A STUDY OF STRUCTURAL HEALTH MONITORING OF BRIDGES

Session 2019

PROJECT ADVISOR

PROF. DR. ASAD ULLAH QAZI

INDUSTRIAL ADVISOR

DR. ALI MURTAZA RASOOL (NESPAK)

SUBMITTED BY

NOUMAN MUSTAFA	2019-CIV-90
M. HAIDER IMRAN	2019-CIV-83
HASHAM AHMED KHAN	2019-CIV-88
REHMAN AWAN	2019-CIV-92

DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF ENGINEERING AND TECHNOLOGY
LAHORE, PAKISTAN

A STUDY OF STRUCTURAL HEALTH MONITORING OF BRIDGES

Session 2019

GROUP MEMBERS

NOUMAN MUSTAFA	2019-CIV-90
M. HAIDER IMRAN	2019-CIV-83
HASHAM AHMED KHAN	2019-CIV-88
REHMAN AWAN	2019-CIV-92

INTERNAL EXAMINER	EXTERNAL EXAMINER
(PROF. DR. ASAD ULLAH QAZI)	(Dr. USMAN HAIDER)

Final year project report submitted in partial fulfilment of the requirements for the Degree of B.Sc. Civil Engineering

DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF ENGINEERING AND TECHNOLOGY
LAHORE, PAKISTAN

DEDICATIONS

Dedicated to all those who kept us going when we wanted to give up.

ACKNOWLEDGEMENTS

First and foremost, we would like to express our sincere gratitude to Allah (S.W.T.), Who gave us the skills necessary to finish this research project. We are grateful to the Department of Civil Engineering at UET Lahore for allowing us to conduct this study which is funded by HEC under the title "HEC NPRU PROJECT NUMBER 15466".

We owe a great deal of gratitude to Prof. Dr. Asad Ullah Qazi, our supervisor and professor, who inspired us to pursue this research. Without his continual, highly expert counsel, energizing supervision, great leadership, and consistent technical and emotional support, this study would not have been possible.

Additionally, we are grateful to Dr. Mazhar Saleem for his technical support during the project. We sincerely appreciate the External Examiner's inspirational leadership, insightful analysis, and sound counsel.

We owe a debt of gratitude to Prof. Dr. Asad Ullah Qazi (Department of Civil Engineering, UET Lahore) for his sincere efforts and incredibly valuable advice. Last but not least, we would like to express our deepest gratitude to our parents and other family members for their unconditional support, kind prayers, and dedication that have enabled us to succeed in this study.

Nouman Mustafa

M. Haider Imran

Hasham Ahmed Khan

Rehman Awan

ABSTRACT

This project includes an in-depth study on the use of Structural Health Monitoring (SHM) methods to assess the condition of bridges in Pakistan. The project begins with a literature review to provide a basis for the research. The suitability of two accelerometers available in the department for SHM was then examined. It was found that Extech's high-performance vibration meter offers a coarser sample rate, while the E-Quake arm triaxial accelerometer records only peak acceleration readings. Therefore, smartphones were chosen as accelerometers to study their usability and effectiveness for SHM in Pakistan. To explore the usefulness of smartphones as SHM tools, a case study of the Old Ravi Bridge located in Shahdara, Lahore is conducted. Smartphones were used as linear accelerometers to record the acceleration versus time response of the bridge when exposed to traffic loads. The data collection method was to place smartphones in the middle of two adjacent areas for one minute to record the response. It was assumed that the class B traffic load runs over the bridge spans. The data was recorded five times to account for changing traffic loads. Once acceleration-time-response data was collected from all 15 sections of the Old Ravi Bridge, data processing was initiated. Due to the non-uniform sampling rate of the smartphone data, the Fast Fourier Transform was not applicable. Instead, the Lomb's spectral periodogram technique using Octave was used to convert the data from the acceleration-time domain to the frequency domain. A power spectral density analysis was then performed to reduce noise and identify the maximum peak representing the natural frequencies of different bridge sections. The acceleration values and natural frequencies obtained were compared to standard values to assess the true structural integrity of each bridge section. The results suggest that smartphones can be used as SHM tools to assess the condition of bridges in Pakistan. Sections 7 and 8, which experienced lateral accelerations of 12 mg and vertical vibrations of up to 50 mg, showed the most problematic behavior. In addition, the natural frequencies in different sections were between 4.8 Hz and 4.6 Hz, which indicates a loss of stiffness of some bridge elements. The usage of cellphones for SHM in Pakistan can therefore help to fulfill the Sustainable Development Goals by increasing the lifespan of bridges and thereby conserving natural resources. Thus, the criteria for the 11th and 12th Sustainable Goals "Sustainable Cities and Communities" and "Responsible Consumption and Production" could be met.

TABLE OF CONTENTS

LIST OF NOTATIONS

SHM	=	Structural Health Monitoring
RSJ	=	Rolled Steel Joists
NDT	=	Non-Destructive Testing

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

For the continuous evaluation of the condition, performance, and safety of structural systems, structural health monitoring (SHM) has emerged as a valuable tool in Civil Engineering. SHM has found extensive application as an early damage detection system in bridges and buildings.

1.1.1 What is Structural Health Monitoring

Structural health involves continuous monitoring and assessment of infrastructure like bridges, dams, and buildings. Continuous tracking of structural integrity ensures that the structure fulfils its intended purpose for the entire service life with minimum preservation expenses. SHM utilizes sensors located at critical locations to determine the location and severity of damage within the structure. These sensors depending upon their type, strain gauge, accelerometers, temperature sensors etc., collect data on various parameters. Collected data is transmitted to a centralized monitoring system, to be processed and analyzed. Analysis results enable the stakeholder to make decisions about maintenance, repair and rehabilitation if required. Thus, the interpretation and analysis of data provide a proactive maintenance approach, enable early diagnosis of structural deterioration, lower the danger of catastrophic failures, and enhance safety. In addition, SHM improves maintenance tactics and minimizes unnecessary inspections and repair costs, while extending the operational life of structures. In addition, it supports decision-making through quantitative information and unbiased assessments of structural situations.

It should be noted that different sensors do not have the same ability to detect the location and severity of damage. Based on the damage detection capability of the instruments, SHM was therefore divided into different levels. The first stages correspond to the ability to detect if there is damage in the structure. While the highest levels serve not only to find the location of the damage but also to predict the remaining life of the structure [15].

1.1.2 Need for Structural Health Monitoring

The developed countries have most of their infrastructure already built. A considerable share of their budget is for the maintenance and rehabilitation of the existing infrastructure. While in underdeveloped countries where the budget is already very scarce, the construction of new infrastructure is a must. Thus, SHM becomes necessary in both developed and underdeveloped countries. The benefit of SHM includes,

- Decrease in the maintenance and rehabilitation cost. Thus, allowing effective use of the budget in developed countries.
- Increase in the service life of critical infrastructure in developed countries.
- Allowing allocation of more budget for infrastructure construction in underdeveloped countries.
- Modification of design equations based on the behavior of the structure under extreme conditions.
- Optimization in the design of future bridges based upon the structural response of a similar type of bridge.
- Minimization of unnecessary inspections and heavy repair works.

1.1.3 Applications of SHM in Civil Engineering

Structural health monitoring has multiple applications in the field of civil engineering. It plays a vital role to ensure the safety, integrity, and optimal performance of the structure throughout its structural life cycle.

In the field of civil engineering artificial intelligence can be used in the following tasks:

- Bridges are key transportation infrastructure components, and SHM helps assess their condition and identify potential problems. By monitoring parameters such as strain, vibration, and deformation, SHM systems can detect changes in structural behavior such as fatigue cracking, corrosion, or excessive deflection. This information aids in maintenance planning, repair decisions, and ensuring bridge structural integrity.
- Monitoring the health of buildings, especially high-rise or exposed to harsh weather conditions. SHM helps detect structural distortions, settlements or foundation problems that may endanger public safety. In addition, SHM can determine how environmental stresses such as wind or seismic activity may affect the structure's structural performance and allow for immediate modifications or evacuations if necessary
- Dams are critical to water resource management, and SHM is used to verify their structural soundness. Stability, foundation movement, and potential dam leakage are all factors that SHM systems can determine by measuring seepage, pore pressure, and deformation. Thus, enabling timely maintenance and repairs, reducing the risk of a dam breach.
- SHM is vital for tunnel monitoring, especially tunnels with difficult geological conditions or those carrying large loads. To find deformations, cracks, or structural instability. SHM monitors variables such as strain, displacement, and water ingress. Continuous monitoring ensures problems are identified early, enabling rapid maintenance, and minimizing disruption to tunnel operations.
- The monitoring of offshore wind farms, oil platforms and other maritime structures is essential in the field of offshore engineering. The performance and structural health of these structures can be evaluated using SHM systems, which collect data on variables such as shaft loads, fatigue damage, and corrosion. Early damage

detection enables preventive maintenance and reduces the risk of structural failure and potential environmental hazards.

1.1.4 Challenges in SHM

Structural failures within a bridge can occur for a variety of reasons including cracking, loss of stiffness, residual stresses, temperature variations, etc. All types of damage to the structural system of the bridge cannot be monitored with a specific instrument. Piervincenzo Rizzo & Alireza Enshaeian, 2021 concluded that proper and effective SHM of bridges can only be performed when the combination of different instruments is used for this purpose. Also, a suitable system is required to interpret the response of the structures obtained from the different instruments for the actual detection and measurement of the damage [14].

1.1.5 Ambient Vibrations in Bridges

The vibrations produced within a bridge when it is open to traffic are known as ambient vibrations. The major sources of ambient vibrations include earthquakes, traffic loads, and wind [11]. This study will focus on the measurement of the structural response of the bridge under the action of ambient loads.

1.1.6 Active Structural Health Monitoring

Using some special tools to stimulate the response of the structure and measuring it is known as active structural health monitoring. Impact hammers, ultrasonic transducers, vibration shakers, etc. could be used as instruments for exciting the structures.

1.1.7 Passive Structural Health Monitoring

Passive structure condition monitoring differs from active structure condition monitoring in that no special tools are used to excite the structure. The response of the structure to ambient loads is recorded. Due to unavailability of actuators, passive structural health monitoring would be used to monitor the structural response of the bridge.

1.1.8 Continuous Structural Health Monitoring

If the sensors are embedded or permanently attached to the structure for the continuous recording of the structural response then this type of monitoring is known as continuous structural health monitoring. Fiber Bragg grating is one of the sensors that could be embedded within the structure.

1.1.9 Non-Continuous Structural Health Monitoring

Monitoring the health of the structure after a regular period is referred to as periodic or discontinuous structural health monitoring. Various techniques can be used for this purpose, including the non-destructive testing approach and destructive testing.

1.2 PROBLEM STATEMENT

The deteriorating condition of bridges in developing countries poses a significant challenge to infrastructure safety and maintenance. In the context of Pakistan, where financial constraints limit the implementation of sophisticated Structural Health Monitoring (SHM) systems, there is a need for cost-effective assessment and monitoring techniques for assessing the structural integrity of bridges. Therefore, this study will focus on the use of smartphones as accelerometers for SHM. For this purpose, a case study would be conducted at the "Old Ravi Bridge" in Shahdara, Lahore to examine the feasibility of using smartphones as an accelerometer.

1.3 RESEARCH OBJECTIVES

The main objectives of this study are:

- To develop an understanding of the different structural health monitoring techniques used in the world.
- To carry out the SHM of Old Ravi Bridge using smartphones as accelerometers.
- To find out acceleration due to ambient vibration in different spans of Old Ravi Bridge.
- To find out the natural frequencies of different spans of Old Ravi Bridge.

1.4 SCOPE OF WORK

This research deals with the SHM application on Old Ravi Bridge using smartphones as accelerometers. The objective function will be to validate the use of smartphones as an accelerometer for SHM in Pakistan. The acceleration response of the bridge due to Class B traffic loading and natural frequencies of all the spans would be computed. This research can be extended easily for the application of SHM using smartphones in different bridges of Pakistan.

1.5 ORGANIZATION OF THESIS

- Chapter 1 describes the overview, problem statement, research objectives, and organization of the thesis.
- Chapter 2 presents the literature review on the SHM of bridges using smartphones as an accelerometer
- Chapter 3 presents a historical review of the Old Ravi Bridge.
- Chapter 4 presents the methodology adopted for the SHM of Old Ravi Bridge using accelerometers.

- Chapter 5 presents the information obtained after the reconnaissance survey of Old Ravi Bridge.
- Chapter 6 illustrates the general behavior of the bridge's spans as well as the behavior of its critical spans when the bridge is in use.
- Chapter 7 presents the conclusions and recommendations based on the results obtained in the project.

