analog signals from the sensor in the form of electric voltage to digital data that can be stored and analyzed using computers. The NI DAQ used in the research has 8 modules. The sensor was connected to the NI DAQ through a coaxial cable. The NI DAQ was connected to a computer through the universal serial bus (USB) port. The NI DAQ was operated and controlled by a software called LabVIEW.

3.2.3 LabVIEW

LabVIEW is a program from National Instruments with a graphical programming interface. Like any other programming language, LabVIEW can be used to create programs to serve different purposes. In our case, we used LabVIEW, Version 14.0.1 to create a program to configure the NI DAQ, collect the signals, and present the data graphically in real time and store the data in a computer. The output was in the form of an ASCII file that could be read and further analyzed using MATLAB.

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Figure 3.2: Components of Data Acquisition system: a) Accelerometers b) NI DAQ c) Computer with LabVIEW

3.3 Signal Processing

Data acquisition is one of the most important tasks in vibration analysis. A challenging task is to analyze and interpret the data. The raw data gathered from the sensors contains noise blended with the desired signal. Much care is required to extract useful information from the noisy raw data. This requires a thorough knowledge of signal processing and vibration analysis.

In this research, the signal processing is done using a MATLAB. It is a programming environment that has a library of built-in functions and allows users to run algorithms to solve numerical problems. The raw data obtained from the data acquisition system consists of discrete instantaneous acceleration sampled at equal time intervals. The amplitude of acceleration is proportional to voltage. To get the acceleration in terms of desired units- m/s^2, the voltage data must be multiplied by a scale factor that depends on the sensitivity of the particular accelerometer.

$$Scale\ Factor = \frac{9.81\left(\frac{\frac{m}{s^2}}{g}\right) * 1000\left(\frac{mV}{V}\right)}{Sensitivity\ \left(\frac{mV}{g}\right)} \tag{3.1}$$

Accelerometer, SN 102082 henceforth called accelerometer 1, has a sensitivity of 488 mV/g. Thus its scale factor is,

$Scale\ Factor\ 1 = 20.104\left(\frac{m/s^2}{V}\right).$

Accelerometer SN 211610, henceforth called accelerometer 2, has a sensitivity of 498 mV/g. Thus its scale factor is,

$Scale\ Factor\ 2 = 19.723\ \left(\frac{m/s^2}{V}\right).$

To collect the vibration signals, the accelerometer was firmly attached to the structure using double sided tape as an adhesive.

3.3.1 Spectrum Analysis

In addition to analysis of the signals in the time domain, frequency domain analysis or spectrum analysis provides valuable information. Spectrum analysis describes the frequency content of a signal. A signal in the time domain can be represented as a sum of sinusoids through Fourier analysis (Haykin, 2003). With this mathematical tool, we can determine the frequency content of any signal.

The Fourier transformation of the signal in time domain was performed in MATLAB. For a continuous signal *f (t),* the Fourier transform is given by

$$F(j\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t} dt. \tag{3.2}$$

For discrete signals of finite duration with N samples, Discrete Fourier transform is given by

$$F[k] = \sum_{n=0}^{N-1} f[n] e^{-j\frac{2\pi}{N}nk}, \tag{3.3}$$

where *f* [n] is the sampled data. The reconstruction of the time domain signal is possible through inverse discrete Fourier transform is given by,

$$f[n] = \frac{1}{N} \sum_{k=0}^{N-1} F[k] e^{j\frac{2\pi}{N}nk}, \tag{3.4}$$

MATLAB uses the Fast Fourier Transform (FFT) algorithm, which is an efficient method to calculate the frequency spectrum.

3.4 Displacement Reconstruction from Acceleration Data

The desired data from a vibrating structure are its displacement, velocity or acceleration histories. With this information and knowledge about the forces acting, conclusions can be drawn about the dynamic properties and behavior of the structure. There are many sensors available in the market to measure these motion quantities among which an accelerometer is the most common sensor (Goldman 1999). Acceleration data is usually measured where the displacement and velocity cannot be measured directly. An accelerometer doesn't require a fixed reference structure as with a direct displacement measuring sensor. Displacement measuring sensors like the LVDT (linearly varying displacement transducer) are difficult to install in easily inaccessible places like under bridge decks, and even if installed their accuracy and reliability is questionable (Park et al. 2005). However, by using an accelerometer together with mathematical signal processing tools, the acceleration signals can be converted to velocity and displacement data.

There are two common methods to get the displacement history from the acceleration history. One method works in the time domain in which the double integration of the acceleration signal with respect to time gives the displacement time history. The second method works in the frequency domain where the mathematical properties of the Fourier transformation are used to get the displacement from the acceleration data. Each of these methods is presented in the following subsections.

3.4.1 Time Domain Method

For sinusoidal motion, acceleration can be written as

$$a = Asin(2\pi f t), \tag{3.5}$$

where 'A' is the amplitude and 'f' is the cyclic frequency of the wave. We know that the acceleration gives the rate of change of velocity while velocity vector gives the rate of change of displacements. Mathematically,

$$a = \frac{dv}{dt} \quad and \quad v = \frac{ds}{dt} \ . \tag{3.6}$$

where 'v' is the velocity and's' is the displacement.

Thus,

$$v = \int adt + \ v_0 = \int Asin(2\pi ft)dt + v_0 = -\frac{Acos(2\pi ft)}{2\pi f} + v_0 \ , \qquad (3.7)$$

where 'v_o' is the initial velocity.

Similarly,

$$s = \int vdt + \ s_0 = -\frac{Asin(2\pi ft)}{(2\pi f)^2} + v_o t + s_0 \ , \qquad (3.8)$$

where 's_o' is the initial displacement. Since we are dealing with discrete data sampled at short time intervals, numerical integration techniques can be applied to obtain velocity and displacement.

Thus, if an acceleration time history is available, velocity and displacement can be reconstructed (Goldman, 1999). It is very important that the initial conditions of velocity and displacement be considered. Otherwise, the reconstructed signal will contain large errors (Park et al. 2005). The time history plot obtained will not depict the actual displacement of the system. Also if the acceleration amplitude is constant, the displacement reduces by one quarter with each doubling of frequency. So, the lower frequency components usually will produce a greater contribution to the estimated displacement data. A high pass filter may need to be applied to the acceleration signal before the integration to get rid of spurious low-frequency components.

Another source of error is the presence of a spurious constant component in the acceleration data. Integration of the constant offset would give rise to a ramp function, which would yield an implausible displacement time history. This error may maybe eliminated by removing the constant component in every integration step (Han 2010).

3.4.2 Frequency Domain Method

The Fourier transform of a discrete series of acceleration is given by,

$$a[k] = \frac{1}{N} \sum_{n=0}^{N-1} a[n] e^{-j\frac{2\pi}{N}nk} \qquad k = 0,1, \ldots, (N-1) \, . \qquad (3.9)$$

Using the property of Fourier transform of integrals, we can get the Fourier transform of velocity v[k] and displacement s[k] as follows,

$$v[k] = \frac{1}{j2\pi k} a[k] \qquad k = 0,1, \ldots, (N-1), \qquad (3.10)$$

$$s[k] = \frac{1}{(j2\pi k)^2} a[k] = -\frac{1}{(2\pi k)^2} a[k] \qquad k = 0,1, \ldots, (N-1). \qquad (3.11)$$

The time history of displacement s[n] can be retrieved by performing inverse Fourier Transform as follows,

$$s[n] = \sum_{k=0}^{N-1} s[k] e^{j\frac{2\pi}{N}nk} \qquad n = 0,1, \ldots, (N-1). \qquad (3.12)$$

The frequency content of the acceleration signals can be converted to displacement easily, however, the exact reconstruction of the time history of displacement entails some error and complications (Han, 2010). The scale factor $1/ (2\pi k)^2$ introduces error as the spurious low-frequency noise gets emphasized over the actual signal high-frequency components. An effective solution to this problem is zero padding the noise frequency component or applying a high pass filter to the data (Han, 2010). We remove the spurious low frequency components by providing a cutoff frequency during the displacement reconstruction. With only the desired frequencies, the displacement estimation gets close to actual value. However, this process may lose phase information of the original signal. This method was used throughout the research.

3.5 Summary

In this chapter, we described the various components of the data acquisition system and the data collection process used in this research. The scale factors for each accelerometer were calculated. Some of the basic principles of signal processing were described in brief in this chapter. Some of the methods to convert instantaneous acceleration data into displacement were described.

4 Vibration Study of the Ford Utility Building

4.1 Introduction

The Ford Utility Building is one of the powerhouses at the University of New Mexico. It is of particular interest in this research because it is believed to be rich in vibration signals generated from various machines running inside it. The Ford Utility Building houses machines such as turbines, generators, and air compressors. It is an example of an industrial plant. Similar machines might be present in a nuclear power plant as well. The goal of this project is to design a capability for remote detection and identification of concealed machinery through radar vibrometry, with a conceivable application being monitoring nuclear proliferation. The Ford Utility Building serves as an accessible facility to run experiments with rich vibrational features.

The primary objective of our vibration study at the Ford Utility Building is to observe the vibrations of the roof of the building. We collected vibration readings from various locations on the roof on different dates to determine the vibration of the roof caused by machinery running below. We tried to ascertain how the vibrations caused by the machines running inside the building are transmitted through the building envelope on to the roof. We tried to identify characteristic features of the signals and aimed to correlate the operating frequencies of the machines running in the building with the frequencies of vibration obtained on the roof. We also wanted to determine if the vibrations of the roof were in a range detectable by the radar. The data collected using accelerometers on the roof serve as "ground truth" data for remote sensing observations.

4.2 Description of Ford Utility Building

The Ford Utility Building provides most of the electrical power, hot and cooling water for the University. It has two natural gas-fired turbine generators, each with 7 MW production capacity, a steam turbine generator, two steam boilers, and two electrically driven centrifugal chillers among other machines. Fig. 4.1 shows the equipment layout inside the Ford Utility Building.

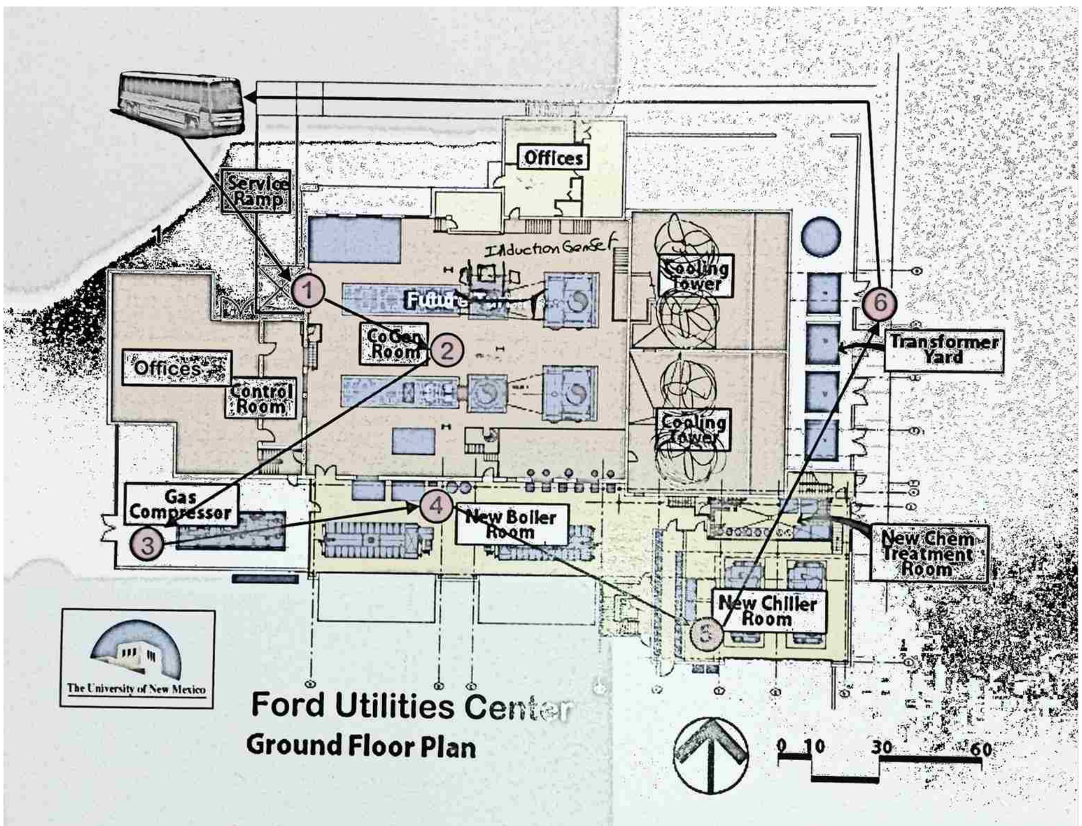

Figure 4.1: Equipment layout in the Ford Utility Building

One of each gas turbine, generator, and heat recovery steam generation (HRSG) unit work as a single unit and are collectively called a "cogeneration plant". There are two such cogeneration plants named Cogen 1 and Cogen 2. On the roof of the building, we can see the turbine combustion intakes, exhaust vents, gas compressors and turbine exhaust stacks. One or both of the cogeneration plants are operated as required by the energy demand of the University.

4.3 Data Collection

The vibration readings were collected on the Ford Utility Building roof on a regular basis. Fig. 4.2 shows the aerial view of the building with the locations where the data were collected. A number of locations though to be observable by remote SAR reflections were selected for data acquisition.

Figure 4.2: Aerial view of the roof of Ford Utility Building with data recording locations (Image Source: Google maps)

The components of Cogen1 and Cogen2 are enclosed in two separate boxes in Fig. 4.2. The components are almost identical for the two cogeneration plants. The naming of the locations of data collection was done in such a way that it identified the cogeneration plant it belonged to. For example, “Cogen2_Loc4” means location 4 of cogeneration plant 2.

Our research team was interested to see if there were vibrations with frequencies lower than 30Hz and with an amplitude greater than one-tenth of a millimeter. This data was required to make sure that there was significant vibration on the roof so that the SAR sensor would detect the vibration from an airplane. The data collected at the roof would act as the baseline data for the comparison with results obtained from the remote detection system.

Table 4.1: Locations for data collection on the roof of the Ford Utility Building

Name of the Location	Description
Loc1	Center of the roof
Cogen1_Loc2, Cogen2_Loc2	Cold air intake
Cogen1_Loc3, Cogen2_Loc3	The floor in front of the evaporative cooler
Cogen1_Loc4, Cogen2_Loc4	Steam releasing exhaust vent
Cogen1_Loc5, Cogen2_Loc5	Exhaust that releases hot air from the bay area

The vibration readings were collected using the data acquisition system described in the previous chapter. Table 4.1 describes the locations selected for vibration monitoring on the roof. The locations selected were not only the on the roof the building itself but also the components associated with various machines projecting from the roof. Fig. 4.3(b) shows Cogen2_Loc2 which is an air inflow for cogeneration plant 2. The operational status of the machines running on the day of the recording was also documented.