CHAPTER 2

LITERATURE REVIEW

2.1 STRUCTURAL HEALTH MONITORING IN CIVIL ENGINEERING

The main idea behind the development of structural health monitoring techniques in civil engineering is to ensure that the structure is fit for purpose throughout its design life. Structures, especially bridges, may be exposed to extreme conditions such as flooding, etc., or other man-made hazards during their lifetime. Therefore, in these extreme conditions, we need to access the structural response to better design critical infrastructure. Also, we must overcome the inability of visual inspection to represent the condition of the structure fully and accurately. While there is some discrepancy in the prediction of structural integrity due to computational difficulties and the lack of appropriate data analysis methods for SHM, the response is still very close to actual conditions. Nevertheless, it is an effective way to minimize repair costs and monitor the behavior of the structure under different loads in real time.

The advancement of technology in recent years has led to the rapid development of sensor-related technologies. Also, computers nowadays can perform advanced numerical simulation methods. Hence leading to the wide use of SHM in bridges [16].

Mainly the reason why there is wide use of SHM in the bridges is due to the fact that these structures are exposed to high dynamic loadings causing fatigue losses within the members. Due to this, local failures may occur that may continue to expand ultimately resulting in the failure of the structure. Hence vibrations in bridges are an effect of dynamic loadings such as traffic, pedestrian, wind, etc. The ability of the bridge to resist these forces is very important for its continued use. This requires the use of technology to detect damage to the bridge and to predict its precise location. Such that efficient and effective maintenance can be performed [10].

Many highly sensitive accelerometers are present for the vibration-based SHM of bridges. But these instruments are also very costly. Their use can be justified for case studies or the determination of force effects. But these instruments cannot be installed on large scales. Hence different scientists have tried to find cheap, effective reliable solutions for these problems. Due to this various case studies have been performed using smartphones as accelerometers.

2.2 SMARTPHONE AS AN ACCELEROMETER FOR SHM

Ekin Ozer, et. al., highlighted some points regarding the use of modern cutting-edge advances in sensor technology and showed us the potential of using mobile phones for SHM. The Author introduced the concept of the Citizen Sensor Network, where citizens can easily use their smartphones to get the data, they need to optimize SHM. Implementing such a network will have a huge positive impact on the cost of collecting structural integrity data. The study also proves the efficiency and performance of smartphones with accelerometers that can provide us with accurate structural vibrations. A comparison is also made between the data collected via smartphones and high-quality accelerometers based on a small shaker table test [4].

Kong Q. et al., measured acceleration produced within the building using smartphones. He validated that smartphones can be used for measuring the structural response within buildings. The building was excited using the actuator available at the top of the building [7].

Zhoa X. et al., performed an experiment to investigate how well smartphones performed as a dynamic testing tool for cable-type constructions [18].

Li J. et al., performed experiment to investigate whether smartphone could be utilized to measure story drift in a building during seismic activity [8].

From above mentioned authors works it could be concluded that importance of the smartphone as an accelerometer is increasing day by day. The main reason is that cheap these instruments are cheap, easily available, and easy to use. To validate their use as accelerometers different researchers have used them in their case studies [6]. The purpose is to find out the reliability of the instruments and to develop a proper SHM system using smartphones.

To test the limits of structural health monitoring via smartphone, a self-anchored concrete suspension bridge was chosen. The chosen test object, the Zhuanghe Construction Bridge in China, was recreated at a scale of 1:28 and was designed to include a 7.14-meter main span, two towers, twisted wire ropes, main cables, and a reinforced concrete box girder. To capture the dynamic responses of the bridge, four smartphones were strategically placed at the centre and one-quarter of the span and secured with double-sided tape. Four iPhone 6s with high-tech sensors, including a three-axis InvenSense MPU-6500 accelerometer and a three-axis Bosch BMA280 accelerometer, as well as a three-axis InvenSense MPU-6500 gyroscope, were all synced at a 100Hz sampling rate. The test result demonstrated that a maximum error of 2.63% was observed for various parameters like acceleration, angle, and displacement [17].

2.3 CASE STUDIES REGARDING USE OF SMART PHONES FOR SHM

Better research and inexpensive but reliable instrumentation are needed to give the SHM broader industrial prospects [13]. Therefore, various researchers have conducted extensive research to provide SHM field prospects and utilization of smartphones is one of the area researched by the researchers.

Zhao X., et al., performed a lab-based study on a cable-suspended bridge. In addition to conventional accelerometers mobile phones were also attached to the bridge. To validate the ability of mobile phones to measure the structural response under extreme conditions the bridge was exposed to earthquake using a shaking table. The results demonstrated that smartphones measured data without much deviation from the conventional accelerometer [19].

Feng M.,et al., performed tests using a shake table to measure the response generated by high-quality accelerometers and mobile phones. They came to the conclusion that within a frequency range of 0.5 Hz to 20 Hz, smartphones gave satisfactory results. They also noted that new-generation smartphones tend to be more accurate than previous generations. Thus, they concluded that cheap acceleration measurement instruments are improving day by day hence the application of SHM in bridges is becoming more and more prominent [5].

Ashish, et al., performed SHM with a smartphone on a real bridge. The data was recorded from the bridge for a whole year. The data was transferred to the cloud server and the purpose of the study was to validate the data collection ability of the smartphones. The authors concluded that the uneven sampling rate is the main problem with using smartphones as accelerometers [1].

Eoi Figueiredo et al., developed software called App4SHM to monitor the acceleration response of the bridge and also measure the natural frequencies. They also performed case studies using the software for SHM on two prestressed concrete bridges [3].

Botao Xie et al., used smartphones to monitor the frequency response of a steel frame. They concluded that smartphones perform exceptionally below the 30 Hz frequency. However, if the object to be monitored is asymmetrical, the likelihood of errors in response measurement increases [2].

Matarazzo T. J., et al., utilized smartphones for the determination of the natural frequencies of the bridge in all three directions. The determination of the frequency of bridges utilizing smart phone proved to be an effective and cheap source of structural health monitoring [9].

2.4 ERRORS IN SMARTPHONE

After measuring the actual vibration response of a bridge and comparing the results obtained with the smartphones, it was observed that older smartphones have an error of about 4-5% in measuring peak horizontal acceleration, while the results from current-generation smartphones differ from the actual ones (which come from high-quality accelerometers) by about 0.96%. Also, when measuring amplitude (g), older smartphones deliver errors in the range of 8-44%, while current-generation smartphones deliver results of 1-17%. Based on these results, it can be said that current-generation smartphones are quite capable and sufficient in monitoring the structural integrity of structural elements [12].

CHAPTER 3

HISTORY OF OLD RAVI BRIDGE

3.1 OVERVIEW

The Ravi Bridge, which crosses the River Ravi in Lahore, Pakistan, is a notable landmark. It links settlements on the western side of the river with the city of Lahore. The bridge is one of the gateways to exit and enter the city of Lahore. The term "Old Ravi Bridge" may refer to a bridge that was built in a previous iteration; numerous bridges have been built over time at various sites.

3.1.1 Before the Partition of the Subcontinent

The first Ravi Bridge was built when the Subcontinent was still a colony. It was a railway bridge that was finished in 1915 and was very important in tying Lahore to other towns in British India. This bridge serves as a crucial transportation route for business and trade.

The bridge was originally constructed in 1915 to cope with Class 18 loading (19 Tons) with the following components and parameters

1) Length - 1462'-6" long bridge with 15 spans 97'-6" each.
2) Roadway - 18' wide with curb 9" on either side.
3) Main Beam - 2 No. Steel plate girders 10 ft. 3 in. high.
4) Bracers - Rolled Steel Joists (RSJ) over Plate Girders.
5) Deck - 5" Steel trough over RSJ.
6) Piers - 6' thick solid masonry.
7) Foundation - Octagonal wells/caissons 73' deep, with 5-3" thick walls of burnt bricks laid in lime mortar.

3.1.2 Deterioration of Old Ravi Bridge

The bridge served for almost a half-century to the people and British rule of the subcontinent for business and intercity purposes. But over time, a larger and better bridge became necessary as a result of growing urbanization and population. So, the renovation of the existing bridge was made utmost importance at that time. A study conducted at that time did not support the retention of the superstructure of the bridge, which had incapacitated to sustain the induced stresses and effects by the incoming traffic, Consequently, the bridge was demolished but its well foundation was retained below the river bed.

3.1.3 Reconstruction of Old bridge

It was decided to reconstruct the bridge above the existing foundations having a wider roadway from the demolished one. Keeping in view the limited load-carrying capacity of existing foundations design of two lanes wide new bridge was carried out with "Class B" vehicular loading, which is approximately 60% of the heaviest bridge loading of Pakistan known as "Class A loading. The reconstruction was carried out in the year 1966-67 having the following features with regard to its sub-structure and super-structure components

1) Length No change, a 1462'-6" long bridge with 15 spans 97'-6" each.
2) Roadway 24' wide (6' wider than the old bridge) with 9" RCC curb on either side.
3) Main Beams concrete girders. 6' high 3 No. pre-stressed post-tensioned
4) Bracers - Pre-stressed post-tensioned concrete diaphragms.
5) Deck - 7" thick RCC Slab
6) Pier transoms - 5'-9" x 2"-9" x 21' RCC cap over 2 No. columns.
7) Pier Columns - 3'-3" dia 2 No. RCC columns over RCC footing/ transom slab.
8) Foundation used. The existing wells / caissons of the old bridge were used.

In 1992, a problem with the columns of pier No.8 (from the Shahdara side) was noticed as the concrete above one-third of their height developed cracks and the cover spalled off. The steel reinforcement was exposed to the atmosphere in the affected segments / sections and corrosion was clearly visible. A Committee of engineers recommended repairs to affected/ damaged segments of the columns by pneumatically applied concrete known as guniting in order to develop a good bond with the existing concrete in the core. The field formation thereupon carried out some remedial measures by filling the concrete where it had already spalled off and constructing a brick wall in between the two columns over the transom slab up to the soffit of the capping beam.

3.1.4 Proposal of a new bridge

The floods of 1955, 1957, 1973, 1975, and 1980 saw exceptionally high river discharge. Water that was too much for the bridges over the road and railway had to pass through openings in the Shahdara protection bund.

The flood commission carefully analyzed the situation in light of the damages caused by these high-water years and made the decision to lengthen the railway and road bridges in order to increase their discharge-carrying capacity. Accordingly, model studies were conducted by IRI in 1979, 2004 and 2005, and it was reported that if 1 no. bay is added on the Lahore side and 8 no. bays are added on the Shahdara side of both bridges, a discharge of 4 lac cusec can be safely passed over a 2344 ft. length of railway bridge along with a bridge of equal length on the road. The after mentioned research also made recommendations regarding several improvements and modifications to river training works.

In view of the foregoing, it is proposed that the Old G.T. Road Bridge's roadway, which measures 24 feet wide, was built to support smaller loads (class "B" loading, with a maximum axle weight of 15,000 pounds). As a result, the bridge cannot accommodate all types of heavy vehicles due to its design load limit. Therefore, only animal-drawn vehicles and other light motorized traffic is permitted on the bridge. Therefore, it is clear that even after being extended, the current bridge is intended to continue to be used by the designated light traffic.

Therefore, a four-lane new bridge is suggested to be constructed at a suitable location in the vicinity of existing road bridges to cater for all types of traffic including present-day heavy loading as well. This would also reduce the extraordinary traffic burden on the existing Shahdara Bridge. The tentative cost of the bridge project was Rs. 1603 million in 2011.

CHAPTER 4

METHODOLOGY

4.1 INTRODUCTION

Availability, low cost, and ease of use have justified the usage of smartphones as structural health monitoring tools. Bridges are among the most endangered structures in transportation infrastructure. For this reason, bridges are inspected after a certain time interval. In the past, monitoring of bridges relied heavily on visual inspections. The weakness of the visual inspection is that it depends on the observer's judgement. Since monitoring activities are scheduled, damage to the bridge after the examination is unlikely to be detected until the next examination, leading to an increase in damage to the bridge.

When visually inspected, the outward appearance of the various bridge components will determine how well the bridge is maintained. Because of these limitations, non-destructive testing and structural health monitoring are growing in popularity. It is important to realize that SHM is an ongoing process that assesses the health of bridges and that NDT can be applied as part of SHM. Due to their low cost, smartphones have been increasingly used as a structural monitoring tool since 2015. Their use has been mentioned in several articles written for SHM.

The following methodology was used to access the "Old Ravi Bridge" structural integrity utilizing smartphones.

4.2 INSTRUMENT LEARNING

Two accelerometers were available in the department. The first step was to become familiar with the available accelerometer tools. The first device was Extech's heavy-duty vibration meter and the second E-Quake Arm's tri-axial accelerometer. After learning the instruments, it was found that the first instrument has a very coarse data sampling rate of 0.5 Hz, while the second instrument has a data sampling rate of 100 Hz. The problem, however, with second instrument was that it could only record the bridge's peak acceleration response. In contrast, the sampling rate of cell phones varied between 200 Hz±5 Hz. The acceleration response was recorded up to 0.0015 g by cell phone.

Figure 4-1 shows Extech's heavy-duty vibration meter. This instrument could record acceleration, velocity, and displacement response. The recorded data is in root mean square (RMS) form. Therefore, the structural response occurs only in the first quadrant on the display screen.