[redacted] [redacted]

Figure 4.3: a) Loc1 b) Cogen2_Loc2

4.4 Observations

The following figures show the acceleration time history and magnitude spectra of the data recorded at some of the locations on the roof. All of the signals were noisy. The frequency spectra were crowded with multiple frequency peaks. Fig. 4.4 shows the plots for the readings at Loc1, at the center of the roof. The maximum acceleration recorded was 0.9 m/s^2. The time history plot shows a random time history. Frequency components seen in the magnitude spectrum were approximately 30Hz, 60Hz and 416Hz among many others.

Similarly, Fig. 4.5 shows the plot for Cogen1_Loc5. This was an exhaust vent for the bay area of Cogen1. As seen in the time history plot, the acceleration waveform is not a clear sinusoidal signal. A peak at a low frequency of 8.38 Hz was seen besides the higher frequency components like 127.5 Hz, 269.6 Hz etc. The maximum acceleration observed in the time history was 8.1 m/s^2.

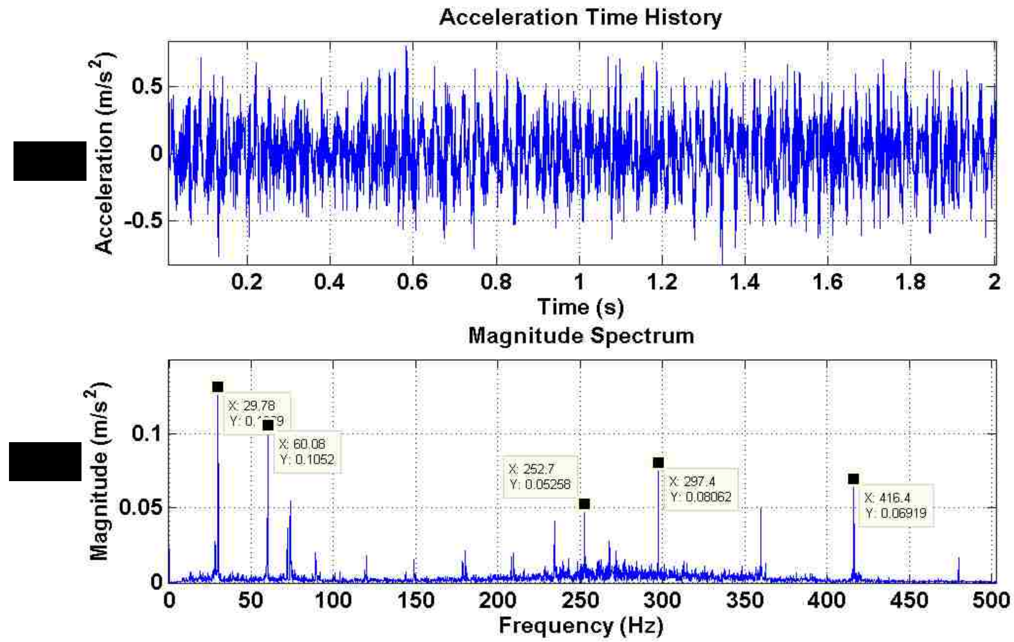

Figure 4.4: a) Time history of acceleration of Loc1 b) Acceleration frequency spectrum

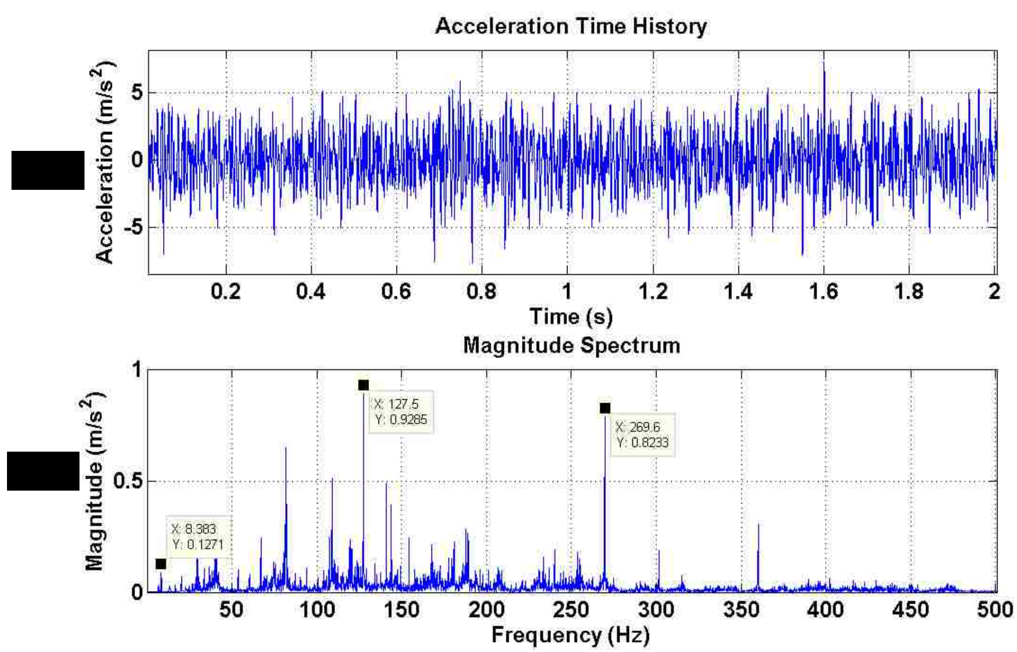

Figure 4.5: a) Time history of acceleration of Cogen1_Loc5 b) Acceleration frequency spectrum

The recording on Cogen2_Loc2 was similar but comparatively smoother as seen in Fig. 4.6(b). A distinct peak was seen at around 60Hz with a magnitude of 2.27 m/s^2.

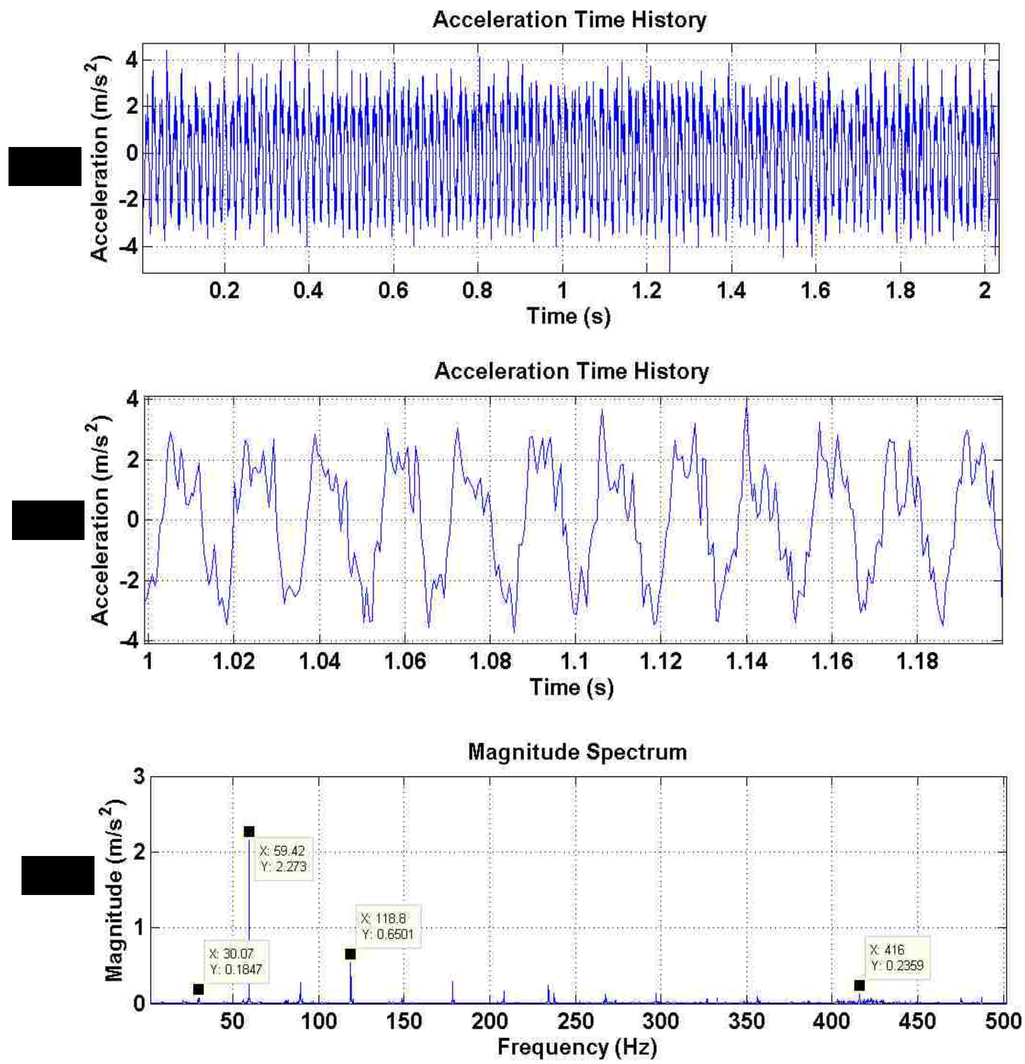

Figure 4.6: a) Time history of acceleration Cogen2_Loc2 b) Magnified Time history of acceleration. c) Acceleration frequency spectrum

The displacement time histories were constructed using the frequency domain method described in Chapter 3. The magnitude of vibration observed in terms of displacement was in the order of less than a tenth of a millimeter. At Loc1, where we saw vibration of 0.5m/s^2, Fig. 4.7 shows the plot for displacement with an amplitude of around 0.008mm. Similarly, Figs. 4.8 and 4.9 show the constructed displacement time histories for Cogen1_Loc5 and Cogen2_Loc2, respectively.

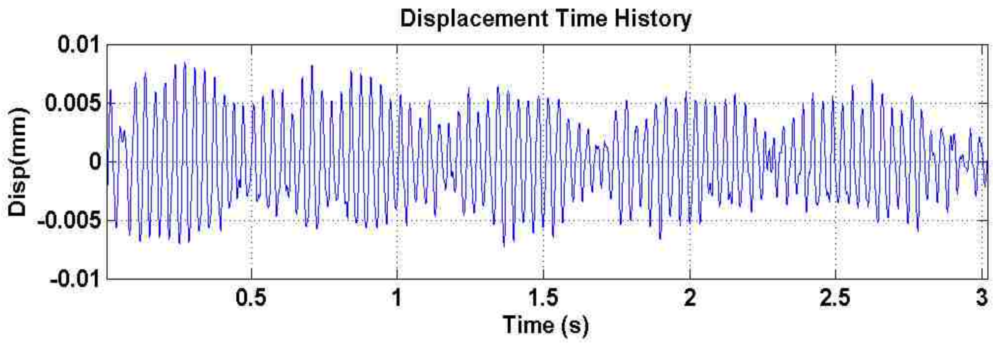

Figure 4.7: Displacement time history of Loc1

As seen in the plots, the maximum displacement observed is close to 0.1mm for Cogen1_Loc5 which was vibrating at 8.38Hz. The displacement of Cogen2_Loc2 was much smaller with a maximum amplitude of 0.03mm. The peak frequency seen in the acceleration time history was 60Hz.

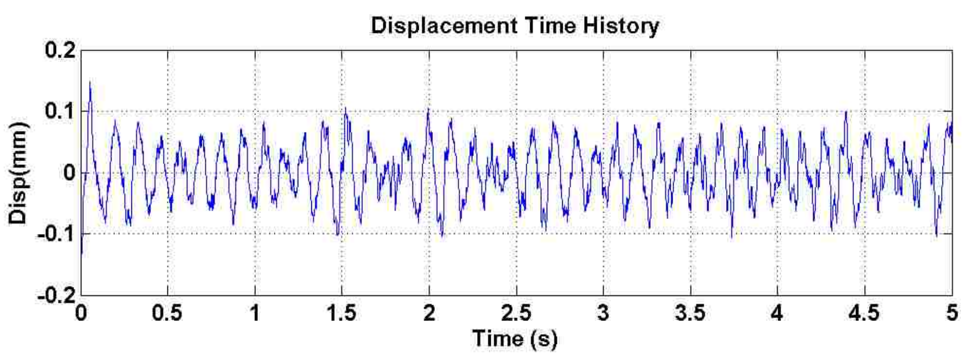

Figure 4.8: Displacement time history of Cogen1_Loc5

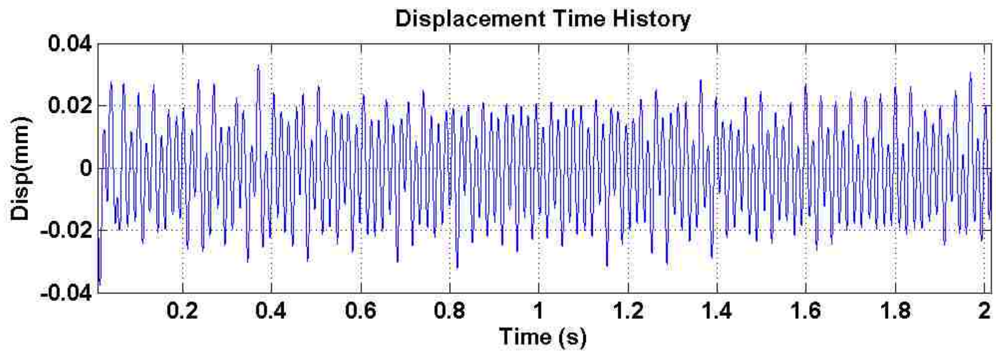

Figure 4.9: Displacement time history of Cogen2_Loc2

4.5 Discussion

Since the Ford Utility Building has machines running at different frequencies at the same time, one would expect the building envelope to respond to all of these vibrating machines. The frequency spectra of the different locations on the roof of the building showed multiple peaks. This is vividly seen in the plot for Loc1 in Fig. 4.4, which is at the center of the roof directly over the space between cogeneration plant 1 and 2. The plot for Cogen2_Loc2, Fig. 4.6, is comparatively less distorted. This is an air inflow for Cogen2 running on the roof. One would expect that the frequency spectrum to show a sharp peak at a particular operating frequency and few other contributing frequencies. It showed a higher peak at 60Hz however, other peaks seen quite significant as well.

The operating frequency of the gas turbine is known to be 15158 rpm (252.63 Hz). The generators run at 3600 rpm (60 Hz) and there were several other ventilating fans running at around 1,750 rpm (29Hz). These frequencies showed up in the frequency spectra especially in the reading of the roof itself, although the acceleration magnitude was very small. It was clear that the signals from the machines running inside the building did transmit through the building envelope. The presence of peaks at these frequencies was observed. However, the frequency spectrum was widespread with frequency components even at high frequencies such as 416 Hz, 475Hz and higher.

The vibration of the roof in terms of displacement was very small. The roof showed vibration amplitude of around only 0.008mm. Cogen1_Loc5 was the structure on the roof that showed the maximum displacement, which was close to 0.1mm. This was the structure that showed vibration at around 8 Hz. Others structures on the roof had the vibration displacement amplitudes of less than a tenth of a millimeter.

4.6 Summary

The roof of Ford Utility Building was very rich in vibrational signatures. Readings at all locations showed a wide frequency content with multiple peaks. We do not know explicitly what these peaks were representing. Were they real signals from the machines running inside, or just noise captured by the sensors or were they some shortcoming of the signal processing tools that we were using? There were frequency signatures close to the operating frequencies of some of the machines running inside the building. However, the differentiation between noise and signal could not be made with certainty. Therefore, further study on the data, data acquisition system and the signal processing tools is required to fully interpret the results. More importantly, experiments in a more controlled environment are necessary to understand the response of structures to vibrating machinery. A clear idea of what kind of readings one can expect from a complex system like the Ford Utility Building is necessary. Thus, the following chapters explore experiments with simpler structures in a laboratory setting.

5 Study of a Vibrating Yardstick

5.1 Introduction

The signals recorded on the roof of The Ford Utility Building showed frequency spectra containing peaks at multiple frequencies. It was difficult to interpret and attribute the frequencies seen to particular machines running inside the building because of the sheer number of machines running at different speeds. It is unclear if the peak frequencies seen actually represent the frequencies of vibration of various machines running inside the building or if they were only byproducts of the mathematical transformations in the post-processing of the signals. As earlier stated, the frequency spectra were generated by performing Discrete Fourier Transforms of the acceleration recordings. It is suspected that the noisy frequency spectrum consisted of duplicated frequency especially because peaks are observed at very high frequencies such as 500 Hz. To build confidence in the observation and data processing, few simple experiments were conducted using a yardstick as a single degree of freedom (SDOF) system.

In linear structural dynamics, the equation of motion for a single degree of freedom system is

$$m\ddot{u} + c\dot{u} + ku = f(t) \ , \qquad (5.1)$$

where 'm' is the mass of the system, 'c' is damping coefficient, 'k' is the stiffness, 'u' is the displacement response and '$f(t)$' is the external force acting on the system. For free vibration, $f(t) = 0$ (Craig and Kurdila 2006).

Equation (5.1) can be written as

$$\ddot{u} + 2\zeta\omega_n\dot{u} + \omega_n^2 u = \frac{\omega_n^2 p(t)}{k} \,, \tag{5.2}$$

where the circular natural frequency ω_n is given by

$$\omega_n^2 = \frac{k}{m} \,, \tag{5.3}$$

The damping ratio ζ is defined as

$$\zeta = \frac{c}{c_{cr}} \,. \tag{5.4}$$

The solution to the second order differential Equation (5.2) for free vibration i.e. *f (t)*=0 is

$$u(t) = e^{-\zeta\omega_n t}(A_1 cos\omega_d t + A_2 sin\omega_d t) \tag{5.5}$$

where ω_d is the damped circular natural frequency, given by

$$\omega_d = \omega_n\sqrt{1-\zeta^2} \tag{5.6}$$

The solution given by Equation (5.5) is an exponentially decaying function of time.

5.2 Experimental Setup

We conducted experiments with a simple cantilever beam that represented a single degree of freedom (SDOF) structure. A wooden yardstick (36”X1.5” X0.25”) was used as the cantilever beam. Experiments were conducted in two different settings. The first experiment setup was in a quiet room where four different trials were conducted. One end of the yardstick was fixed to a table using a clamp, with part of its length free to vibrate. The experiment was performed in a quiet office room to prevent unwanted vibrational noise from corrupting the signal so that the pure vibration of only the structure could be recorded.

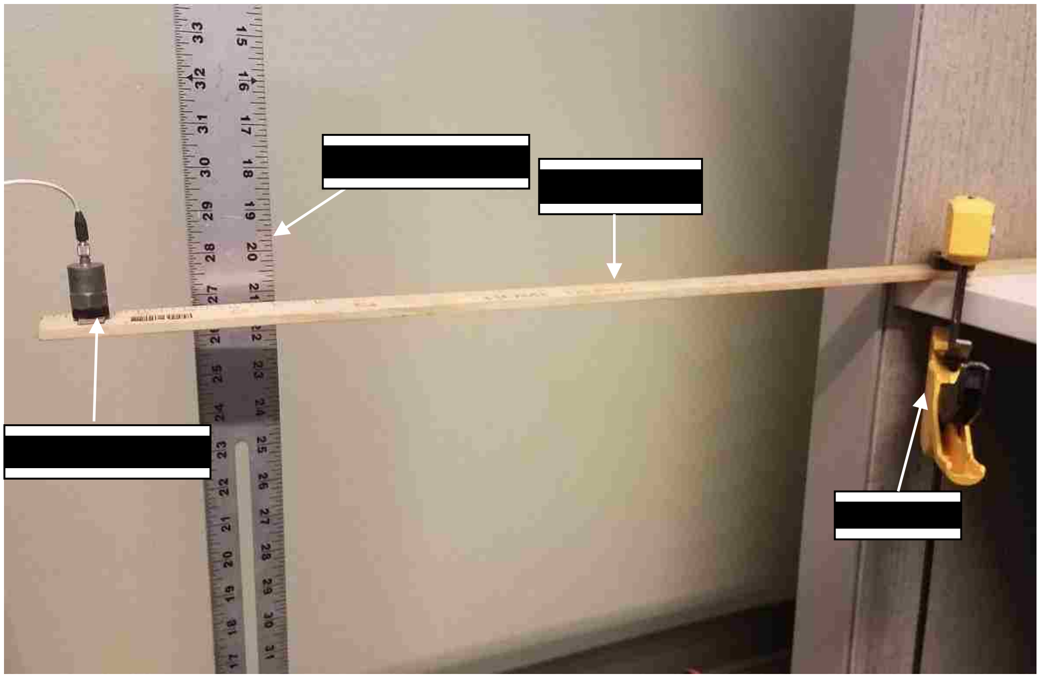

Figure 5.1: Experimental Setup I

The experimental setup is shown in Fig. 5.1. An accelerometer was glued to the free end of the yardstick to measure the vertical acceleration. The clamp was firmly tightened to provide a fixed support at one end of the yardstick. A vertical measuring scale was placed near the vibrating yardstick to measure the amplitude of vibration. To initiate the vibration in the yardstick, its free end was released from an initial displacement. Initial displacements of 1”, 0.5” and 1/8” were used in Trials 1 to 3 respectively. The length of yardstick free to vibrate as a cantilever beam in each trial is listed in Table 5.1. In Trial 4, the yardstick was manually forced to vibrate. The yardstick was moved up and down about 1” from its horizontal axis by hand.

In Experimental Setup II, the arrangement was carried to the roof of the Ford Utility Building. Experiment 2 was conducted with the yardstick clamped to Cogen2_Loc4, one of the exhaust vents of cogeneration plant 2. The experimental setup is shown in Fig. 5.2.

Figure 5.2: Experimental Setup II

The length of the yardstick free to vibrate was fixed at 22" as we had done in one of the previous experiments. Similar to Experiment 1, the yardstick was initially displaced and released to vibrate freely and the acceleration was recorded. Reading on the Cogen2_Loc4 at the location where the yardstick was clamped was also taken as baseline data.

5.3 Observation

The signals recorded in the experiments were processed using the MATLAB program as discussed before and plots for the acceleration time history and frequency spectrum were generated. For Experiments 1, Trials 1 to 3, in which the free vibration of the yardstick was studied, the acceleration time history showed a smooth decaying function of time as expected. The corresponding frequency spectrum showed a single sharp peak. Fig. 5.3 shows the time history and magnitude spectrum plots of acceleration observed in Trial 2 which was typical for these trials. The maximum acceleration recorded was 40.92 m/s^2. The frequency spectrum showed a single sharp peak at 8.67 Hz. There were no significant higher frequency components seen in the frequency spectrum. Table 5.1 lists the peak frequencies seen in the frequency spectrum for the three different trials which had different lengths of yardstick vibrating.

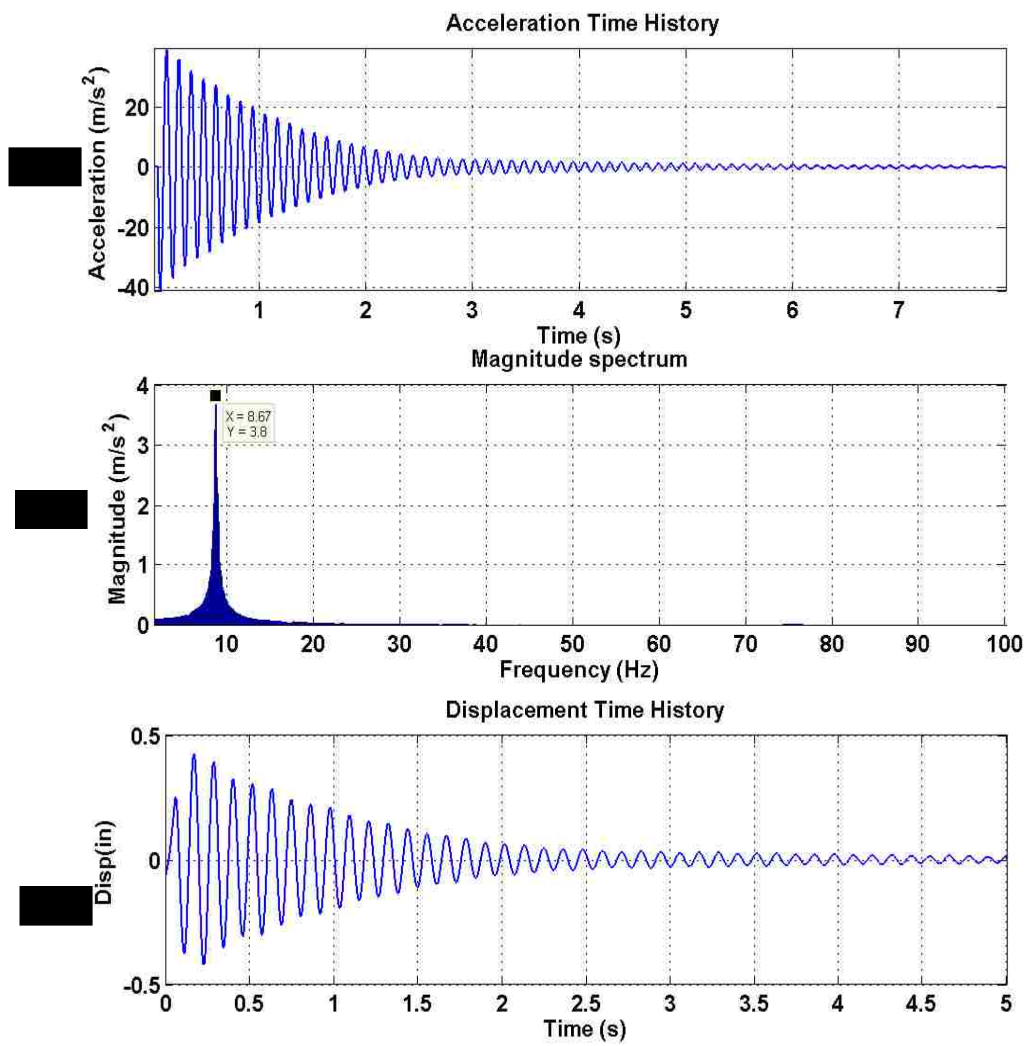

Figure 5.3: a) Time history of acceleration in Experiment 1-Trial 2 b) Acceleration frequency spectrum c) Time history of displacement

In Trial 4, the yardstick was put into forced motion. Fig. 5.4 shows the time history of acceleration for Trial 4. A fairly smooth waveform that was close to a sinusoid is seen. The maximum amplitude observed of vibration was 8.1 m/s^2 while the frequency spectrum showed a distinct peak at 2.66 Hz. The displacement time history of the yardstick for Trial 4 is shown in Fig.5.4 (c). Again, the waveform was smooth with the frequency of 2.66 Hz and an amplitude close to 1 inch.

Table 5.1: Fundamental frequency of vibration of the yardstick in Experiment 1

Trial Number	**Length of yardstick free to vibrate**	**Frequency of vibration**
1	11 in	26.2 Hz
2	22 in	8.67 Hz
3	30 in	5.07 Hz

Fig. 5.5 displays the acceleration recording at Cogen2_Loc4. Similar to the readings at other locations studied on the roof of Ford Utility Building discussed in the previous chapter, Cogen2_ Loc4 showed a noisy time history plot. The maximum acceleration recorded was 0.4 m/s^2. Amongst multiple peaks, 59.49 Hz was the highest in the frequency spectrum.

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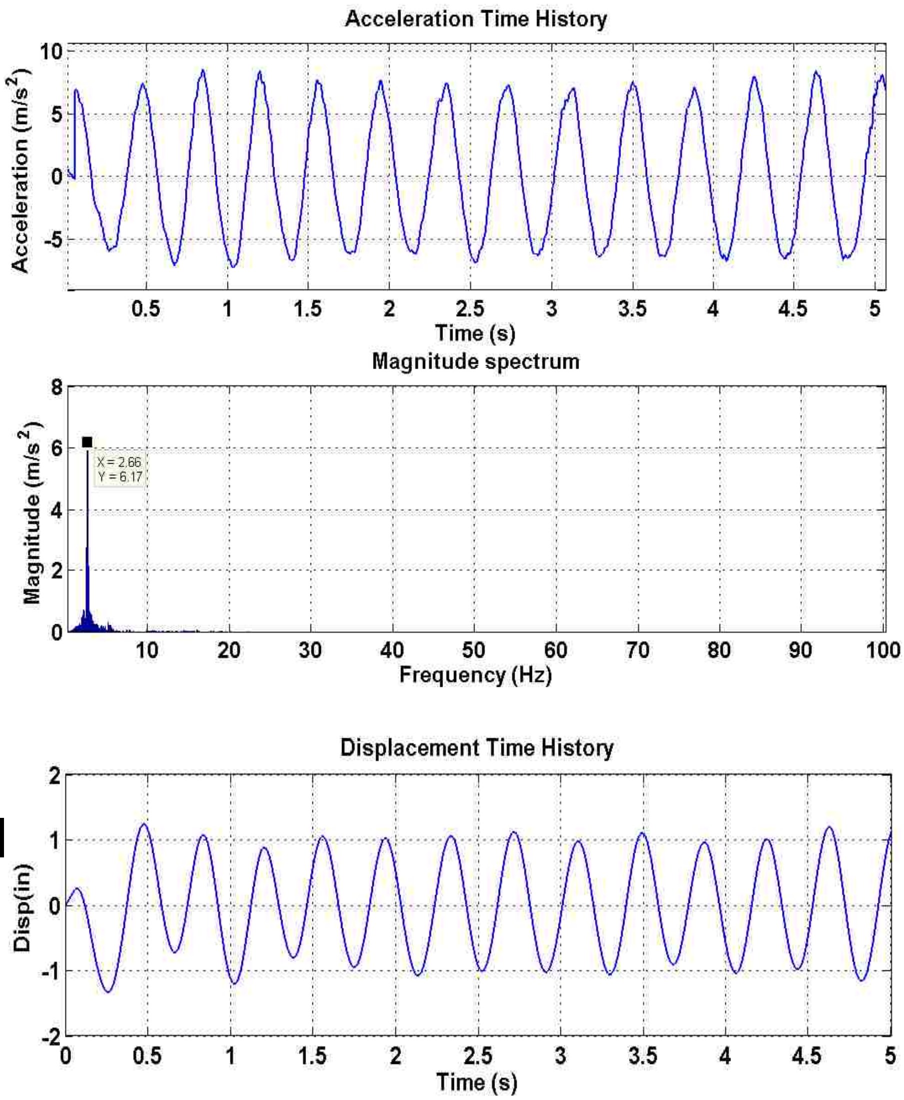