Figure 4-1 Extech Heavy Duty Vibration Meter

Figure 4-2 shows E-Quake ARM Triaxial Accelerometer. This instrument could record the peak acceleration response of the structure. The software of the instrument could perform the Fast Fourier Transform of the acceleration response but the frequency response is not recorded by the instrument. Hence the response could not be used for further processing but could only be used to get visual interpretation.

Figure 4-2 E-Quake ARM Triaxial Accelerometer

4.3 RECONNAISSANCE SURVEY

The reconnaissance survey of the Old Ravi Bridge was the first on-site operation after literature research and instrument learning. During the reconnaissance survey, geometric information, and general conditions of the different parts of the Old Ravi Bridge were recorded. The geometric parameters include, among other things, the number of spans, the total length of the bridge, the number of intermediate supports and their supporting mechanisms, the width of the roadway and the location of the membrane. To gather all the data needed for the reconnaissance study, two field surveys were conducted.

4.4 DATA ACQUISITION

Ambient Vibration Testing was used for acquiring the data on acceleration from the bridge. Ambient vibrations are the excitations produced within a bridge under regular traffic loading. In this type of response monitoring no external excitations like mechanical vibrators are used. Accelerometer records the excitations within the structure for both forced (traffic loading) and free vibrations.
After the selection of the testing approach, it was decided to place the accelerometer right next to the curb. The two-sided tape was also used to ensure a rigid connection between the smartphone and deck wearing surface. The following figures show the placement location of smartphones on the bridge.

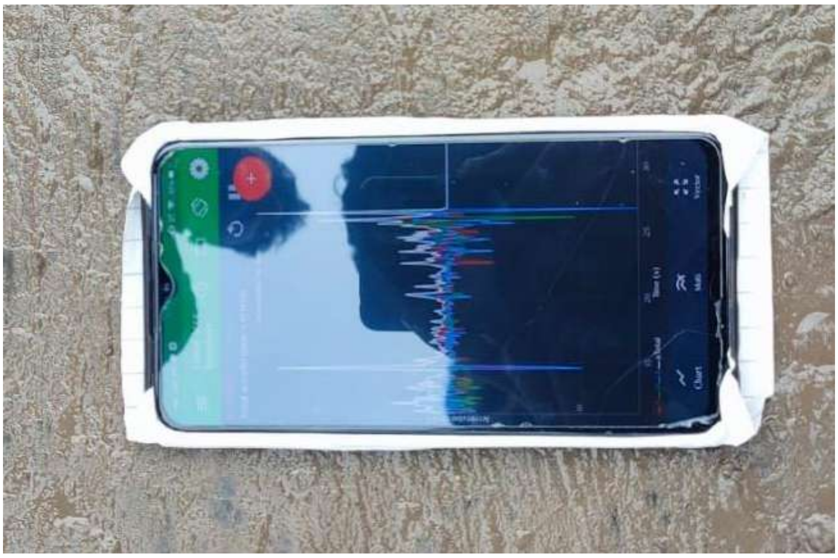

Figure 4-3 Data acquisition using physics toolbox suite software

Figure 4-3 shows the mobile phone placed on the bridge-wearing surface. The response of the bridge is recorded using the Physics Toolbox Suite software. Double-sided tape was used to ensure a rigid connection between the bridge and the mobile phone.

Figure 4-4 Acceleration response measurement using smartphones

Figure 4-4 presents the actual response capturing of the bridge under the action of ambient loads. The mobile phone is placed at the center of the third span of the bridge. The purpose of placing the mobile phone at the center of each is to record the maximum acceleration produced in the bridge and to capture the first mode of vibration of the bridge.

4.5 SOFTWARE USED AND REFERENCE AXIS

The software to be utilized for the acquisition of acceleration response is the physics toolbox sensor suite. Physics toolbox sensor suite records the acceleration response in three dimensions. The x-axis in the software would denote acceleration along the span of the bridge. While y-axis would denote the acceleration along the cross-section of the bridge and the z-axis would denote the acceleration in the vertical direction as shown in the figure 4-5. The axis of prime importance would be z-axis. Because it records the vibration response of the structure in vertical direction. To ensure that the above-mentioned axis system is maintained in each span of the bridge. The smartphone would be placed in the same orientation as in the figure 4-4.

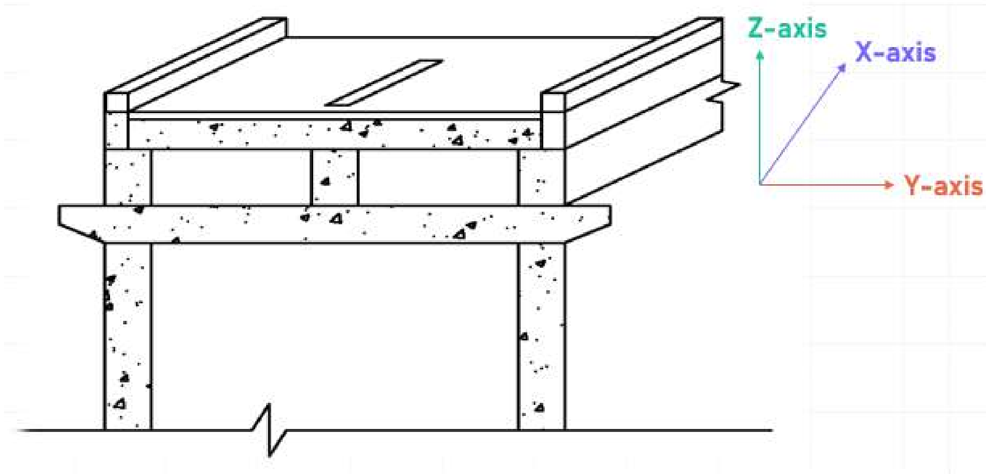

Figure 4-5 Cross-section of bridge and Reference axis for acceleration measurement

4.6 LOCATION OF INSTRUMENT INSTALLATION

The smartphones were installed next to the curbs in the middle of each span. The purpose is to ensure that the accelerometer is capturing the maximum acceleration within the span. It also helps in capturing the first vibrational mode of the structure. The top view and cross-section of the bridge are shown in the figure 4-6 and figure 4-7 respectively, with the instruments placed in specific place.

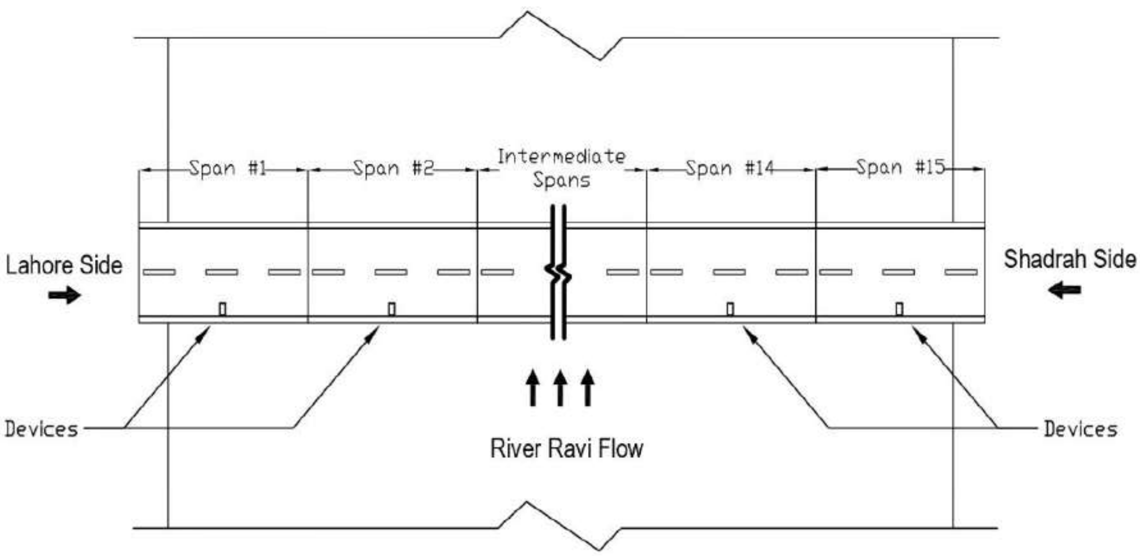

Figure 4-6 Plan view showing smartphone placement location

Figure 4-7 Instrument placed at the Centre of the span

4.6.1 Data Acquisition Assumptions

The following assumptions have been made for the acquisition of data from different spans of the bridge.

- The vibration response of the spans of the bridge would be against Class B loading. The barriers present at the start of the bridge ensure no vehicle heavier than Class B enter the traffic stream on the bridge.
- The traffic loading is enough to excite different modes of vibration within the structure.
- At each location, the response would be recorded for 1 min to account for the variability of traffic at different spans of the bridge.
- The response of the bridge would also be measured at different visits to check the variability in the smartphone-measured response.
- Also, at each mid-span location, the readings of 1 min intervals would be taken 5 times.
- Two adjacent spans would be monitored at the same time.

4.7 DATA PROCESSING

The data collected via the smartphone does not have a uniform sampling rate. Therefore, the Fast Fourier Transform could not be applied to transfer the data to the frequency domain. Therefore, to analyze data and convert it to frequency domain data, Lomb's spectral periodogram algorithm technique would first be applied to generate a response against a uniform sampling rate. A Fast Fourier Transform would then be applied to transform the data into the frequency domain. Then the MATLAB Power Spectral Density function would be applied to separate the peaks from the frequency domain data (i.e., remove noise from the frequency domain data). The highest peak value determined would be the natural frequencies of the bridge spans. This acceleration response and natural frequencies would be used to ensure the structural integrity of the span.

CHAPTER 5

RECONNAISSANCE SURVEY

5.1 OVERVIEW

A reconnaissance survey, sometimes referred to as an initial survey or a feasibility study, is carried out to acquire basic facts and information about a certain location or project site. Usually, it is the first phase of a larger investigation or research. Reconnaissance surveys are mostly used to gather information for follow-up research or to determine a project's viability and feasibility.

Some typical aspects of a preliminary survey are:

- Purpose and Objective
- Study area selection
- Data Collection
- Site assessment
- Risk analysis
- Stakeholder analysis
- Preliminary recommendations
- Site study

Similarly, the reconnaissance survey of Old Ravi Bridge was conducted to find out the above aspects.

5.2 SIGNIFICANCE OF OLD RAVI BRIDGE

Here are some key points highlighting the significance of the Ravi Bridge:

- **Transportation link:** The Ravi Bridge is an important transportation link that allows for the transportation of people, cargo, and automobiles across the Ravi River. Shahdara Town, Sheikhupura and Gujranwala are all connected to Lahore via this important highway that runs through the eastern regions of the city.
- **Historical Importance:** It is one of Lahore's older bridges, the Ravi Bridge is significant historically. It was initially built during the British colonial era and has seen the expansion and development of the city over time.
- **Cultural heritage:** The Ravi Bridge has become firmly integrated into the culture of Lahore. It appears frequently in literary works, paintings, and photographs, and serves as a symbol of the city's history and its relationship with the river.

- **Economic Impact:** The bridge is vital in promoting economic activity as it facilitates trade and commerce. It enables goods to be transported between Lahore and adjacent industrial sites, thereby supporting the general economic development of the region.
- **Symbol of connectivity:** The Ravi Bridge unites many communities and neighborhoods on both sides of the river, symbolizing the connectedness and harmony of Lahore. It acts as a symbolic landmark that encourages a feeling of identification and affiliation among city dwellers.

5.3 PRESENT CONDITION OF THE BRIDGE

The bridge was inspected from above and the railings and curbs were found to be in good condition, but the wearing surface was damaged in a few places. Significant damage to the expansion joints was noted. Drainage pipes are clogged throughout the bridge, causing water to pool on the deck, seep into concrete members and corrode reinforcement. Only one span on the Shahdara side and four spans on the Lahore side of the bridge were found dry and could be inspected from the underside. The beams, membranes, RCC columns and pier transoms of these spans are in good condition. The rest of the bridge was inaccessible due to the running water and therefore could not be inspected. Following are the few pictures attached that were taken during the Reconnaissance survey:

Figure 5-1 Heavy Vehicle Restriction Barrier at entrance and exit

In Figure 5-1, the obstruction (steel beam) at the entrance from both sides is placed. The purpose is to not let enter the heavy vehicle on the bridge as it was declared unfit for heavy loading after 2018. Only small vehicles like passenger cars, motorbikes, rickshaws, animal carts etc. are allowed to move on the bridge.

Figure 5-2 Defective Expansion Joint

Figure 5-3 Expansion Joint

In the above Figure 5-2 and Figure 5-3, the expansion joints were not in very good condition and have been seriously damaged. Immediate repair of these expansion joints would lessen the obvious vibrations while standing on the bridge.