Figure 5.4: a) Time history of acceleration of the yardstick in Trial 4 b) Acceleration frequency spectrum c) Estimated time history of Displacement

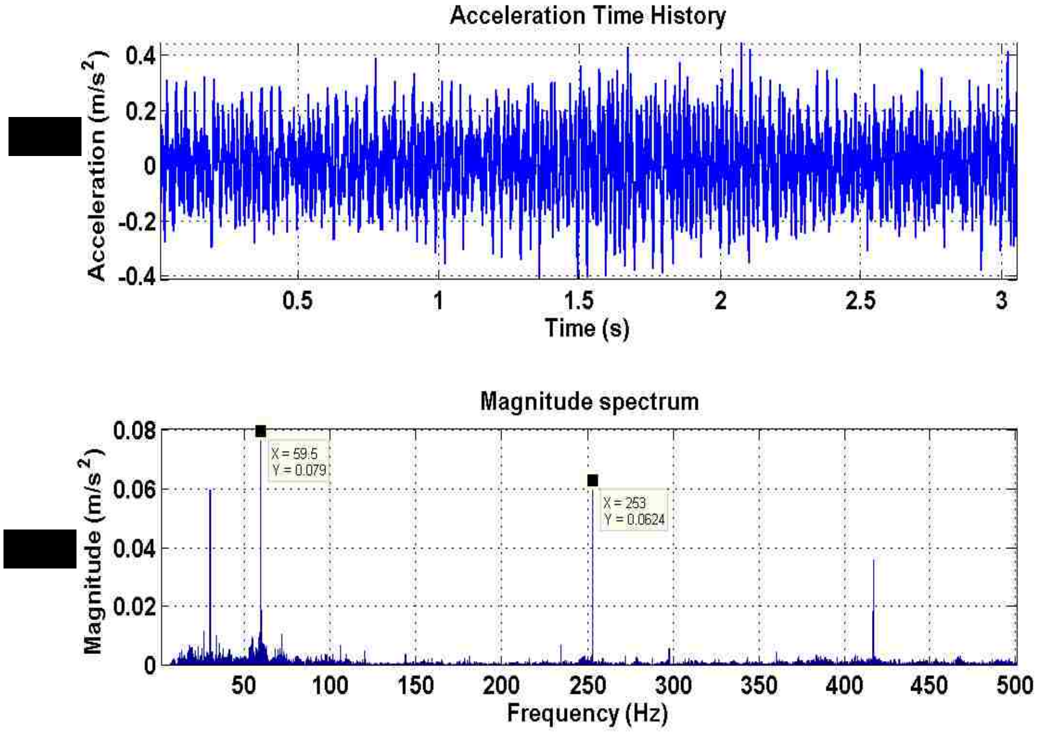

Figure 5.5: a) Time history of acceleration of Cogen2_Loc4 b) Acceleration frequency spectrum

Fig. 5.6 shows the time history acceleration recorded on the yardstick in Experiment 2 which was conducted on the roof of the Ford Utility Building. The waveform appeared to be a somewhat smooth decaying wave. The plot of the frequency spectrum showed a sharp peak at 8.03Hz without other significant frequency components. However, a closer look at the magnified plot of the frequency spectrum did reveal a few higher frequency components like 253 Hz, 416 Hz that were seen in Cogen2_Loc4.

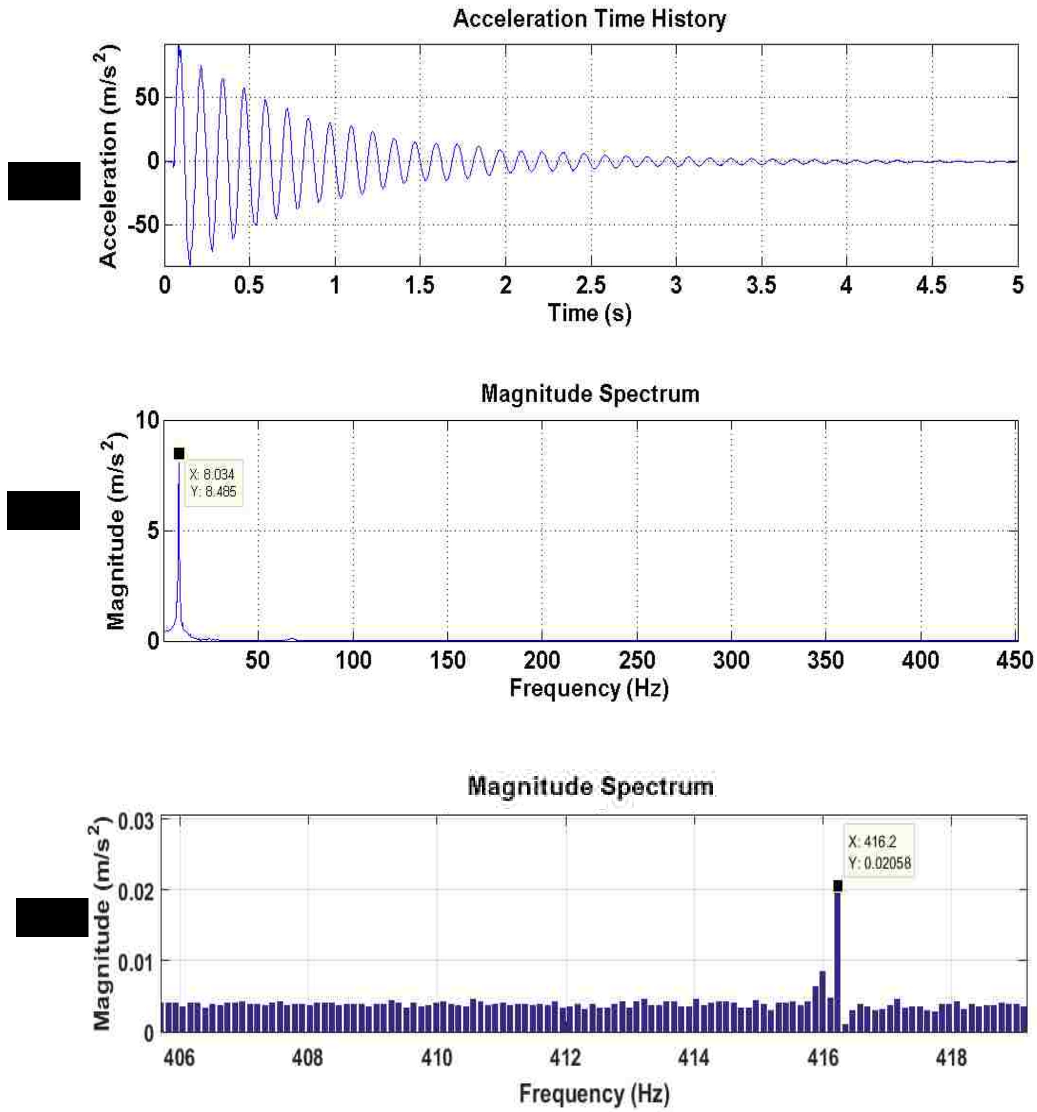

Figure 5.6: (a) Time history of acceleration of Experiment 2 (b) Acceleration frequency Spectrum (c) Magnified frequency spectrum

5.4 Discussion

The response of the yardstick was as expected for the vibration of a damped SDOF structure. With proper clamping for a fixed support, the yardstick acted as a cantilever beam. As we know from linear structural dynamics, the solution for a damped system under free vibration is an exponentially decaying curve given by Equation (5.5). In free vibration, the structure vibrates sinusoidally at its natural frequency and damps out exponentially. The sharp peaks seen on the frequency spectra at 26.2 Hz, 8.67 Hz, and 5.67 Hz for Trials 1 to 3 respectively in Experiment 1 indicate the natural frequency of vibration for the particular length of the yardstick. We would expect the natural frequency of the yardstick to increase with the decrease in the length of the yardstick as this causes the mass to decrease and the stiffness to increase. The experimental results confirmed this.

Analysis of the displacement plots generated from the acceleration data showed reasonable output. For Trail 1-3 in Experiment 1 in which the free vibrations of the yardstick were studied, the constructed displacement plot showed a decaying function of time similar to the actual oscillation of the structure. In Trial 4 however, the time history of displacement plot resembled a sinusoidal curve which again, corresponded to the actual motion. The amplitude of vibration in terms of displacement seen on the curve was about 1 in. This was a close estimation of actual amplitude of about 1 inch provided during the excitation.

The readings of Cogen2_Loc4 on the roof of Ford Utility Center showed noisy vibration with multiple peaks in the frequency spectrum but the amplitude of acceleration was small compared to the acceleration at the free end of the yardstick. The signatures of Cogen2_Loc4 were almost invisible in the plots for Experiment 2 where the yardstick was attached to Cogen2_Loc4. Nonetheless, a magnified plot of the magnitude spectrum showed the presence of the frequency contents of Cogen2_Loc4 as seen in Fig. 5.6 (b). This underscores the fact that vibration data we acquire from a structure contains vibration signatures of the foundation it rests upon. Also, signals from vibrating sources in close proximity are collected by the sensors as well. When we are looking at the magnitude spectrum of a structure with a high amplitude of acceleration, the vibrations of the environment may seem to disappear in the plots because of their small amplitude. It seems as if it is almost a noise-free data. But if we are looking at a small amplitude of vibration, the high frequency, low amplitude (noise) becomes dominant. As is seen in the plot for Cogen2_Loc4 in Fig 5.6, the frequency spectrum has an overwhelming number of peaks. The magnitude of the acceleration of Cogen2_Loc4 is around 0.2 m/s^2 which is very small. So the signal is indistinguishable from the surrounding noise. Certainly, the data collected in Cogen2_Loc4 contains signals for the numerous machines running close by. The readings also depend on the location and orientation where the sensor is attached to the structure.

5.5 Summary

We conducted several benchmark experiments with a simple single degree of freedom (SDOF) structure to increase our understanding of the dynamic response of structures. Experiment 1 was conducted in a quiet office room to prevent unwanted noise from clouding the vibrational signals. Free and forced vibration of the cantilever beam were studied. Using accelerometers to acquire the vibration signals and applying the signal processing tools discussed in Chapter 3, we were able to extract meaningful results from the data. Smooth time history plots of acceleration and displacement were observed for free vibrations of the yardstick. The frequency spectrum was clean and showed a single peak at the fundamental frequency of vibration. In the forced vibration as well, the displacement data generated through processing of the data showed the expected results based upon to the experimental observations.

In the experiment conducted with the yardstick on the roof of the Ford Utility Building, the acceleration time history was smooth. The frequency spectrum showed a sharp peak at around 8 Hz, as shown in Fig 5.6, for free vibration. However, it also contained many of the higher frequency components seen in the recordings of Cogen2_Loc4.

These simple benchmark experiments helped us build confidence in our data acquisition system and the signal processing tools that we were using to analyze data from the Ford Utility Building. We wanted to further the study into the response of a structure to dynamic excitation caused by rotating machines. Thus we conducted experiments on the doghouse using DC motors which are described in the following chapter.

6 Vibration Study with the Doghouse

6.1 Introduction

The dynamic response of an approximately linear single degree of freedom (SDOF) system was studied in the previous chapter. We determined the natural frequencies of the first mode of vibration for different lengths of a cantilever beam under free vibration. Also, we were able to construct the displacement histories of the yardstick using the acceleration data. Results from these benchmark experiments conducted on the SDOF structure increased our confidence in the data acquisition system and the signal processing tools. Our bigger goal was to understand the response of structures due to enclosed machinery.

Although the results of the yardstick experiments and their interpretations were straightforward, the observations made on the roof of the Ford Utility Building were not fully understood. One of the reasons for this ambiguity was because the Ford Utility Building is in itself a huge complex structure. Its response couldn't be easily predicted. Additionally, the number of complicated machines running inside was overwhelming. We wanted to study the response of a much simpler structure to vibrating machinery.

The doghouse is a simple laboratory structure that represents a building envelope. Using a DC gear motor with an off-balance mass to excite the doghouse, the response of the structure to a simple rotating machine could be studied. The motivation for using the doghouse and the gear motors with known operating frequency is to have control over the experiment. This gives a structure much simpler than the Ford Utility Building plus the details of the motors used to vibrate the structure are known beforehand. This allows us to better interpret the results.

6.2 Description of Doghouse

The doghouse is a simple hollow cuboidal structure (48''x 30''x 30") with walls made of 20Ga galvanized steel. The edges of each plate are screwed to a wooden pine (1.5"X1.5") framework. The screws are spaced at 4". A sheet of 0.5" thick oriented strand board (OSB) is used as the base of the doghouse. More details are provided in (Ghimire 2017).

6.3 Vibrational Study Using DC Motor with Off-balance Rotating Mass

As it was stated earlier, we wanted to study structural vibration due to machinery in a more controlled environment with precise knowledge about the system. To accomplish this goal, we conducted several experiments with the doghouse using DC motors as a source of vibrations.

6.3.1 Equipment

- DC Motor: A DC gear motor with operating frequency of 5.05Hz (303rpm) at 12VDC. As seen in Fig. 6.2, the motor was bolted tightly to the center of the roof of the doghouse.
- Inverter: An inverter that converted AC to the desired 12VDC output.
- Microcontrollers: These were used to operate the motors and to control the speed of the motors.

Fig 6.1 shows this equipment. The data acquisition system was same as described in previous chapters.

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Figure 6.1: Equipment used in the experiment: a) DC motor b) Microcontroller c) Inverter

6.3.2 Experimental Procedure

Several experiments were conducted with the doghouse. In Experiment 1, the free vibration of the roof of the doghouse was studied. In order to initiate the vibration, an impulse was applied at the center of the roof of the doghouse with a hammer. An accelerometer was attached at the center of the roof of the doghouse using double-sided foam tape to record the response.

In Experiment 2, the vibrational response of the doghouse to a DC motor with rotating off-balance mass was studied. The setup is shown in Fig. 6.2. The motor was attached to the center of the roof and it was run at a maximum speed which induced vibration on the doghouse. Similar to previous experiments, the accelerometer was attached using double sided tape on the roof and long side wall of the doghouse to record the accelerations at both locations. On the roof, the Accelerometer 1 was placed 2” from the motor whereas Accelerometer 2 was placed at the center of the long side wall.

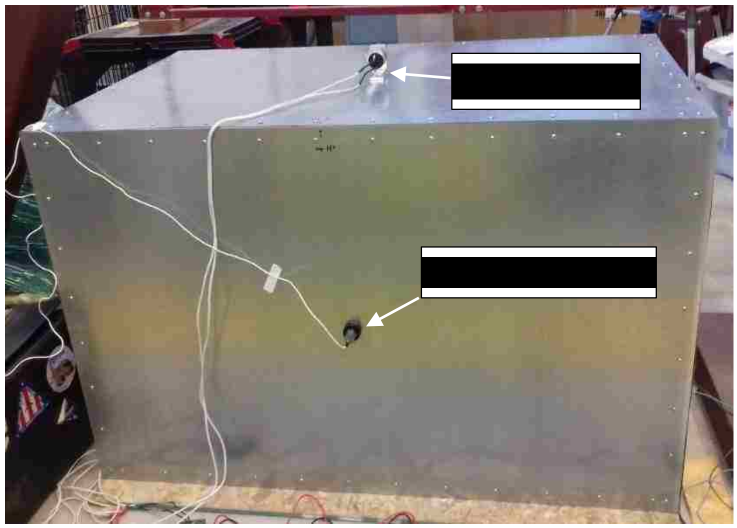

Figure 6.2: Setup for Experiment-2

6.3.3 Observations

In Experiment 1 where the roof of the doghouse was excited with an impulse, the time history plot of acceleration showed a decaying curve. The curve was noisy at the time of impact as shown in Fig. 6.3, however, it smoothened out as it decayed. The acceleration frequency spectrum showed a sharp peak is at 13.36 Hz along with various smaller peaks at a variety of frequencies.