Figure 5-4 Brick wall between the piers

In Figure 5-4, It can be seen that the brick wall was made in between piers of the span 8 from the Shahdara side. It was made because, in 1992, it was noticed that the concrete above one-third of their height was spalled off and the reinforcement were exposed to the atmosphere. So, a quick remedial measure was adopted to fill the concrete where it was spalled off and constructed a brick wall in between two columns over the transom slab up to the soffit of the capping beam.

Figure 5-5 Deteriorated Bearing Plate

In Figure 5-5, the Bearing plate condition of the bridge is shown. It can be seen that the bearing plate of the bridge has been totally deteriorated and it has been filled with debris.

Figure 5-6 Cassian Foundation

In above Figure 5-6, the foundation of the bridge can be seen. By looking at the naked eye it can be observed that the bridge foundation looks in very good condition. The façade of the foundation was in acceptable condition except some efflorescence was present on the bricks which is due to the salt present in the river Ravi.

CHAPTER 6

VIBRATION RESPONSE RESULTS

6.1 OVERVIEW

The vibration data collected by using mobile devices was analyzed using octave programs. The dominant mode of vibration is in the z-direction. The natural frequencies of all spans lie in the range of 4.4 Hz to 4.8 Hz. The detailed analysis results of all spans can be found in Appendix A. In this chapter, the general behaviour of all spans and the behaviour of critical spans are discussed.

6.2 GENERAL BEHAVIOR

In Figure 6-1, the acceleration data in the x direction is plotted in the time domain. It was observed that accelerations in this direction are minimum, and their values generally did not exceed 3 mgs.

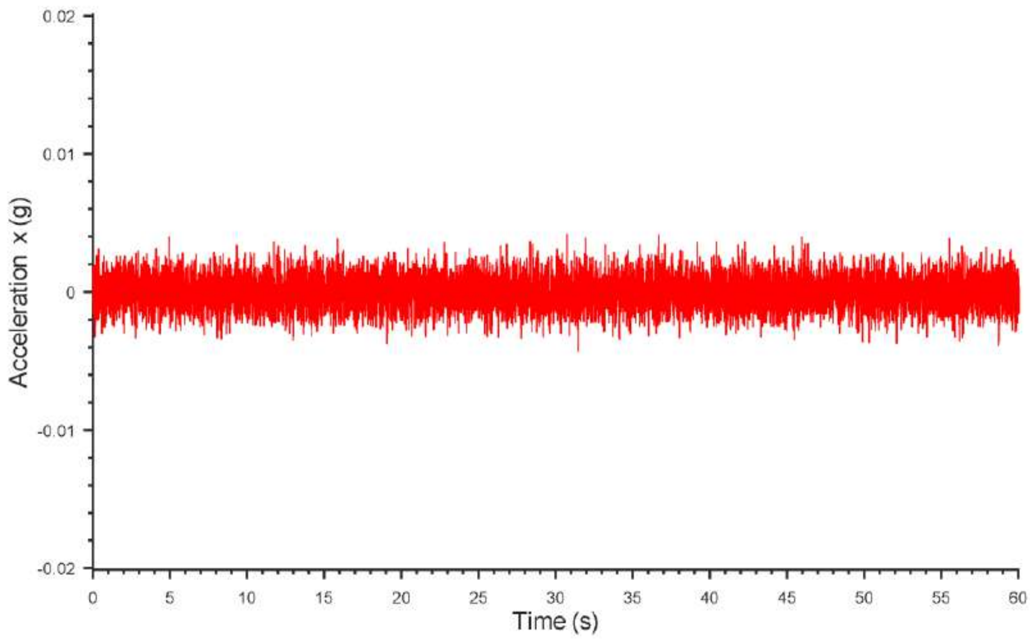

Figure 6-1 General Behavior in x-direction, Time domain

Figure 6-2 represents the same data plotted in the frequency domain, revealing that no significant mode of vibration was excited about this direction.

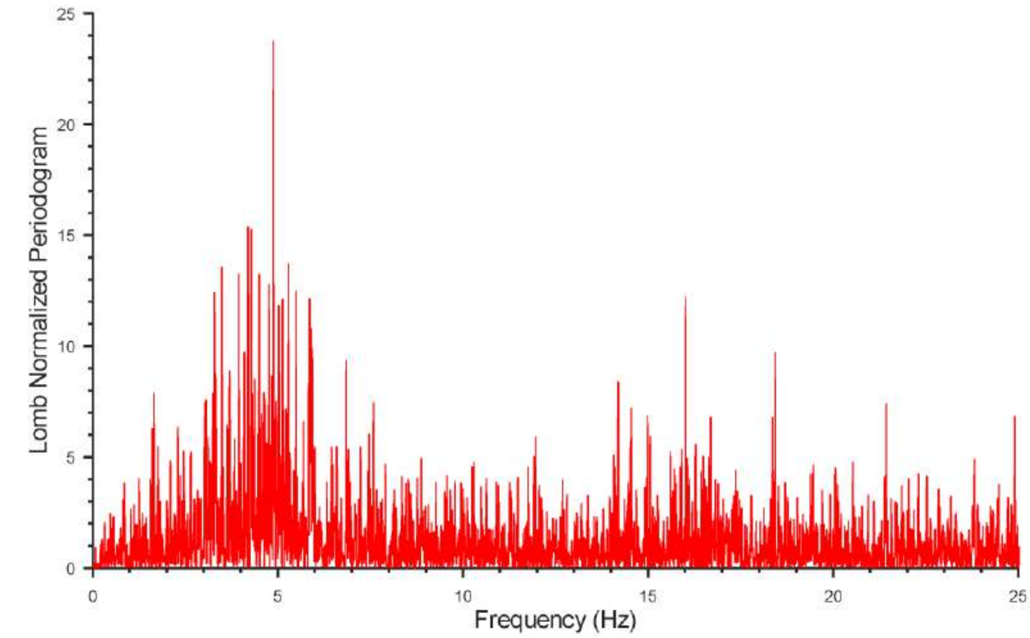

Figure 6-2 General behaviour in the x-direction, Frequency domain

In figure 6-3 and figure 6-4, representing y direction, similar behavior was observed. The accelerations did not exceed 5 mgs, but lower frequencies ranging from 2.5 to 4 Hz were more prominent.

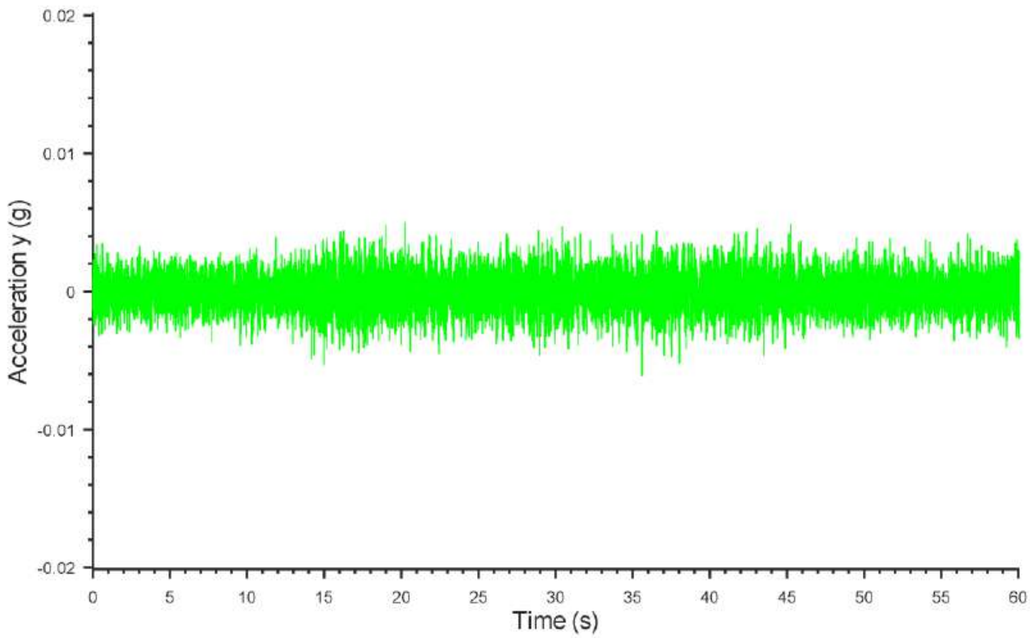

Figure 6-3 General Behavior in y-direction, Time Domain

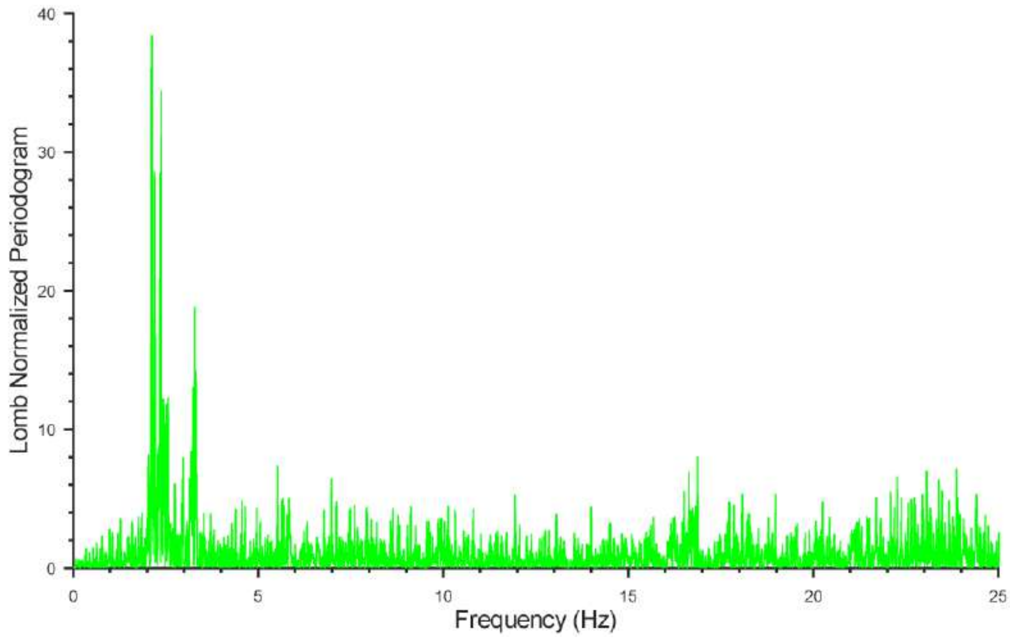

Figure 6-4 General Behavior in y-direction, Frequency Domain

In the z direction, the accelerations were most prominent. Generally, their magnitude remained below 20 mgs. Time domain data is shown in Figure 6-5, and frequency domain data is shown in Figure 6-6. It was observed that one vibration mode was significantly excited in this direction, occurring at the natural frequency, which was typically around 4.8 Hz or more.

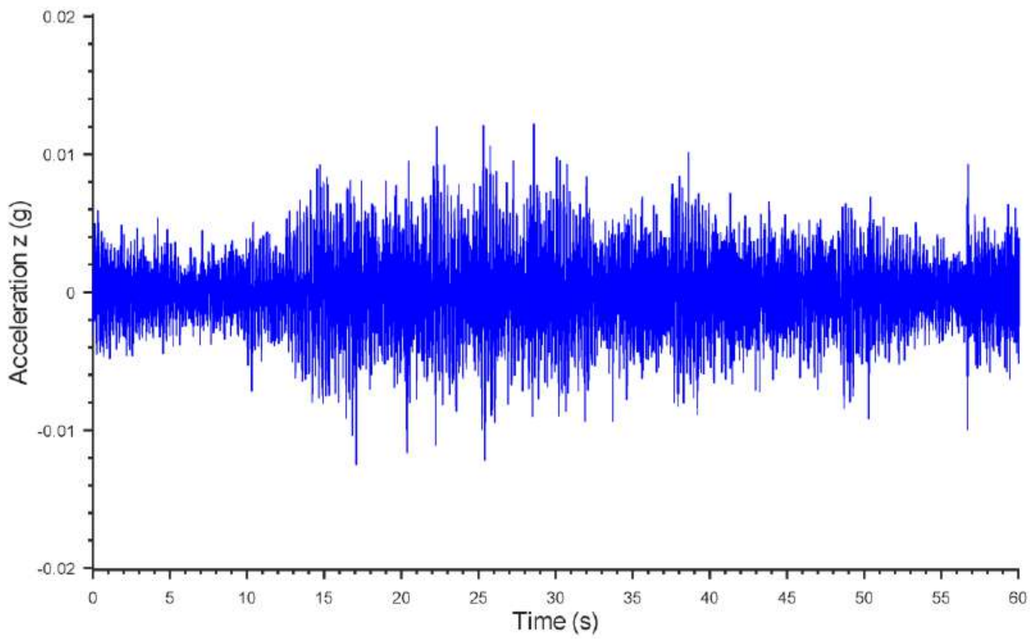

Figure 6-5 General behaviour in the z-direction, Time domain

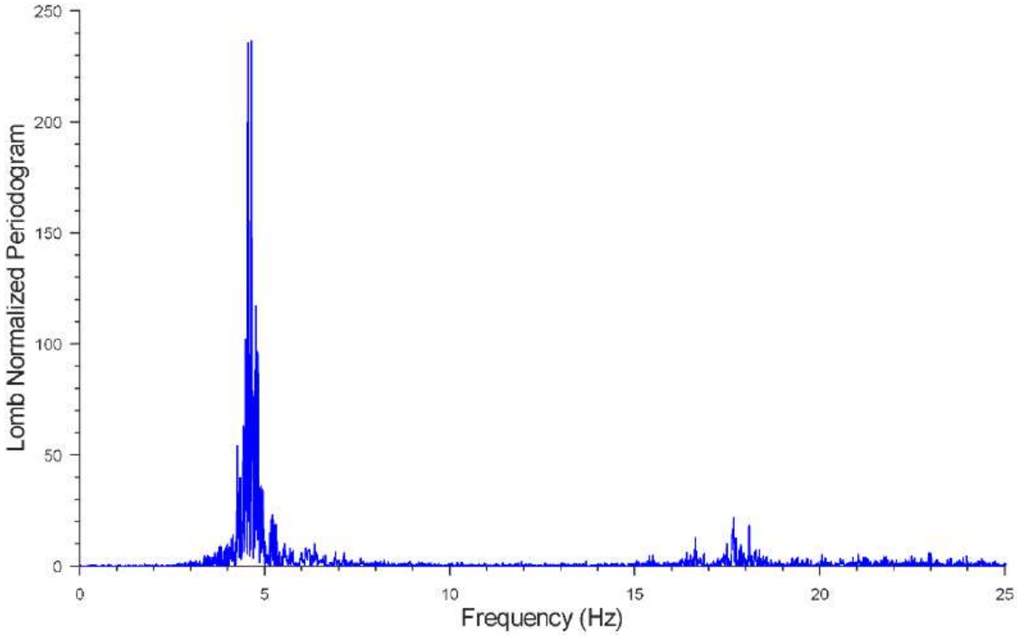

Figure 6-6 General behavior in the z-direction, Frequency domain

6.3 CRITICAL SPAN BEHAVIOR

The middle two spans, span number 7 and 8, exhibited the most critical behavior. Figure 6-7 and Figure 6-8 show the acceleration data in the x direction. It was observed that the acceleration reached up to 5 mgs, and the lower frequencies were much more prominent than the general behavior of spans.

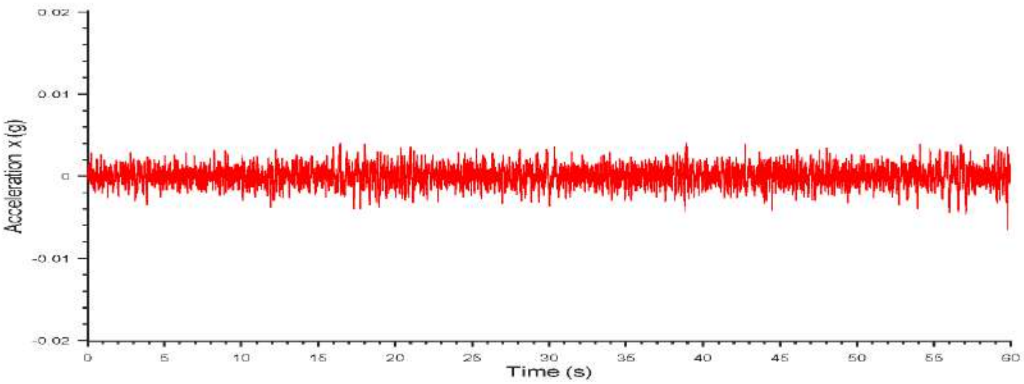

Figure 6-7 Critical span behaviour in the x-direction, Time domain

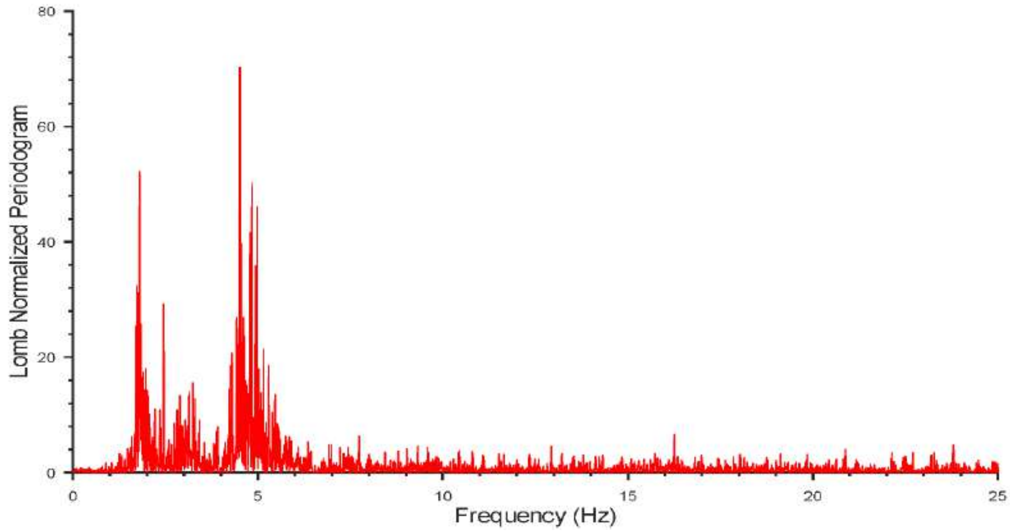

Figure 6-8 Critical span behavior in the x-direction, Frequency domain

Figure 6-9 and figure 6-10 shows that in the y direction, the acceleration reached up to 12 mgs with the most prominent frequency of around 2.5 Hz.

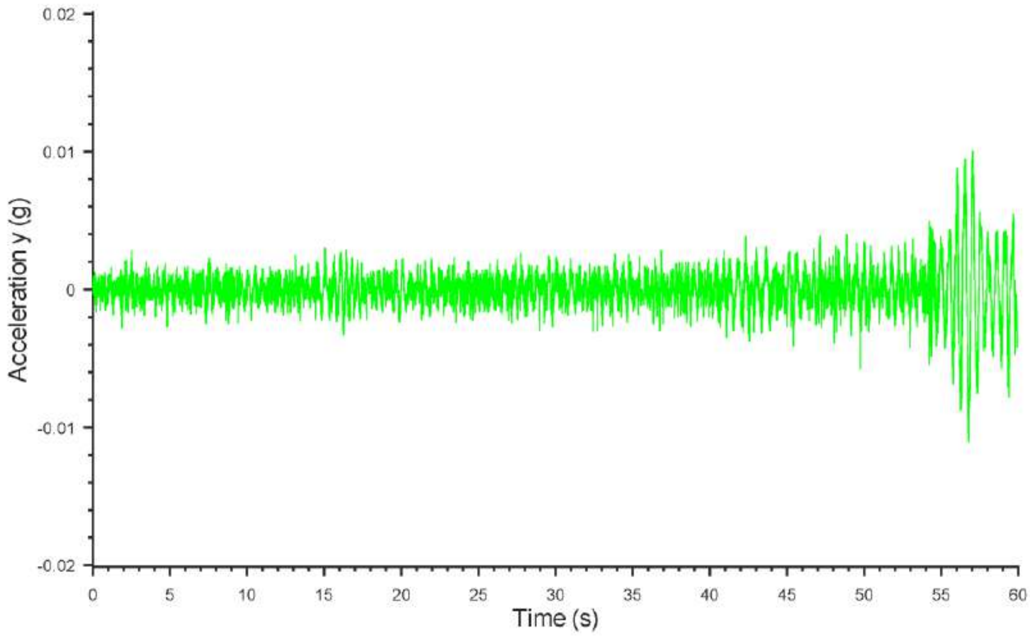

Figure 6-9 Critical span behaviour in the y-direction, Time domain

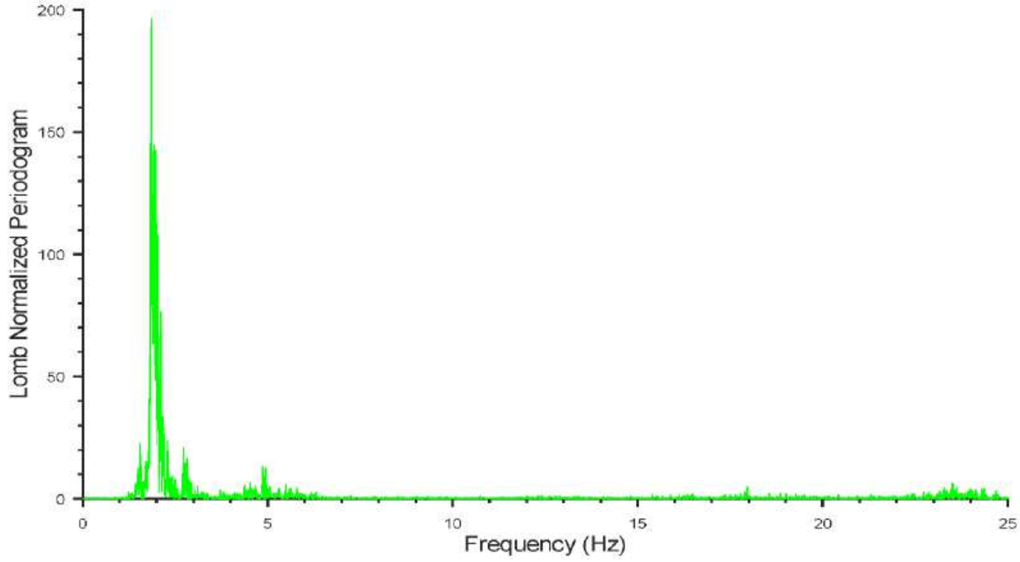

Figure 6-10 Critical span behavior in the y-direction, Frequency domain

In figure 6-11 and figure 6-12 the magnitude of acceleration in the z direction reached up to 50 mgs. The frequencies observed in critical spans were 4.4 Hz. The natural frequencies of most vehicles lie in the range of 1.5 – 4.5 Hz. Thus, resonance can occur in these spans