Fig. 6.4 (a) shows the time history and frequency spectrum of the roof of the doghouse with the motor running. The frequency of operation of the motor with the off-balance weight was 5 Hz. The plots of the signals recorded for the experiment show noisy data.

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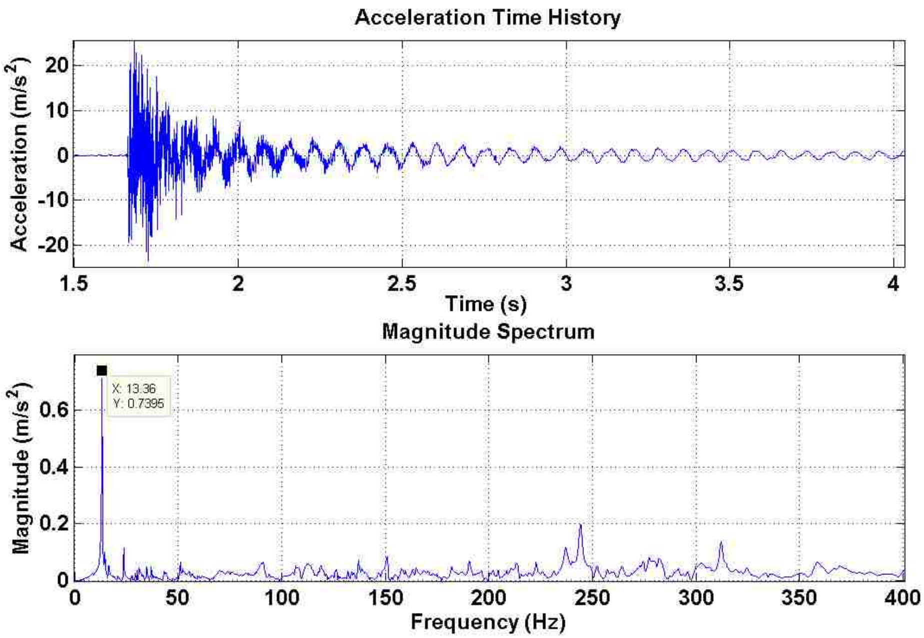

Figure 6.3: a) Time history of acceleration of the roof of the doghouse in Experiment 1 (free vibration) b) Acceleration frequency spectrum

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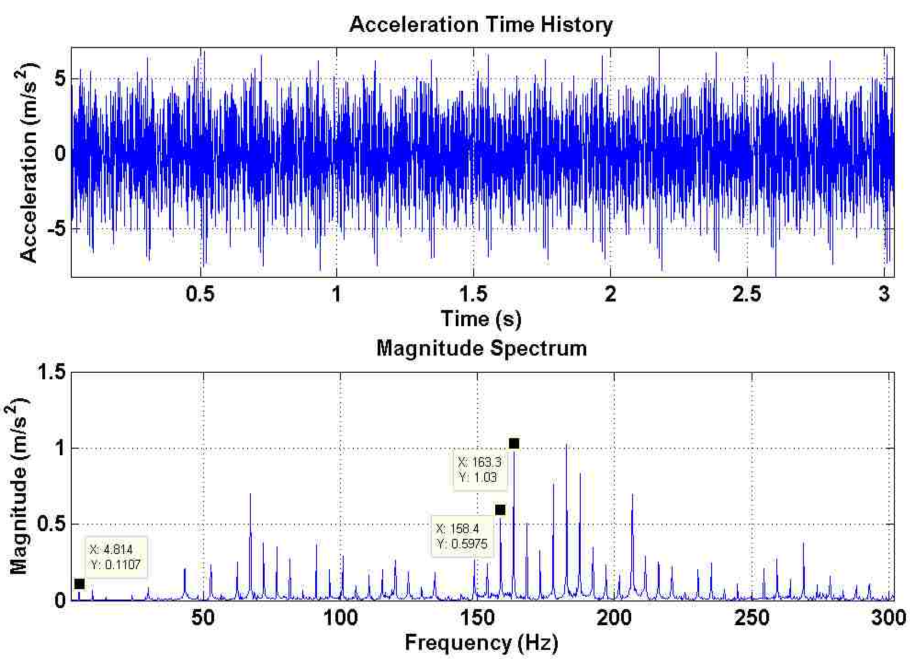

Figure 6.4: a) Time history of acceleration of the roof of the doghouse with the motor running b) Acceleration frequency spectrum

The time history plot didn't show a smooth sinusoidal curve at around 5 Hz. Instead, a highly random curve was observed. The frequency spectrum shows multiple peaks at frequencies much higher than the operating frequency of the machine. The displacement plot was apparently dominated by the fundamental frequency of 4.8 Hz. The amplitude of displacement was observed to be approximately 0.1mm as seen in Fig. 6.5.

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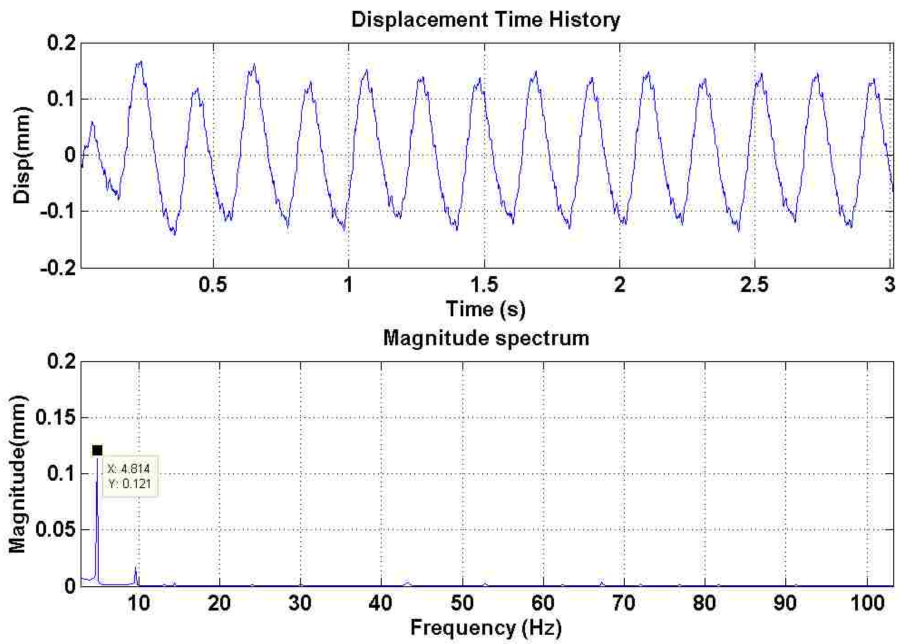

Figure 6.5: a) Time history of displacement of the roof of the doghouse with the motor running b) Displacement frequency spectrum

Fig. 6.6 shows the time history and the frequency spectrum of the data recorded on the long side wall of the doghouse when the motor attached to the top of the doghouse was running. The data was recorded with Accelerometer 2 simultaneously as the acceleration of the roof was recorded. A similar response was seen on the long side of the doghouse although the amplitude of acceleration was much smaller. Clearly, the harmonic frequency components were more prominent. As seen in Fig 6.6 the highest peak on the frequency spectrum is at 168.4 Hz. The maximum acceleration recorded was 1.89m/s^2. The magnitude of the lowest frequency content at 4.847 Hz was only $0.01 m/s^2$. The displacement magnitude was around 0.02mm.

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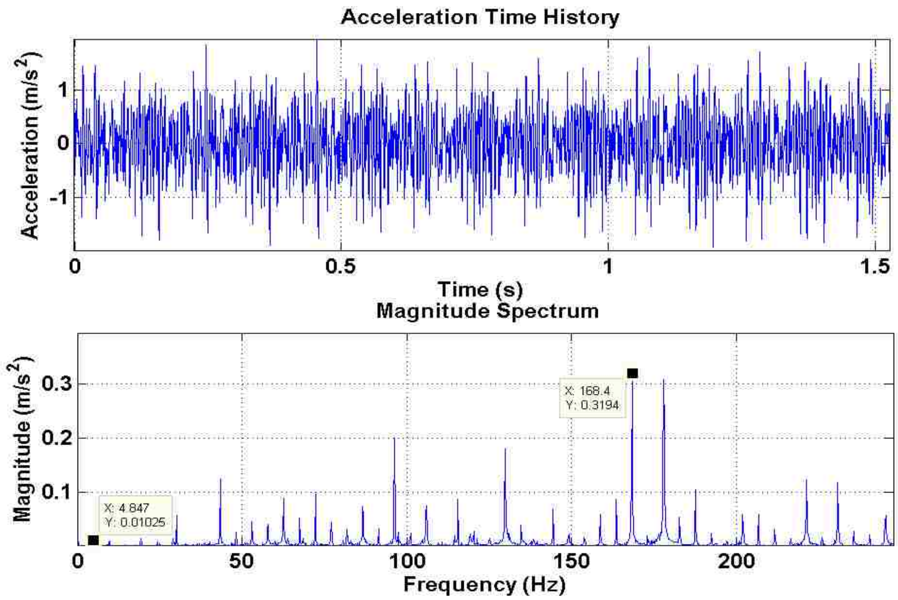

Figure 6.6: a) Time history of acceleration of the long side wall of the doghouse with the motor running b) Acceleration frequency spectrum

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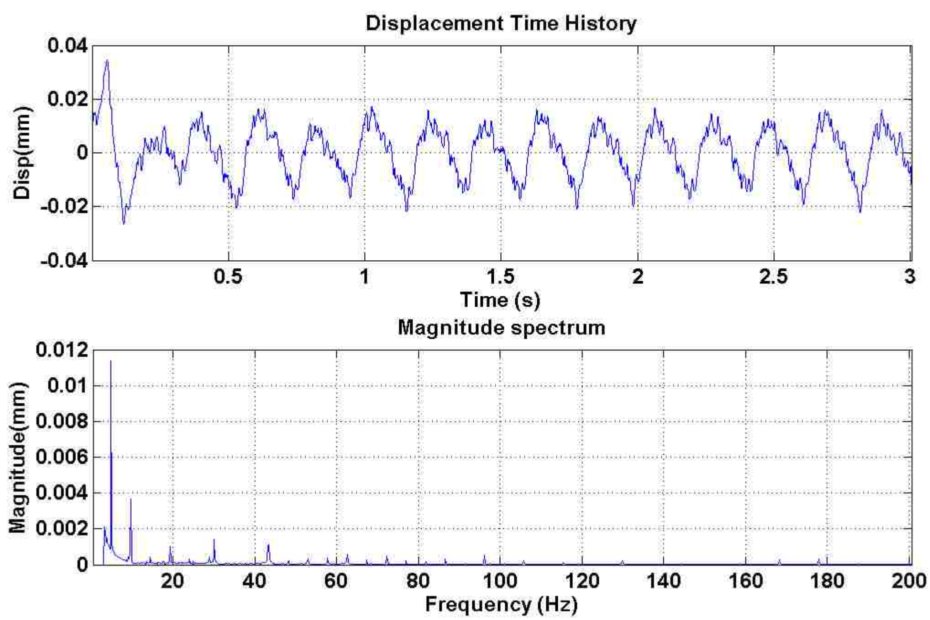

Figure 6.7: a) Time history of displacement of the long side wall of the doghouse with the motor running b) Displacement frequency spectrum

6.3.4 Discussion

In Experiment 1, the results seem reasonable in the sense that a damped structure, in free vibration, vibrates at its natural frequency and this vibration eventually dies out. One clear peak is seen in Fig. 6.3 at 13.36 Hz which indicates the fundamental frequency of vibration of the roof. It is, however, important to recognize that a structure has infinite modes of vibration because theoretically, it has an infinite number of degrees of freedom. The lowest mode of vibration requires the least amount of energy per unit of displacement amplitude and is usually excited. Other modes with different frequencies of vibration may be excited as well.

The plots seen for the center of the long side wall of the doghouse looked very similar to that of the roof. Understandably, the amplitude of vibration was as much as four times larger on the roof because the rotating motor was attached to the roof. However, these plots, Fig 6.4 and Fig 6.6, revealed something interesting. In both of the acceleration frequency spectra, we saw the first peak at around 4.8 Hz, although that was not the peak with the highest amplitude. This was close to the operating frequency of the motor. Other peaks seen spread throughout the frequency spectrum were harmonics of that fundamental frequency and they possessed higher acceleration magnitudes.

Harmonics are defined as frequencies that are integer multiples of the fundamental frequency, which is also called the first harmonics. The US electrical system produces harmonics that are voltages with frequencies that are integer multiples of 60Hz. A combination of harmonics added together forms a distorted waveform. Another way to look at it is, a distorted waveform would contain harmonics of the fundamental frequency.

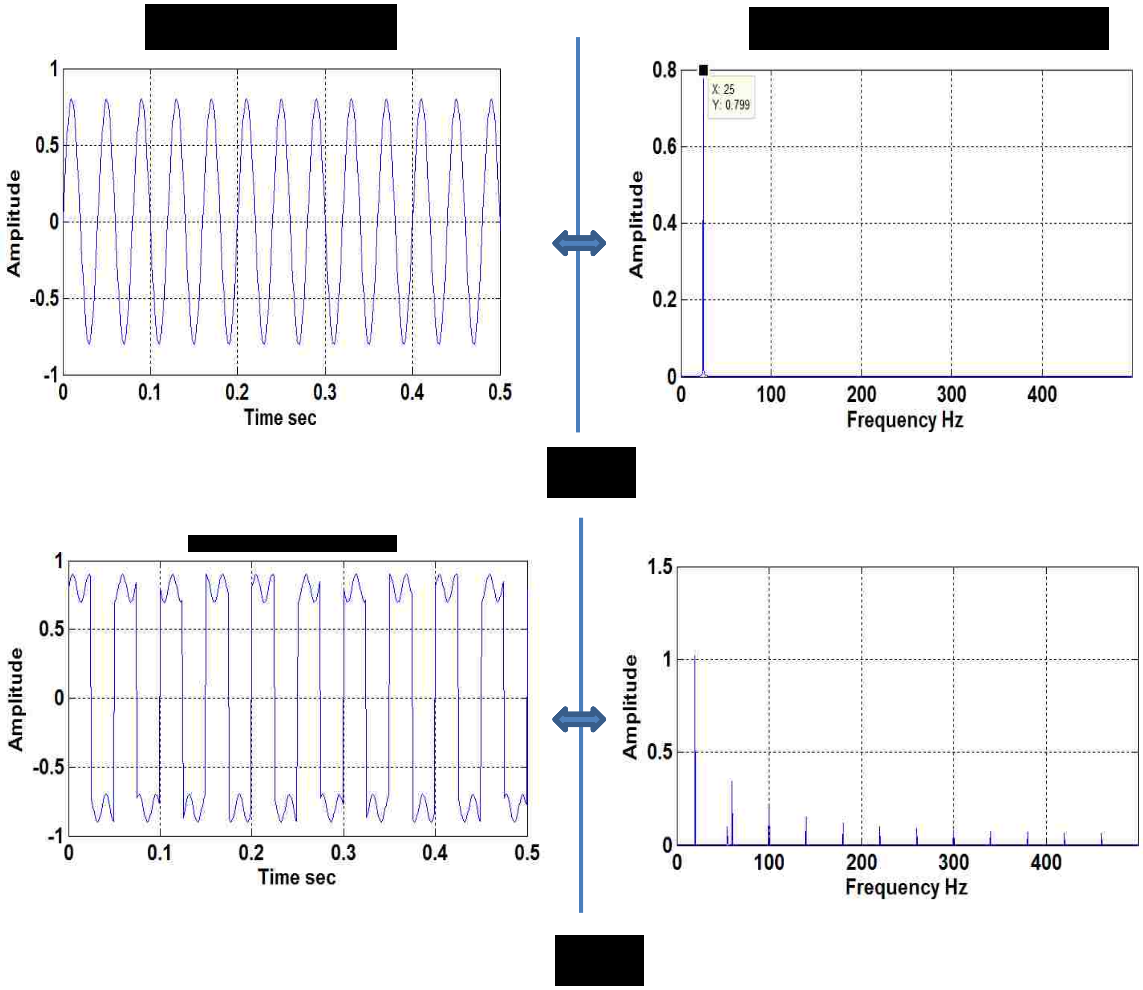

Figure 6.8: a) Sinusoidal wave in time and frequency domain b) Distorted wave in time and frequency domain

The Fourier transform of a pure sinusoid gives a single sharp peak at the frequency of the wave. However, when some distortion is present in the wave, the Fourier Transform yields a frequency spectrum with harmonics as seen in Fig. 6.8. As was explained in Chapter 4, the Fourier Transform expresses a wave as a combination of sine waves. In other words, the frequency components seen in the frequency spectrum contribute to the synthesis of the signal in the time domain. The frequency content of a square wave has thousands of harmonic frequencies because of its sharp edges. Usually, the amplitude of harmonics decreases with increase in frequency. Higher frequency components are usually seen in the frequency spectrum of a curve with an abrupt change in slope. Not all harmonics necessarily show up in the frequency spectrum. As in the case of a square wave, only odd harmonics contribute to the reconstruction of the wave.

We took another look at the readings that we had been collecting on the roof of the Ford Utility Building. Fig. 6.9 shows the frequency spectrum of Cogen2_Loc2, one of the locations on the roof of the building. A closer look at the frequency spectrum revealed something interesting. There was a peak at 30Hz and several other peaks at higher frequencies. The higher peaks were harmonics of this frequency.

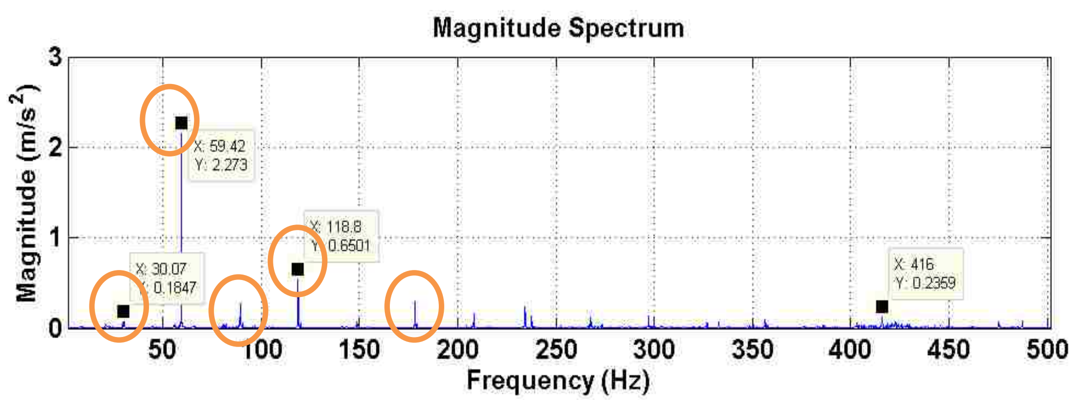

Figure 6.9: Acceleration frequency spectrum of Cogen2_Loc2

The frequency spectrum can be inconclusive especially when trying to identify a machinery by looking at the frequency of the machine. Were the higher frequencies seen in the readings on the roof of Ford Utility Building associated with an actual machine running at those frequencies or were they only the harmonics of a lower fundamental frequency? In case of the doghouse, we knew that we had a motor was turning the off-balance mass at around 5Hz. One can make a good guess of the operating frequency of the motor by looking at the plot of the frequency spectrum as Fig 6.4(b). With the measured acceleration data, we have the ability to perform the spectrum analysis, however, to draw a definitive conclusion out of it requires knowledge of structural vibration.

6.4 Vibration of the Doghouse with DC Motor without Off-balance Rotating Mass

The gear motor itself is a complex system. The motor converts electromagnetic energy into rotational mechanical energy. The motor produces rotation in a shaft and the coupled gearbox alter the speed and torque of the motor. In our experiments, we were using a DC gear motor. At first glance, only the rotating mass is seen rotating at the stipulated frequency, 5 Hz. However, the motor rotor and the gears rotate at much higher speeds. We have observed in previous experiments that the frequency spectrum contained high frequency components. It is very likely that the vibration of the gearbox itself is present in the signal collected on the doghouse. Thus, experiments to study the vibration of the gearbox alone was conducted.

6.4.1 Experimental setup

Two experiments were performed with the motor. In the first experiment, the eccentric mass attached to the gear motor was removed as illustrated in Fig 6.10(a). In the second experiment, the gear system attached to the motor was also removed as seen in Fig 6.10(b). In each experiment, the motor was attached to the top of the doghouse using double-sided tape. The accelerometer was placed about 2” away from the rotating motor.

Figure 6.10: a) DC gear motor without the off-balance rotating mass b) DC motor without the off-balance rotating mass and gear system

6.4.2 Observation

The magnitude of acceleration recorded on the roof of the doghouse with the motor running without the off-balance mas was in the range of 0.5m/s^2 as shown in Fig. 6.11(a). The frequency spectrum shows some high frequency components in the recorded data as shown in Fig. 6.11(b). Although small in magnitude, frequency components like 147 Hz, 290 Hz are seen to dominate. A similar observation was made with the motor running without the off-balance mass as well as the gear system as shown in Fig 12. Some disturbance can be seen added by the gears. If a linear system is assumed for the doghouse, we can say that these signals from the gear motor without the rotating mass are transmitted and recorded reading with the gear motor.

6.4.3 Discussion

The accelerometer that we are using is very sensitive. It is capable of reading very small vibrations. Apparently, the motor and gearbox produced some intrinsic vibration at high frequency, although the acceleration magnitude was small. These signals would show up as noise in all the readings. This would be true for other machines as well. In the Ford Utility Building, we are looking at heavy machines such as generators and turbines. Although they have a specific operating frequency, they probably have complex gear systems that are rotating at various frequencies. They probably emanate different frequency signatures.

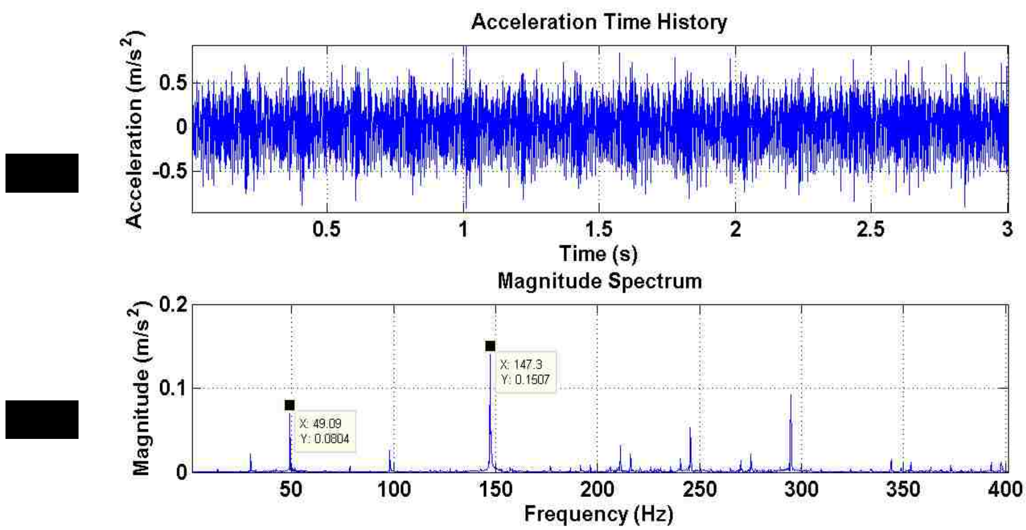

Figure 6.11: a) Time history of acceleration of the roof of the doghouse with the gear motor without off-balance mass b) Acceleration frequency spectrum

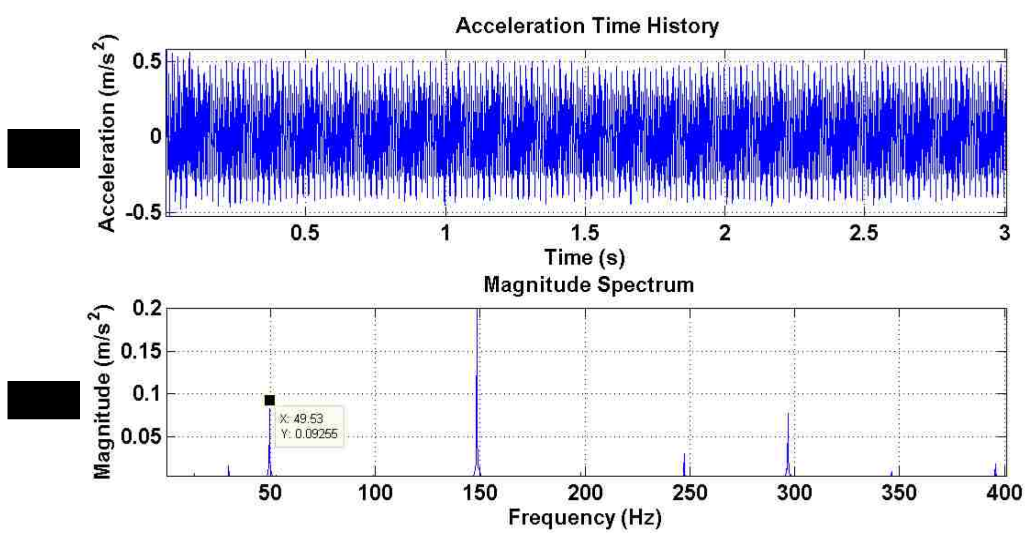

Figure 6.12: a) Time history of acceleration of the roof of the doghouse with the motor without off-balance mass and gear system b) Acceleration frequency spectrum

6.5 Summary

We studied the vibrational response of a laboratory structure to a rotating machine in this chapter. The doghouse was our building representative model and 5 Hz DC gear motor was used as machinery. We conducted several experiments on the doghouse. With the motor with an off-balance mass attached to the roof of the doghouse, vibrational signals on the doghouse were captured. It was observed that the acceleration time history plot was very noisy. The frequency spectrum of acceleration had harmonics of the fundamental driving frequency of the off-balance mass of around 5 Hz with much higher magnitude than the fundamental frequency itself. It was expected that the motor would cause a sinusoidal vibration corresponding to the rotation of the off-balance mass. Clearly, this was not the case. High distortion was seen in the waveform. The displacement caused by the gear motor was seen to be around 0.1mm. Additionally, we dug deeper into the mechanism of the DC gear motor and studied the effect of the gearbox and the motor itself. It was observed that the gear system inside the motors produced vibration at high frequencies around 300 Hz.

The results from the doghouse experiment helped us to better understand the vibrations due to machinery. It was clear that the acceleration frequency spectrum can be very complicated with the presence of harmonics of the fundamental frequency of the machine. We revisited some of the observations made at the Ford Utility Building and saw the presence of harmonics. Again, one should be very careful with the interpretation because the higher frequency components can also be actual signals from separate machines running at varying frequencies, especially in a building like the Ford Utility Building.

We have attributed all the distortion to the gear motor up to this point. It is however not clear if the doghouse itself had a role to play in the distortion of the signal. Should we expect a signal like the ones seen with the motor in every experiment with the doghouse? To understand this, we needed to conduct experiments with other sources of vibration and see the response of the doghouse. The following chapter explores this idea.

7 Vibrational Study of the Doghouse Using a Speaker

7.1 Introduction

As discussed in earlier chapters, although small in size, the gear motor used for the experiment is a complicated machine. We have seen in all our experiments with the doghouse and the gear motor that the data is very noisy and the frequency spectrum is crowded with multiple frequency components. Our goal for using the doghouse and the rotating motor was to see the response of the structure excited by an external source running at a particular known frequency. The gear motor did run at a known frequency. However, it also introduced undesired higher frequency signals. Therefore it was not a good source of vibration to excite the structure harmonically. The observations made in experiments discussed in the previous chapters raised questions about whether the doghouse itself generated the noisy data. We have been considering the doghouse as a simple linear structure. However, if we look into details, the doghouse was constructed using steel plates screwed to the wood framework. There is an interaction between two materials: steel and wood, and the screw connections make matter even more complicated and difficult to model.

There wasn't a definitive answer as to what was causing such a widespread frequency spectrum. We needed a much simpler source of vibration to study the pure response of the doghouse. What would be the response of the doghouse excited by a pure sinusoidal signal? Will it still give a distorted signal as seen with the motors? To answer these questions, in the following experiments we used an audio speaker as a source of vibration.

Pure sinusoidal signals with varying frequencies were generated digitally using MATLAB. These signals were then played through a speaker. A speaker is a device primarily used to convert electrical signals into sound. Inside a speaker, there is a permanent magnet and an electromagnet. The electromagnet has a flexible cone attached to it. When electrical signals pass through the electromagnets, they get magnetized. The direction of magnetic field however changes with the direction of current flow so that it gets attracted and repelled by the permanent magnet, generating vibrations. These vibrations are transmitted to the cone attached to the electromagnet and transmitted through the air in the form of sound waves. We were interested to see if the speaker could cause the doghouse to vibration at a particular frequency.

7.2 Experimental Setup

The experimental setup was similar to the one we had previously seen with the doghouse experiments in Chapter 6. Instead of the gear motor, the speaker was attached to the center of the roof of the doghouse, as illustrated in Fig. 7.1. The speaker was connected to the audio output of a computer which played the pure sinusoidal signal generated using MATLAB. Sinusoidal signals with frequencies of 25Hz, 75Hz, 100Hz, 250Hz, 300Hz, and 400Hz were generated and used for the test. Fig. 7.2 shows the time history plot of the sinusoidal signal generated with a frequency of 100Hz. The amplitude of the constructed input signal was altered to create different sample signals. The accelerometer placed beside the speaker recorded the vibration of the tops side of the doghouse in each experiment. The amplitude of the speaker was controlled by the volume control in the computer.