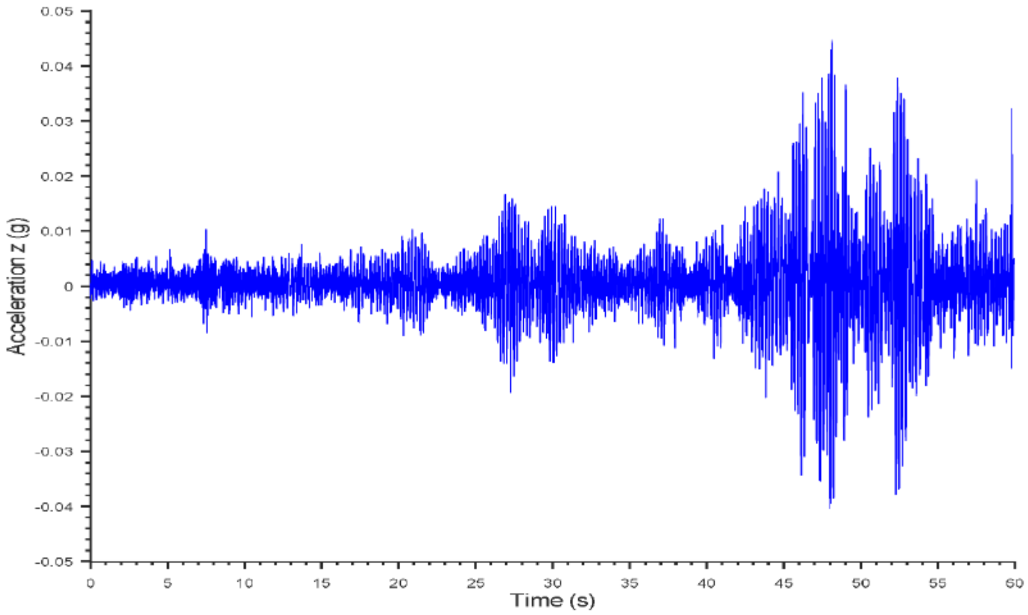

Figure 6-11 Critical span behavior in the z-direction, Time domain

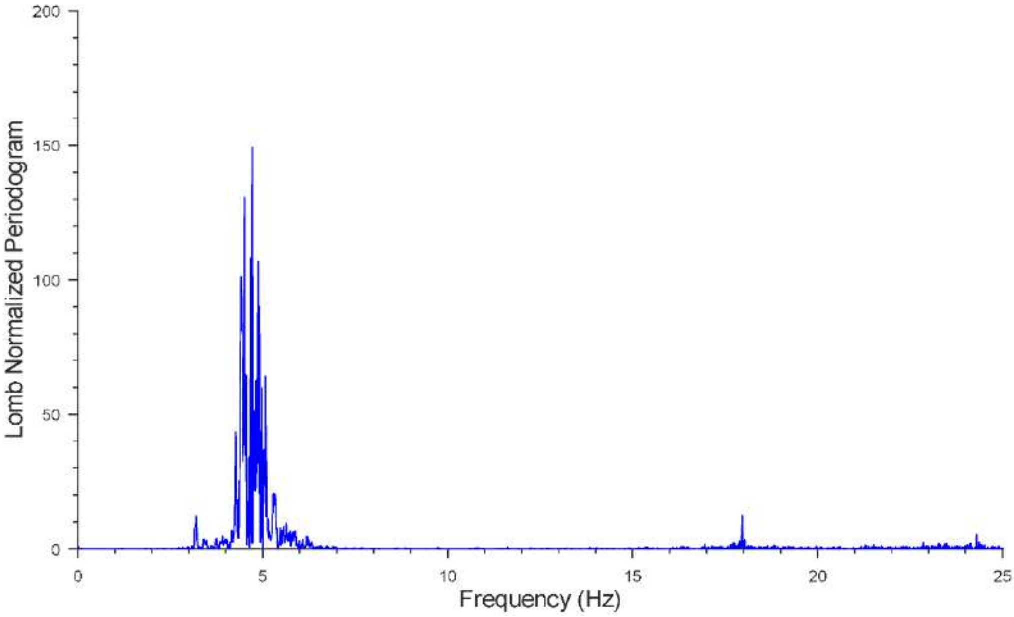

Figure 6-12 Critical span behavior in the z-direction, Frequency domain

6.4 COMPARISON OF MAXIMUM ACCELERATIONS

The maximum accelerations in the general behavior of spans and in critical span for x, y, and z directions are given in Table 6-1. The general behavior of spans showed maximum accelerations within certain ranges. In the x direction, the accelerations did not exceed 3 mgs in general but reached up to 5 mgs in the critical span. In the y direction, accelerations were generally below 5 mgs, but increased up to 12 mgs in the critical span. The z-direction exhibited the most prominent accelerations overall, staying below 20 mgs in general behavior but reaching up to 50 mgs in the critical span.

Table 6-1 Comparison of Maximum Acceleration

Direction	**Maximum Acceleration (mgs)**	
	General Behaviour	**Critical Span Behaviour**
x	3	5
y	5	12
z	20	50

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

Structural Health Monitoring (SHM) plays a crucial role in ensuring the integrity and safety of bridges. SHM refers to the process of continuously monitoring and assessing the structural condition of bridges to detect any potential defects or damages that may compromise their performance. This monitoring is essential as bridges are subjected to various environmental and operational loads throughout their lifespan, which can lead to structural deterioration and, in extreme cases, catastrophic failure. Therefore, performing SHM on bridges is vital to identify and address any emerging issues promptly, enabling timely maintenance and repair actions to be taken.

Mobile devices with built-in accelerometers have emerged as a potential tool for conducting Structural Health Monitoring (SHM). The accelerometers in these devices can measure the accelerations experienced by the structure. The advantage of utilizing mobile accelerometers is their widespread availability and low cost, making them a practical option for bridge monitoring. By leveraging the computing power and connectivity of mobile devices, engineers can collect acceleration data from multiple locations, allowing for a broader assessment of the bridge's health.

The vibration data collected by using mobile devices was analyzed using octave programs. The detailed analysis results of all spans can be found in Appendix A. Based on these results it was found that the middle two spans, span number 7 and 8, exhibited the most critical behavior. These spans rest on the middle piers that are connected by the masonry wall. It was found that these spans have also started exhibiting lateral vibrations of up to 12 mgs, which can lead to the sliding of the deck slabs.

In the critical span, the natural frequency observed was 4.4 Hz, whereas generally, it was more than 4.6 Hz in other spans. The natural frequencies of most vehicles lie in the range of 1.5 – 4.5 Hz. Thus, resonance can occur in critical spans. If (due to lack of previous data), it is assumed that all spans had the same natural frequency, then this decrease in frequency will indicate loss of stiffness, and immediate strengthening is required.

7.2 RECOMMENDATIONS

Based on the findings and conclusions drawn from the study on Structural Health Monitoring (SHM) of bridges, the following recommendations are proposed:

- Structural Health Monitoring should be made a vital part of the operation and maintenance of a structure. It is because even if some structures are passing in visual inspection, their acceleration analysis can reveal some critical behavior.
- Accelerometers in mobile devices are a viable and cost-effective tool for the measurement of acceleration data for the structural health monitoring of bridges. These are widely available, have long battery life, and have user-friendly software. In developing countries, such as Pakistan, mobile devices can pave the way to SHM without the procurement of expensive and heavy-duty vibration meters.
- The study should be repeated every year, to assess if the structural health is continuously deteriorating, and if strengthening is required. New data should be compared with this one and if a further decrease in natural frequency is observed, then immediate strengthening of the bridge should be done.

REFERENCES

[1]. A. S., J. D., X. W., & ShogoMatsunaga. (2020). Smartphone-Based Bridge Seismic Monitoring System and Long-Term Field Application Tests. *Journal of Structural Engineering*.

[2]. Botao Xie, Jinke Li, & Xuefeng Zhao. (2019). Research on Damage Detection of a 3D Steel Frame Model Frame Using Smartphones. *Sensors*.

[3]. Eoi Figueiredo, Ionut Moldovan, Pedo Alves, Hugo Rebelo, & Laura Souza. (2022). Smartphone Application for Structural Health Monitoring of Bridges. *Sensors*.

[4]. Feng M. Q., Fukuda Y., Mizuta M., & Ozer Ekin. (2015). Citizen Sensors for SHM: Use of Accelerometer Data from Smartphones. *Sensors*, 2980-2998.

[5]. Feng M., Fukuda Y., Mizuta M., & Ozer E. (2015). Citizen Sensors for SHM: Use of Accelerometer Data from Smartphones. *Sensors*.

[6]. Franciso Vega, & Wen Yu. (2022). Smartphone based structural health monitoring using deep neural networks. *Sensors and Actuators:A. physical*, 346.

[7]. Kong Q., Allen R.M., Kholer M. D., Heaton T. H., & Bunn J. (2018). Structural Health Monitoring of Building Using Smartphones. *Seismological Research Letter*, 594-602.

[8]. Li J., Xie B., & Zhao X. (2020). Measuring the Interstorey Drift of Buildings by a Smartphone using a Feature Point Matching Algorithm. *Structural Control Health Monitoring*.

[9]. Matarazzo T. J., Santi P., Pakzad S.N., Carter K., Ratti C., Moaveni B., . . . Jacob N. (2018). Crowdsensing Framework for Monitoring Bridge Vibrations Using Moving Smartphones. *IEEE Xplore*, 577-593.

[10]. Mousavi, A., Zhang, C., Masri, S., & Gholipour. (2021). Damage detection and characterization of a scaled model steel truss bridge using combined complete ensemble empirical mode decomposition with adoptive noise and multiple signal classification approach. *Sage journals*.

[11]. Nurul Shazwin Idris, K. H. (2015). A Review of Ambient Vibration Techniques on Bridges. *Applied Mechanics and Materials*, 1002-1006.

[12]. Ozer, E., Maria Feng, Yoshio Fakudo, & Masato Mizuta. (2015). Citizen Sensors for SHM: Use of Accelrometer Data from Smartphones. *MDPI*.

[13]. Peter, C. (2018). Structural Health Monitoring: Closing the gap between research and industrial deployment. *Sage Journals*, 1125-1244.

[14]. Piervincenzo Rizzo, & Alireza Enshaeian. (2021). Challenges in Bridge Health Monitoring: A review. *Sensors*.

[15]. Rytter, A. (1993). Vibration Based Inspection of Civil Engineering Structures. *Journal of Sound and Vibrations*.

[16]. Xu, G., L., Gao, & X. (2014). Some key issues and challenges of building the structural health monitoring systems of bridges. *scientific.Net*, 91-98.

[17]. Xuefeng Zhoa, Kwang Ri, Ruicong Han, Yan Yu, Mingchu Li, & Jinping Ou. (2016). Experimental Research on Quick Structural Health Monitoring Techniques for Bridges Using Smartphone. *Hindawi*.

[18]. Zhao X., Han R., Ding Y., Yu Y., Gaun Q., Hu W., . . . Ou J. (2015). Portable and Convient cable force measurement using smartphone. *Civ. Structural Health Monitoring*, 481-491.

[19]. Zhoa X., Yu Y., Li M, & Ou J. (2015). Cloud-Structural health Monitoring Based on Smartphone; Procedding of the International Confrence on Vibroengineering. *JVE International*, (pp. 26-28). Nanjing.

APPENDICES

APPENDIX A: ANALYSIS RESULTS

The acceleration data recorded on different spans in x, y, and z directions are plotted in time domain and the transformation results of the data in frequency domain are also plotted.