Figure 7.1: Vibration of doghouse using a speaker

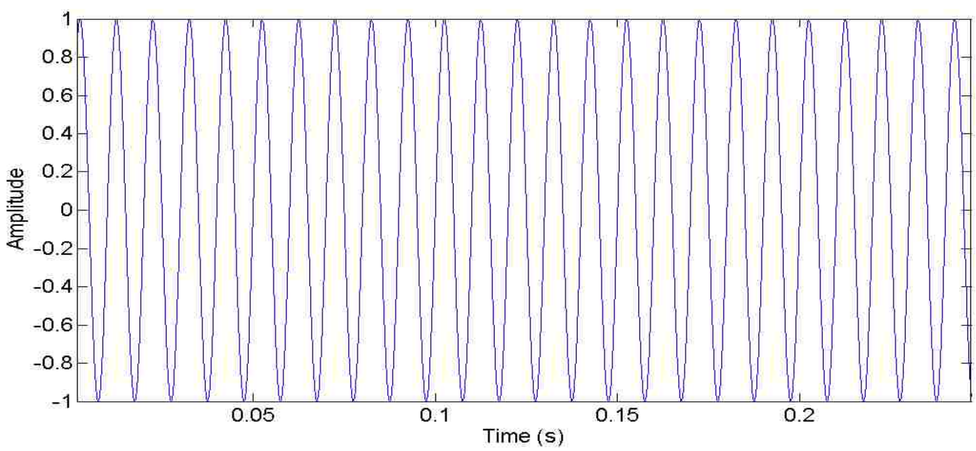

Figure 7.2: 100 Hz sinusoidal signal generated using MATLAB

7.3 Observations

It was observed that the speaker did cause vibration of the doghouse. The accelerometer recorded vibration for all sample signals, varying in amplitude and frequency. Fig. 7.3 shows the time history plot of the acceleration recorded when the 75 Hz signal was played through the speaker. The time history waveform has some distortions and consequently depicted in the frequency spectrum. There was a peak 75 Hz with some higher frequencies coexisting. For signals 100 Hz and higher, the time history of the recorded acceleration signals showed waveforms very close to a pure sinusoid. Fig. 7.4 displays the observation made for a 250 Hz signal. The frequency spectrum had a sharp peak at 250 Hz. The waveforms were even smoother at higher frequencies i.e. 300Hz and 400Hz.

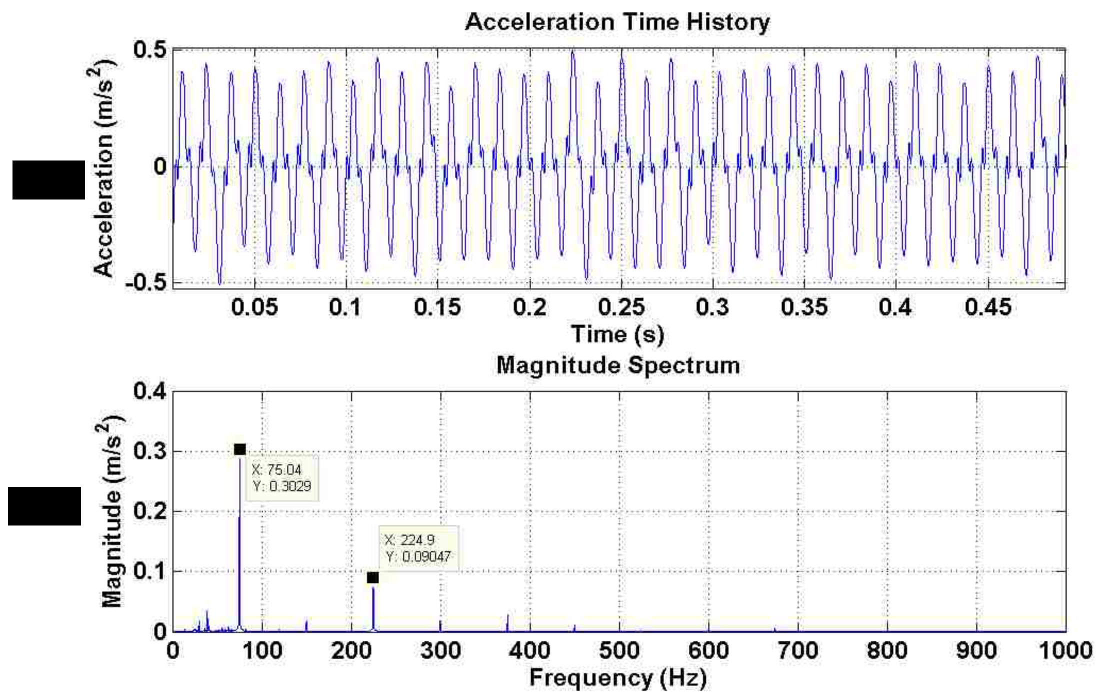

Figure 7.3: Time history of acceleration of the roof of the doghouse excited with 75 Hz signal   b) Acceleration frequency spectrum

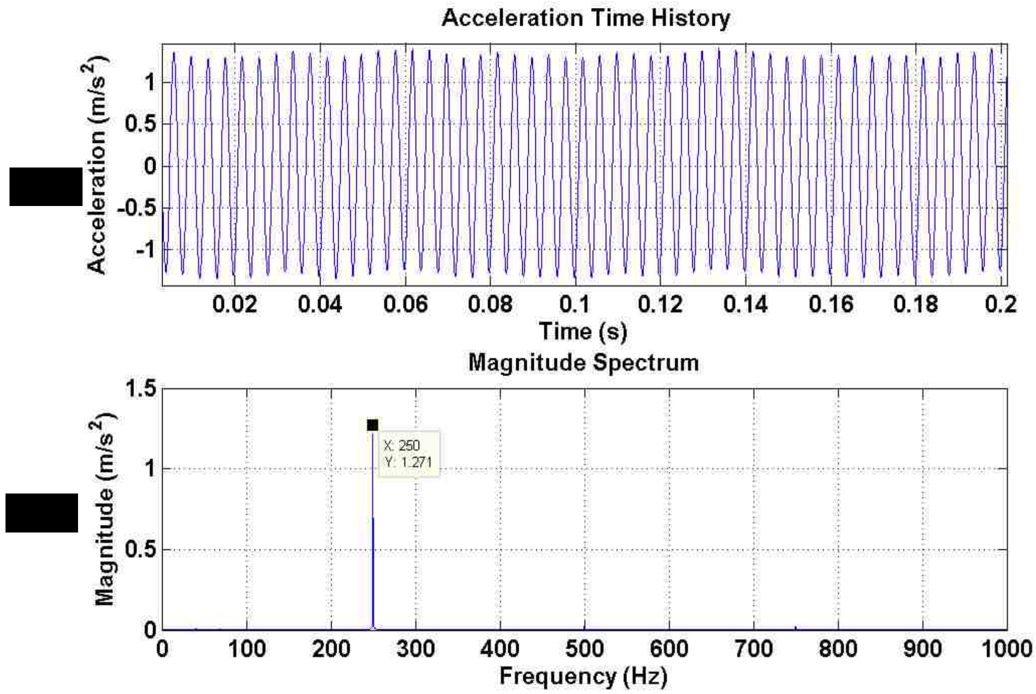

Figure 7.4: a) Time history of acceleration of the roof of the doghouse excited with 250 Hz signal b) Acceleration frequency spectrum

7.4 Discussion

The vibration signals recorded on the doghouse were very smooth, almost complete sinusoids, especially for input signals with frequencies higher than 100Hz. The input signal was pure sinusoids and the speakers worked as a good stimulator of pure sinusoidal vibration. The response of the doghouse to the vibration forced by the speaker was as expected for a linear system. Unlike the response that we had seen from the structure excited by the gear motor, the response observed in these experiments did not have a widespread frequency spectrum. The frequency of the forcing signal was clearly observed as a single sharp peak in the frequency spectrum. This was a clear indication that the roof of the doghouse was vibrating at that particular frequency.

Not many harmonics were observed in the frequency spectrum of the different recordings except at the lower frequency signals i.e. 25Hz and 75Hz where a few harmonics were seen. These harmonics were formed by a phenomenon called a harmonic distortion of the speaker. A linear harmonic distortion causes change in phase in the output only, however, a nonlinear distortion causes new frequencies to be added to the original signal. Harmonic distortion is caused by different factors such as diaphragm asymmetry, irregular magnetic field distortion and input source to the speaker as well (Hwang et al. 2004).

Human beings can hear signals at the frequency range of 20Hz to 20 KHz and audio speakers are designed to work within this range. Near the threshold frequencies, harmonic distortion can often be seen. This effect can also be seen in when the amplitude of the sound is substantially increased. In acoustics, although some orders of harmonic contribute to making the sound more pleasant, they are usually undesired.

An important finding through this experiment was that the noise and distortion seen in the recordings on the doghouse in previous experiments with gear motors was associated with the gear motor itself. The roof of the dog house behaved as a linear system for the vibration induced by the speaker and it was possible to get a clear signature of the forcing frequency from the structure.

7.5 Summary

In this chapter, we discussed the vibrational study of the doghouse excited by an audio speaker. In the previous experiments with the doghouse and gear motors, the vibrational signals recorded on the roof of the doghouse were very noisy. Even though the doghouse was excited by a motor of 5 Hz frequency, the frequency spectrum of acceleration did not show a peak at 5 Hz. Instead, multiple higher harmonics were dominant. When the doghouse was excited by the audio speaker that played sinusoidal waves generated in a computer, the time history of acceleration of recorded showed a smooth sinusoidal waveform. The frequency spectrum had a clear peak at the frequency of the signal that was played, i.e. the forcing frequency.

8 Study of Human Perception of Vibration

8.1 Introduction

The primary human sensory organs are eyes, ears, nose, tongue, and skin. These are respectively associated with the senses of sight, hearing, smell, taste, and touch. These organs are receptors of external stimuli. They are interfaced with a complex neural network such that the signals they generate in response to the external stimuli are transmitted to the brain via the neural network. The brain processes these signals, identifies the stimulus and sends out signals for the appropriate response. Although each sensory organ has its own special job, these organs work in unison to detect and collect information about the stimulus. Over time, our sensory and neural networks have evolved into a very efficient and reliable biological system. Our brain has the ability to retain information and recognize patterns, and thus with frequent exposure, human senses are excellent estimators of vibration.

The aim of this study is to understand how human beings perceive vibrations. Vibration is a complicated phenomenon in a sense that it stimulates different sensory organs. The human senses of touch, hearing, and sight all play a role in how vibration is perceived. In this study however, we are mostly interested in the perception of vibration through touch. We are interested in the how the level of perception of vibration through touch is affected by amplitude and frequency of vibration.

We were able to induce vibration of the desired frequency on the doghouse using the audio speaker. As seen in the previous chapter, for signals above 100Hz we were able to detect an almost sinusoidal response of the doghouse without significant harmonics, to a purely sinusoidal external vibration. This gave us the ability to excite the doghouse at the desired frequency.

8.2 Experimental Setup

The experimental setup was similar to the previous experiment that we had conducted with the doghouse and an audio speaker. This experiment was also conducted in a lab without any significant vibration due to any other machinery. The source of vibration for the doghouse was the speaker. As we had done in our previous experiment, the speaker was attached to the center of the roof of the doghouse such that it would cause the roof of the doghouse to vibrate. The speaker was connected to the computer audio output. Using the MATLAB code, pure sinusoidal signals of different frequencies were generated and played through the speaker such that the roof of the doghouse also vibrated at the same input frequency. An accelerometer was glued beside the speaker to measure the induced vibration on the roof of the doghouse.

8.3 Study I: Threshold Values for High Frequency Vibration

The objective of this experiment was to determine the threshold values of high frequency vibration (higher than 100 Hz). We define the lowest amplitude of vibration felt by the index finger, in terms of acceleration, as the threshold value for the frequency. 100Hz, 125Hz, 150Hz, 200Hz, 250Hz, and 300Hz were the six frequencies that were studied. This study was conducted with five individuals.

8.3.1 Procedure

The sample signals were played in random order. In each trial with a signal, the amplitude of the signal was started with 0. The subjects were asked to place their index finger over the roof of the doghouse 3" away from the speaker and asked to feel the vibration. The amplitude of signal was increased until the test subject felt the vibration in their finger. Recording of vibration of the roof of the doghouse using an accelerometer was done simultaneously with the test with human subjects.

8.3.2 Observation

It was observed that human hands are very sensitive to vibration. Vibration as low as 0.04m/s^2 was detectable through a human hand. At 300 Hz the mean threshold was 0.04m/s^2. The lowest sensitivity was observed at 150 Hz where the mean threshold acceleration was 0.27 m/s^2. The sensitivity decreased from 100 Hz until 150Hz and increase as the frequency was increased. This is shown in Fig. 8.1.

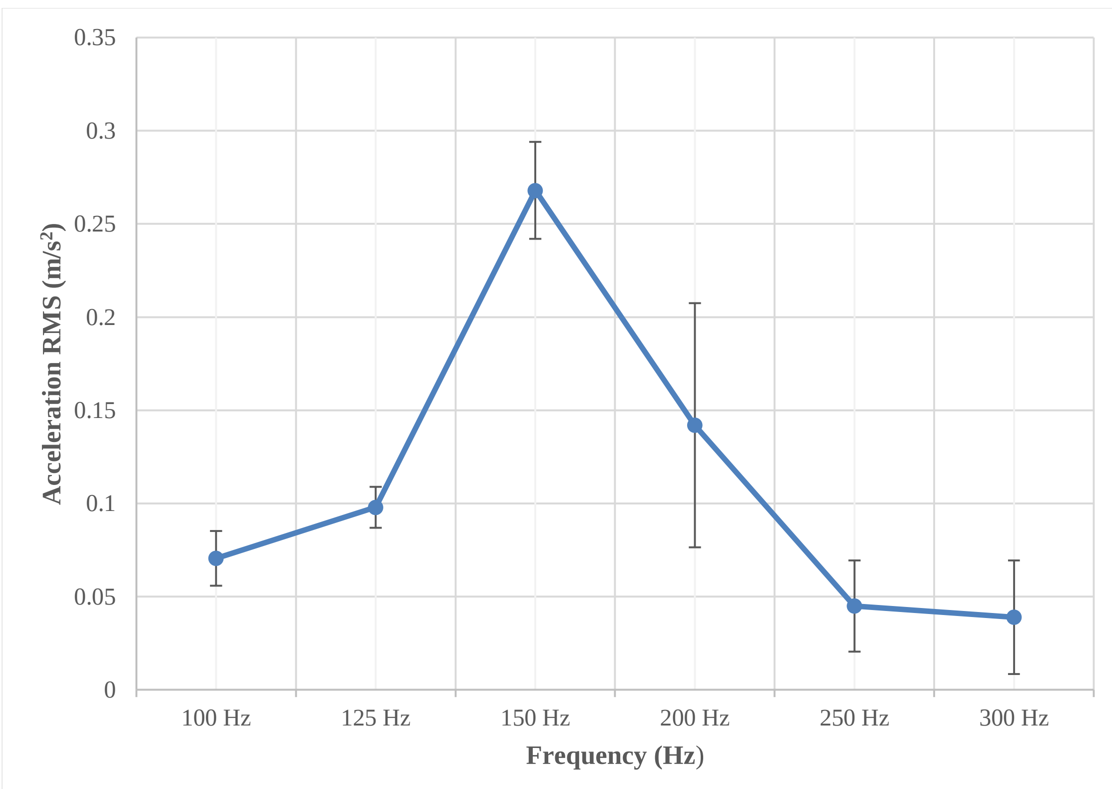

Figure 8.1: Threshold vibration for a human finger

The maximum and minimum values for acceleration for each frequency in the data from the five subjects are shown as limits in the plot as well. It is observed that the obtained result is more consistent in frequencies lower than 150Hz. A linear relationship between frequency and amplitude, however, was not seen.