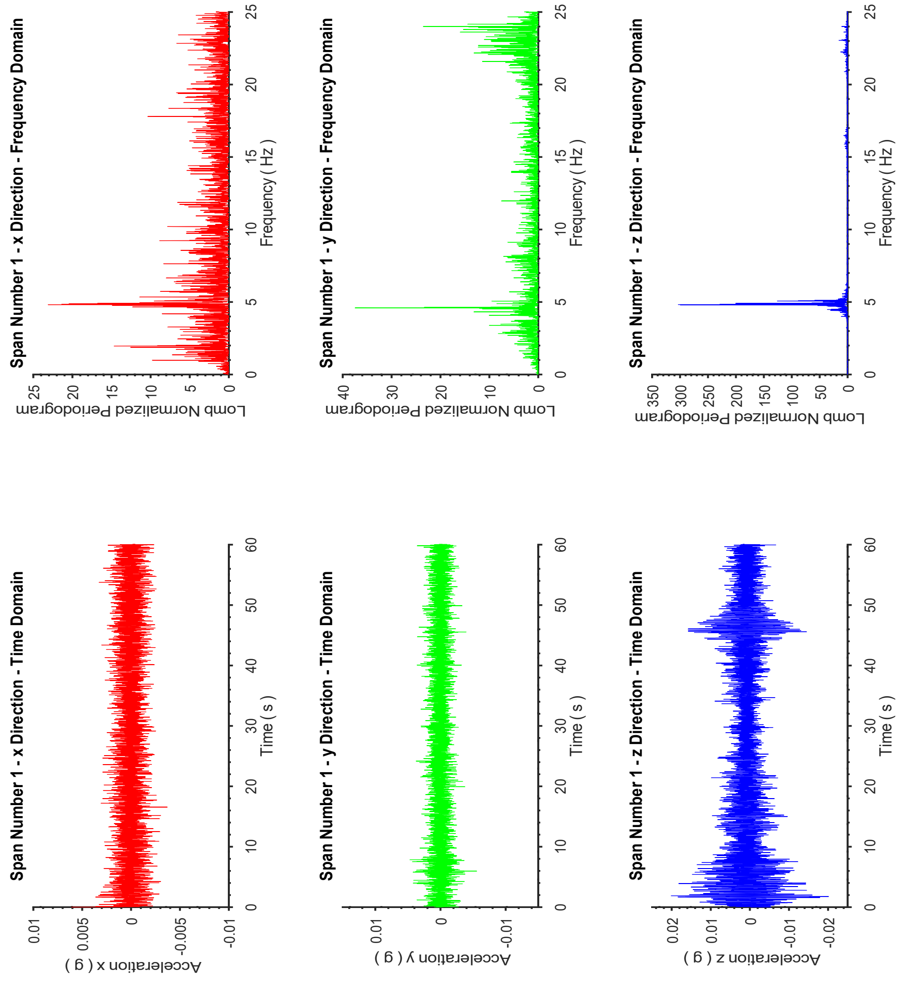

Figure A-1 Results of Span Number 1

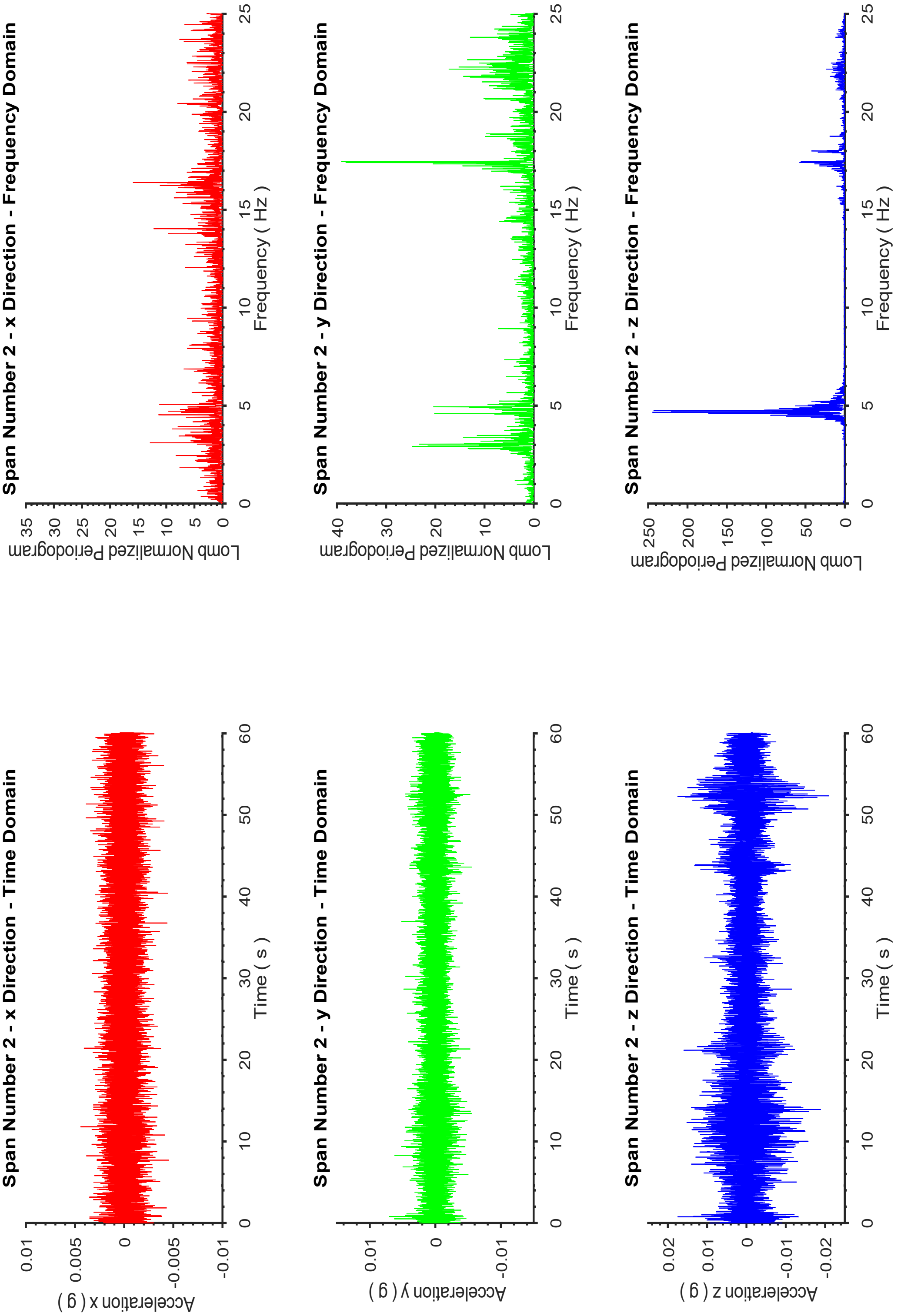

Figure A-2 Results of Span Number 2

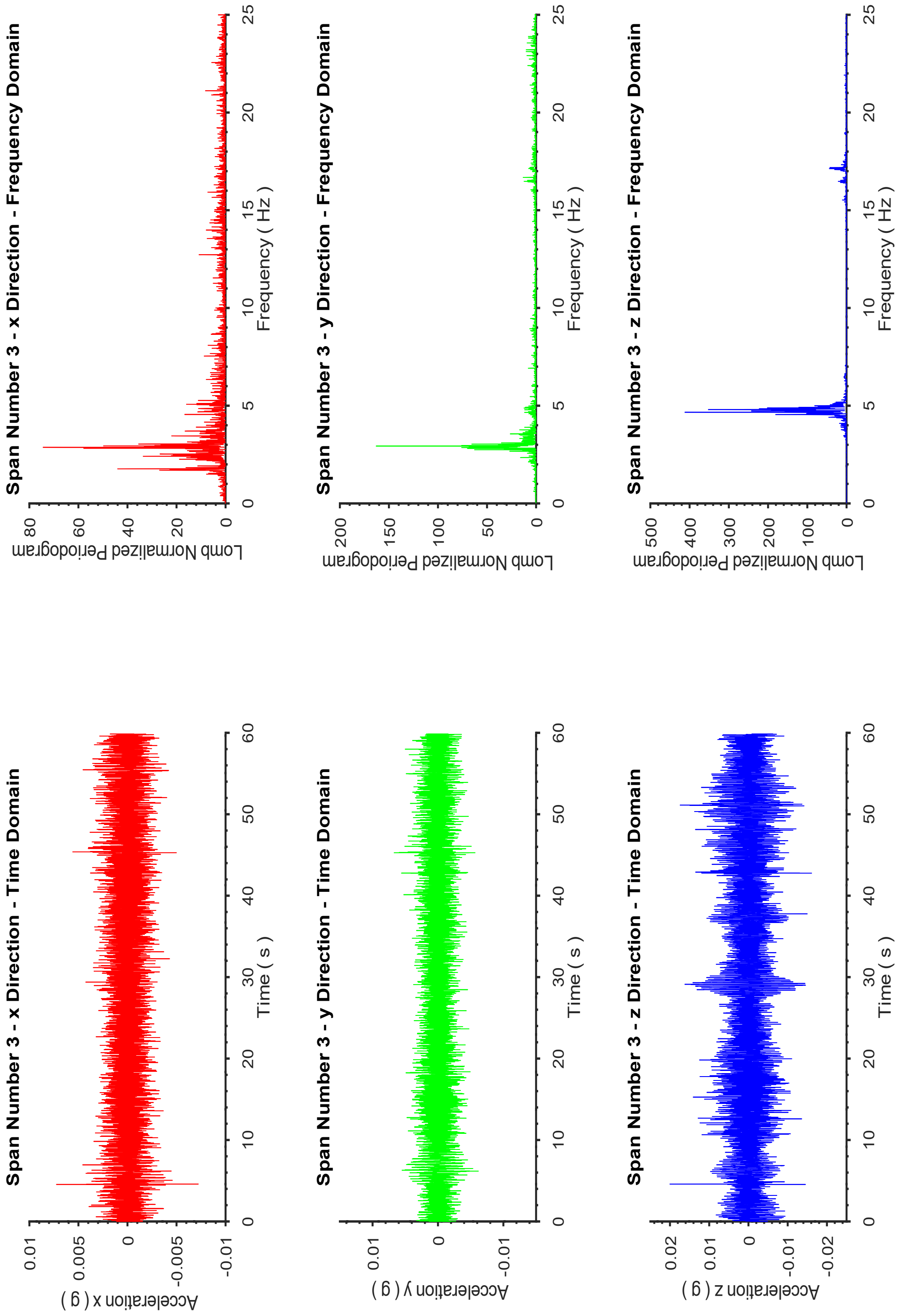

Figure A-3 Results of Span Number 3

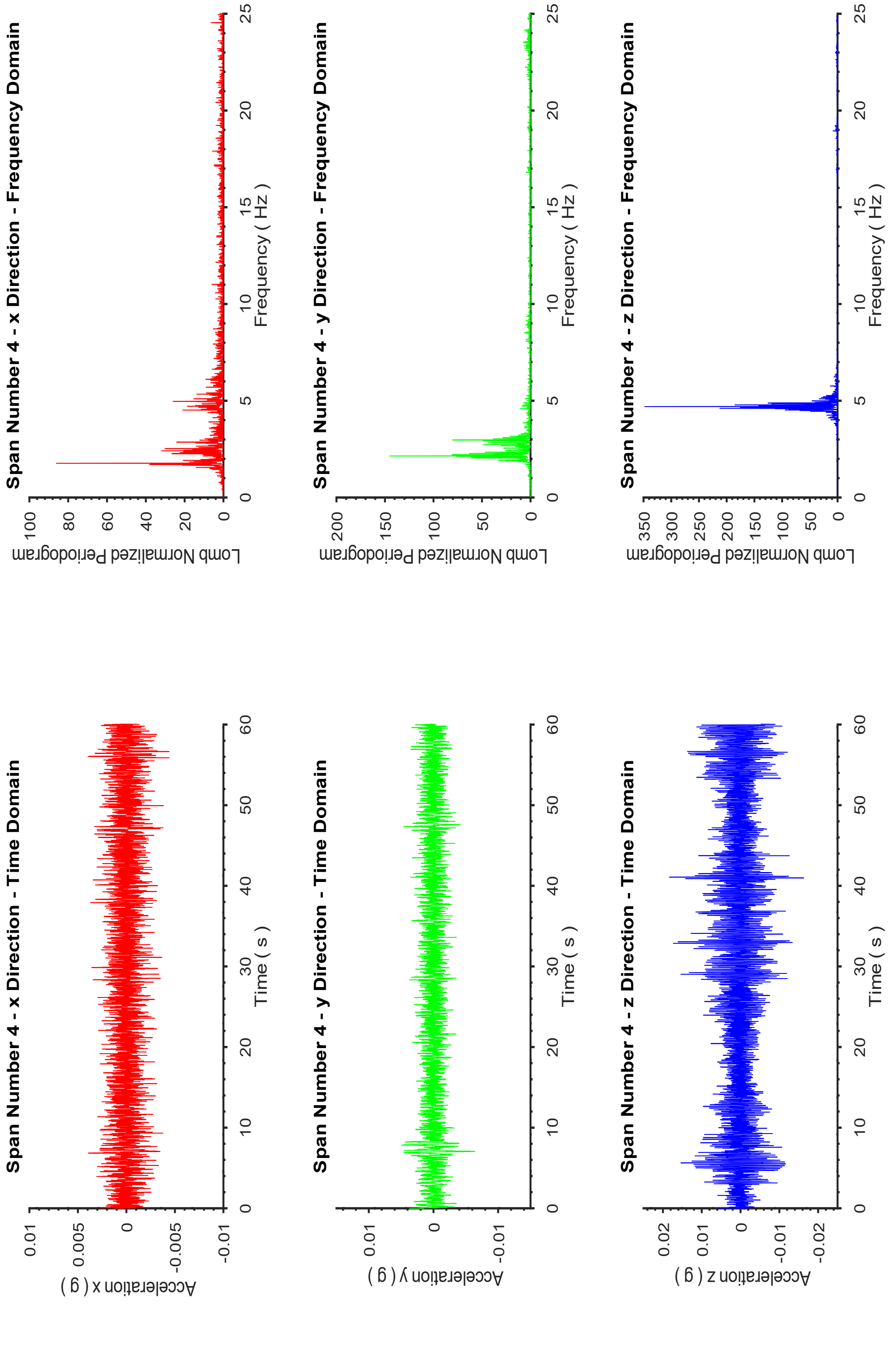

Figure A-4 Results of Span Number 4