8.4 Study II: Level of Perception with Change in Magnitude

The objective of this experiment was to determine the effect of amplitude on the level of perception of vibration through the sense of touch. The experiment was conducted with the same five volunteers.

8.4.1 Procedure

Each volunteer was subjected to 40 different combinations of signals with varying amplitude and frequency in random order. The frequencies of signals used were 100 Hz, 125 Hz, 150 Hz, 200 Hz, 250 Hz, 300 Hz whereas amplitudes of vibration varied. The subjects were seated on a chair next to the doghouse and they were asked to place their index finger on the top of the doghouse 2" away from the speaker. Once they were ready, the signals were played for a duration of 10 seconds. After each sample signal, the subjects were asked to fill out the questionnaire for the particular sample signal. The question was "Did you feel any vibration in your finger?" The subjects were asked to rate their experience on a scale of 0 to 5. A score of 0 meant no sensation of vibration at all, while 5 meant feeling to a point of annoyance. After each sample, a short break of 10 seconds was taken before the next sample signal was played.

8.4.2 Observations

It was observed that for all the sample frequencies, the level of perception of vibration through touch increased with the increase in the magnitude of the acceleration of the signal. Fig 8.2 shows the graph of the level of perception versus the magnitude of acceleration for each of the six sample frequencies. Note that threshold value of perception for each frequency is obtained from the previous study and assigned a zero value for the level of perception. The graph is very steep for frequencies 100 Hz and 300 Hz meaning with a small change in amplitude of the acceleration, the effect of human sensation increases drastically.

8.5 Discussion

In Study I in which the threshold value of acceleration for the perception of vibration through touch was determined, the signal with 150 Hz had the highest threshold value, meaning it was the least perceptible. A linear relationship between the frequency of signal and acceleration magnitude threshold value of perception was not seen. Instead, the graph between frequency and acceleration was bell-shaped with the peak at 150 Hz. The vibrations with frequencies 100 Hz and 300 Hz had a lower threshold value. This observation was supported by the results in Study II where the level of perception increased significantly with slight increase in the magnitude of acceleration for these frequencies.

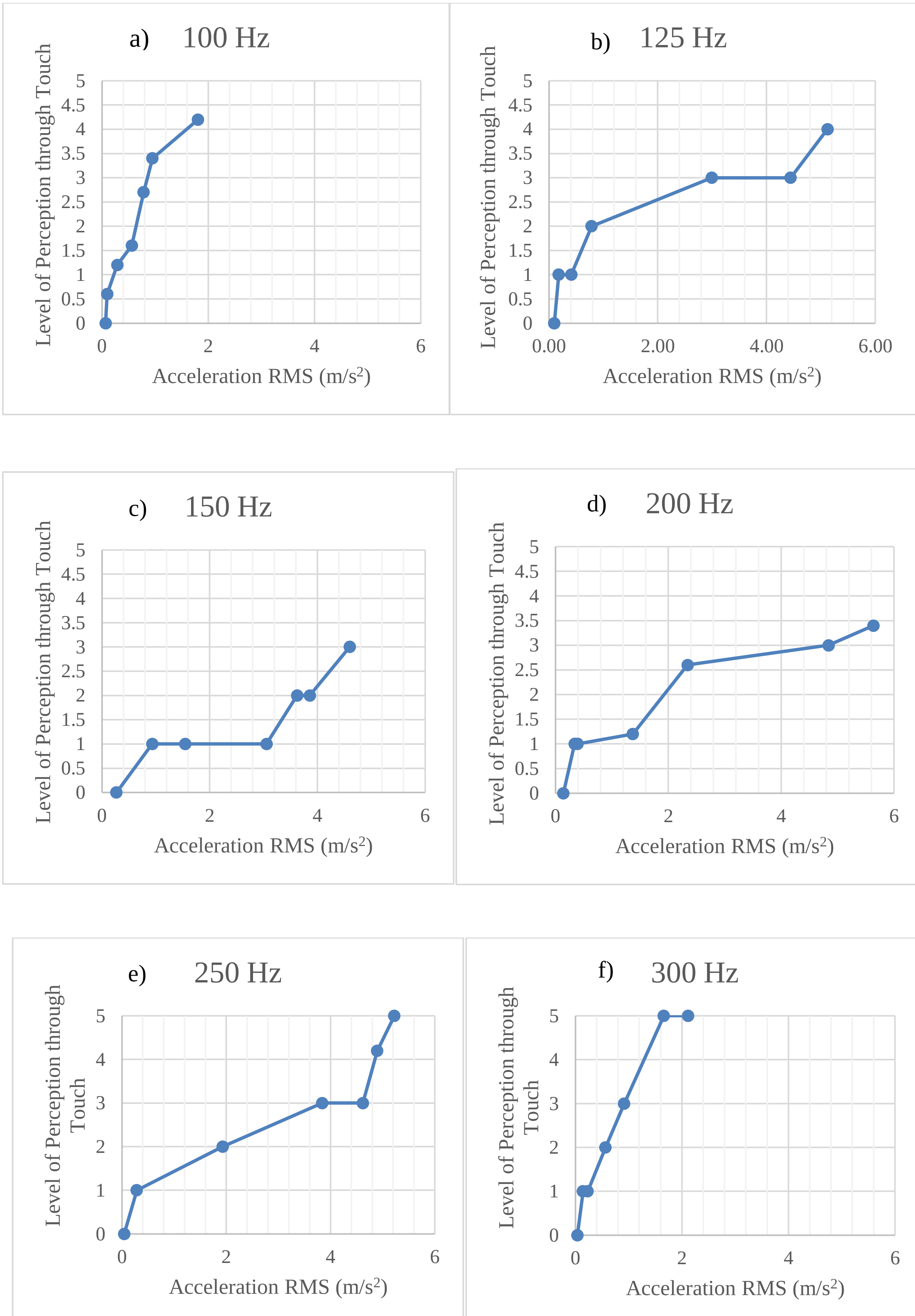

Figure 8.2: Graphs showing the level of perception with varying acceleration amplitude

8.6 Summary

In this chapter, we studied the perception of vibration through human touch. It was observed that human fingers are very sensitive to vibrations. Vibrations as small as $0.04m/s^2$ was detectable through touch. It was also observed that the level of perception of vibration changes for vibrations of different frequency and amplitude.

This was a simple experiment to verify that human senses have the potential to work as mechanical sensors. Combining the pattern recognition capability of human beings with experience and ample exposure to vibration, human sense can potentially be used as a sensor to get not just qualitative but quantitative data from the vibration. This can be a useful ability in the identification of machinery.

Human ears are also good sensors of vibration. Human beings are able to hear sounds within the frequency range of 20 Hz to 20000 Hz. Since sound is usually associated with vibration we can make a good guess about something vibrating or a machine running by just by listening to the sound and without actually seeing or touching the vibrating object. For example, when a car starts producing an unusual sound, an experienced driver or a mechanic can tell which part of the car making the sound and if there is something wrong with it, just by listening to the sound. Although they might not know exactly what frequency or amplitude the sound signal is, they can certainly feel the difference. Similarly, the sense of sight is very important in the sense of vibration. The level of perception changes with a change in amplitude and frequency of vibration. In Chapter 5, where we studied the free vibration of a cantilever beam of various lengths, the frequency of vibration increased with the decrease in length of the structure. The amplitude in terms of displacement however decreased. The vibration of low frequency and high amplitude was clearly more perceptible.

9 Summary and Conclusions

9.1 Summary

In this thesis, we studied the vibration of structures excited by operating machinery. The main goal of the project that this thesis supports is to be able to remotely detect and identify machinery concealed inside a building by capturing vibrational signals from the housing building envelope. The study of the Ford Utility Building was continued in this research. Before actually flying an airplane to remotely detect vibration from the Ford Utility Building, it was necessary to determine if the roof of the building carried the vibrational signatures of the machines running inside. Also, it was imperative that the roof showed vibrations at levels detectable by the remote radar sensor. We took readings on the roof of the building to determine if the roof carried vibrational information about the machines running inside.

The data from the Ford Utility Building was very noisy and at first, we could not fully understand it. To better interpret the results from the Ford Utility Building, we conducted several benchmark experiments with a yardstick representing a simple cantilever beam. We found that the readings that were taken on a vibrating structure also contain signals from the structure's surroundings. In addition, these benchmark experiments also helped us build confidence in our data acquisition and signal processing tools.

We furthered our research in structural vibration due to machinery with laboratory experiments in a controlled environment. Experiments were conducted using the doghouse, representing a simple building and DC motors as rotating machines. These experiments gave us a clearer idea about how harmonics can be prominent in the signals collected from a structure excited by machines. Also, the effect of the gear system of a motor in the data collected from a structure excited by the motor was studied. Additionally, the response of the doghouse to pure sinusoidal excitation was studied using an audio speaker as the source of vibration.

Finally, we explored the human perception of vibration through touch. We performed studies with five volunteers to determine the threshold amplitude of vibration for the perception of vibration of various frequencies through the human finger. The frequencies tested ranged from 100 Hz to 300 Hz. It was seen that for vibration with varying frequencies, the threshold of the amplitude of acceleration of vibration varied.

9.2 Conclusions

The roof of the Ford Utility Building is very rich in vibration. A wide range of frequency content was observed in all the readings taken on the roof. Mostly, frequencies higher than 30 Hz were seen in the readings. The signals on the roof of the building contained vibrational signals of the machines operating below. The building envelope could certainly transmit the vibrational signatures of enclosed machinery. However, in the case of Ford Utility Building, the magnitude of these signals in terms of displacement was very small. The displacement magnitude on the roof was in the range of one-hundredth of a millimeter. Maximum displacement observed was 0.1mm which was on one of the machines on the roof. Some of the structures on the roof showed acceleration about 5 m/s^2 with a frequency higher than 30 Hz. Also, because the building had a number of machines running at various frequencies, the traces of frequencies of these machines were seen in the acceleration frequency spectra. Because the magnitude of vibration on the roof was so small, the signals seemed to be blended with noise.

It was clearly seen in the experiments with the gear motors that the harmonics can be significant in the frequency spectrum of acceleration. Vibration recordings from machinery and structures excited by machinery are likely to be noisy. In the frequency spectrum of those signals, harmonics are likely to be present with varying magnitudes. In fact, their acceleration magnitudes can be more significant than that of the 1^{st} harmonic. This can be very misleading when we are trying to identify the operating frequency of a machine using the frequency spectrum. It is important to look at the whole frequency spectrum to see the presence of harmonics and find the fundamental frequencies. A sound knowledge and experience in signal processing and vibration analysis are required to make an accurate assessment. It is also noted that even though the acceleration time history is noisy with high frequency contents, the displacement reconstruction yields much smoother curves. The displacement time history curve is dominated by low frequency components of the signal.

Through our experiment on human perception of vibration, we saw that the human sense of touch is sensitive to vibration. Humans are able to detect very small vibrations through touch, with acceleration magnitudes as low as $0.04 m/s^2$ for certain frequencies. Also, the level of perception varied with a change in amplitude and frequency of the vibration. The results indicate that human senses can sense the difference in vibration and thus if we can train our senses, they can potentially be used as mechanical sensors.

9.3 Future Research

We took baseline readings on the roof of the Ford Utility Building and determined that the roof produced signatures of the machines running inside. The roof was very rich in vibration although the magnitude of vibration was low with a maximum displacement of around one-tenth of a millimeter. The research team has been able to conduct a flight test over the building with the SAR. The dotted circles in Fig. 9.1, which is a SAR image of the Ford Utility Building represent the locations where data has been recorded using an accelerometer. It will be interesting to see the results from the SAR vibrometry and see if significant vibrations are detected on the roof that can be used to identify machines inside the building. Further, the correlation between the data that we collected using accelerometers and the data collected by the SAR can be studied to check the reliability of the remote sensor.

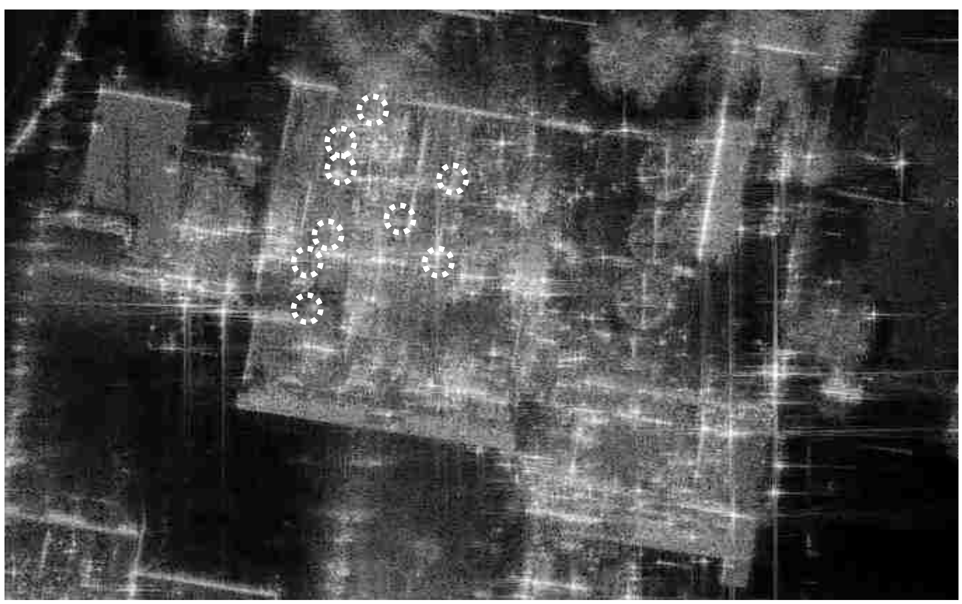

Figure 9.1: SAR image of the roof of the Ford Utility Building

Further research can be conducted to understand the human perception of vibration. If knowledge of threshold values of vibration can be broadened, it can be used in defining acceptable limits of vibration in the design of structures. Other human senses like the sense of sight and hearing can be further explored in detecting vibrations. The ability to make a quantitative assessment of vibration with human senses can supplement mechanical sensors. Identification of operating machinery has been a huge part of this research and trained human senses can be an asset for this purpose. In fields like structural health monitoring and condition monitoring of machines, vibration assessment using human senses can be helpful to take timely preventive actions.

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