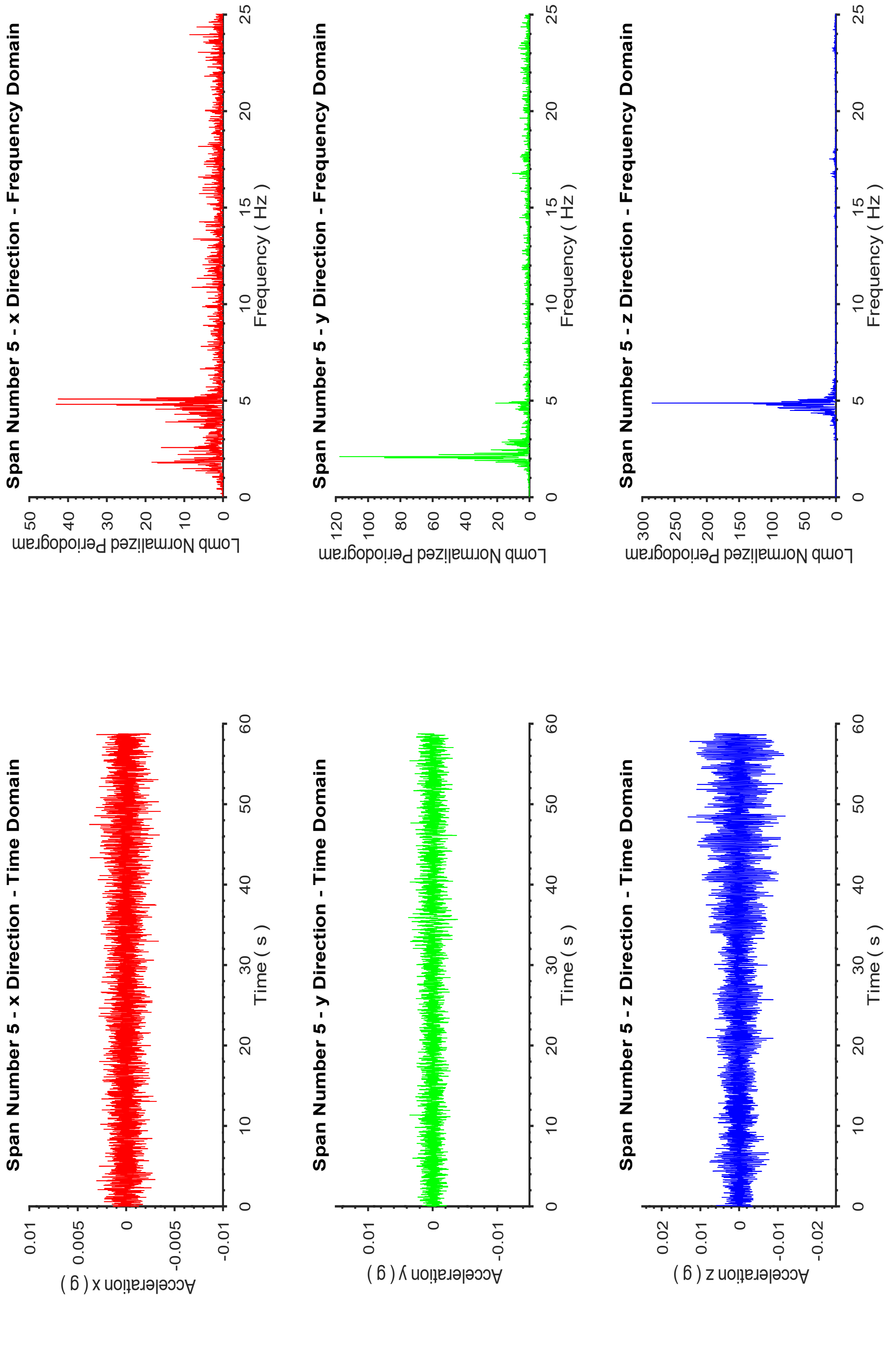

Figure A-5 Results of Span Number 5

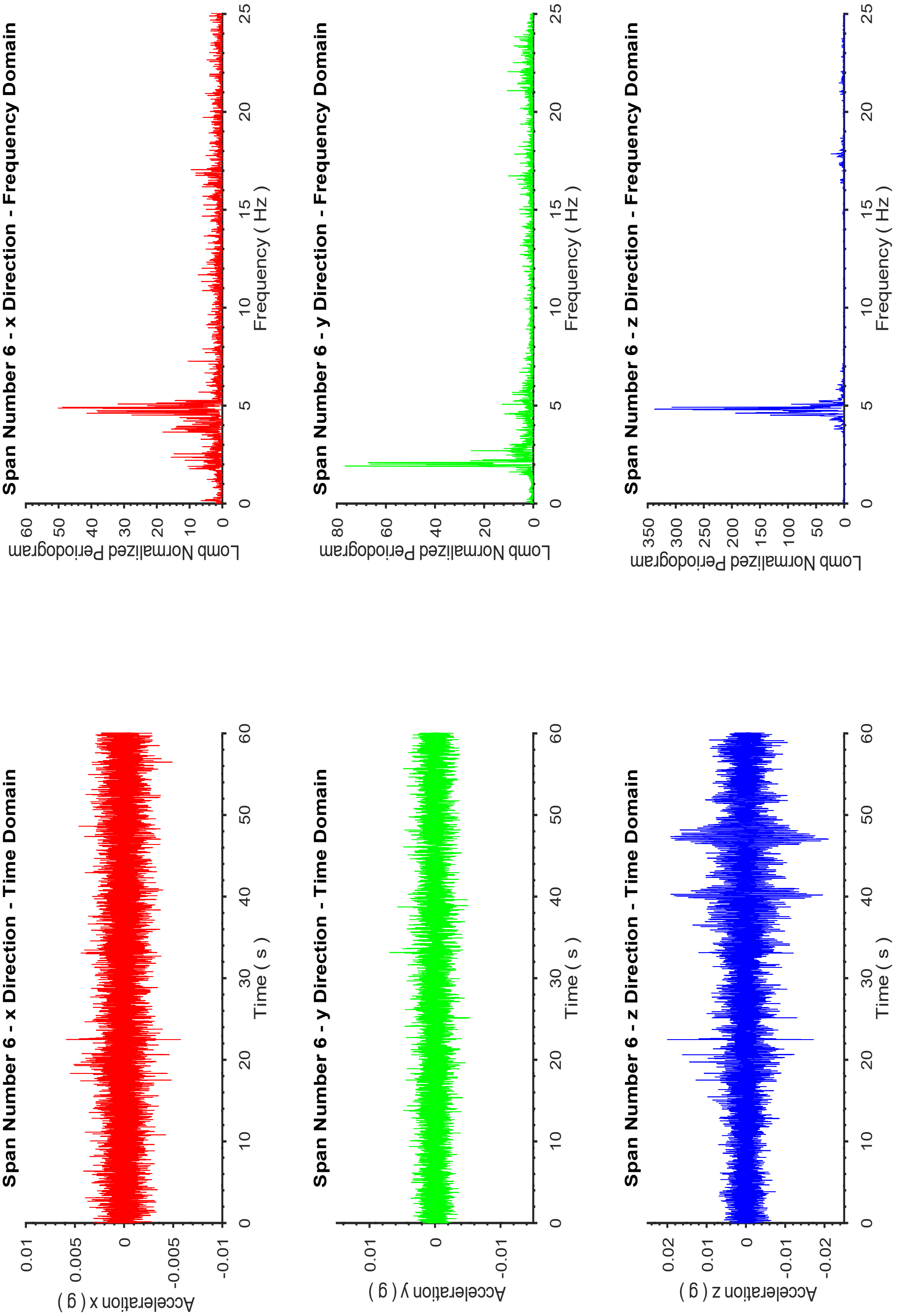

Figure A-6 Results of Span Number 6

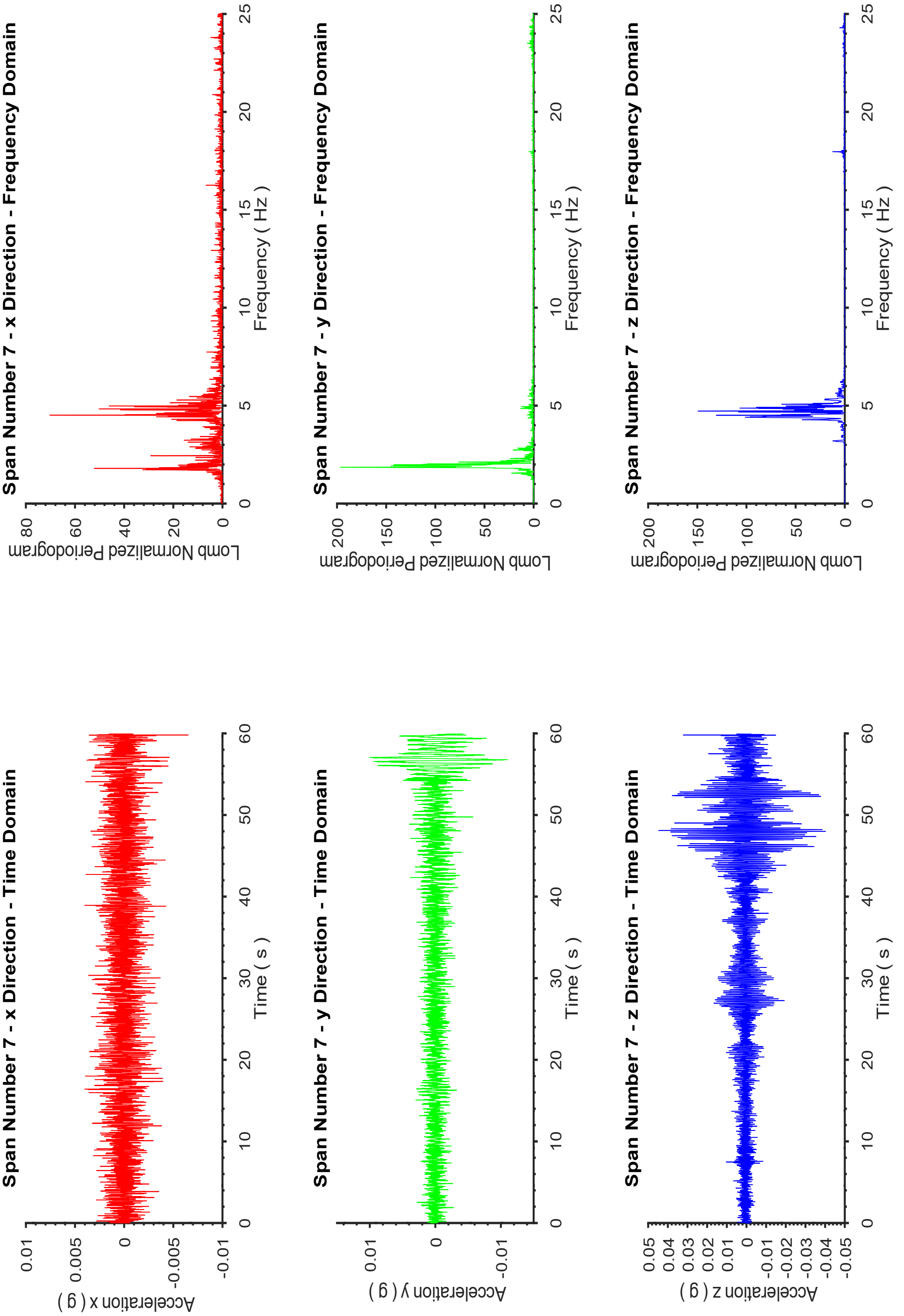

Figure A-7 Results of Span Number 7

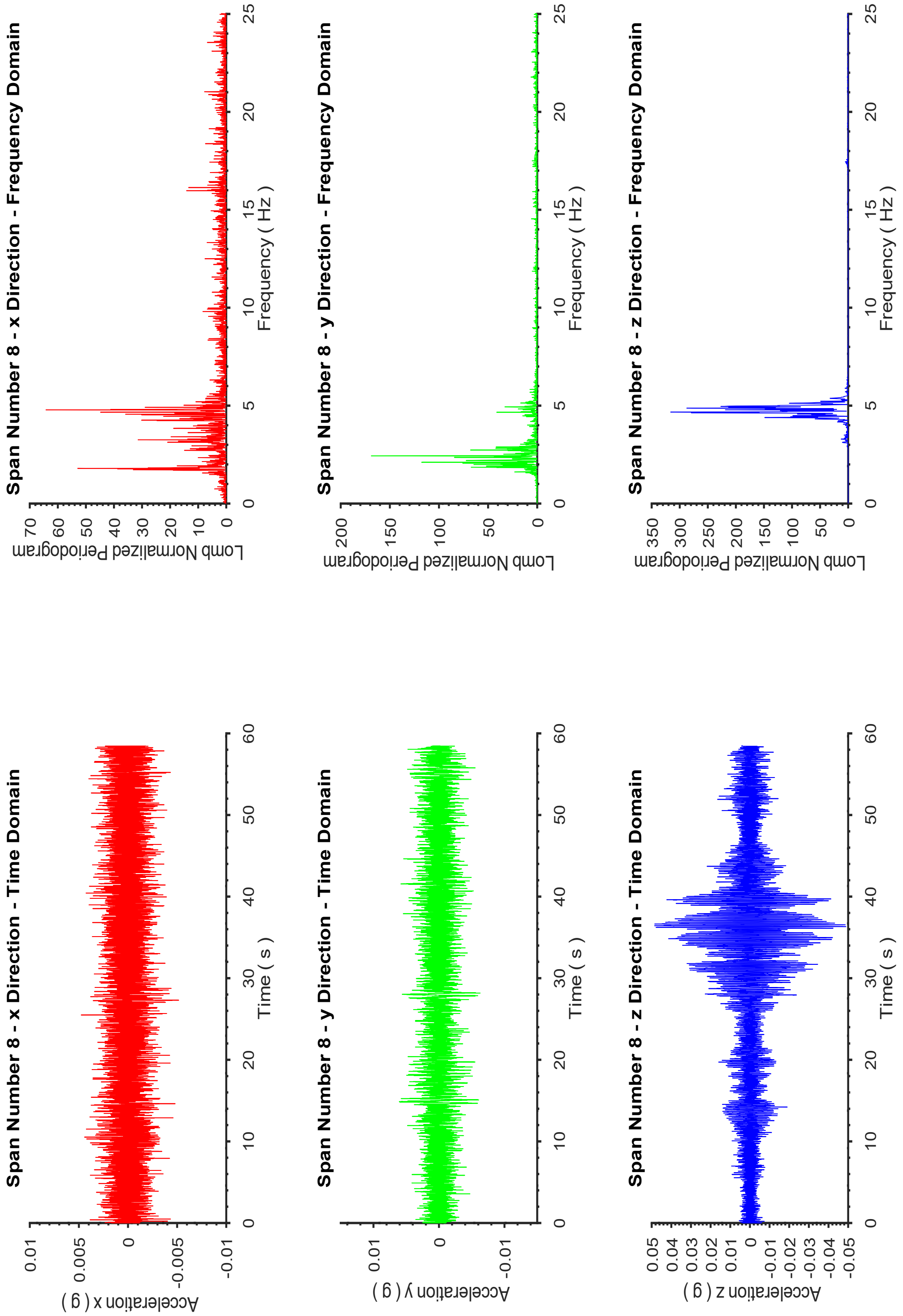

Figure A-8 Results of Span Number 8

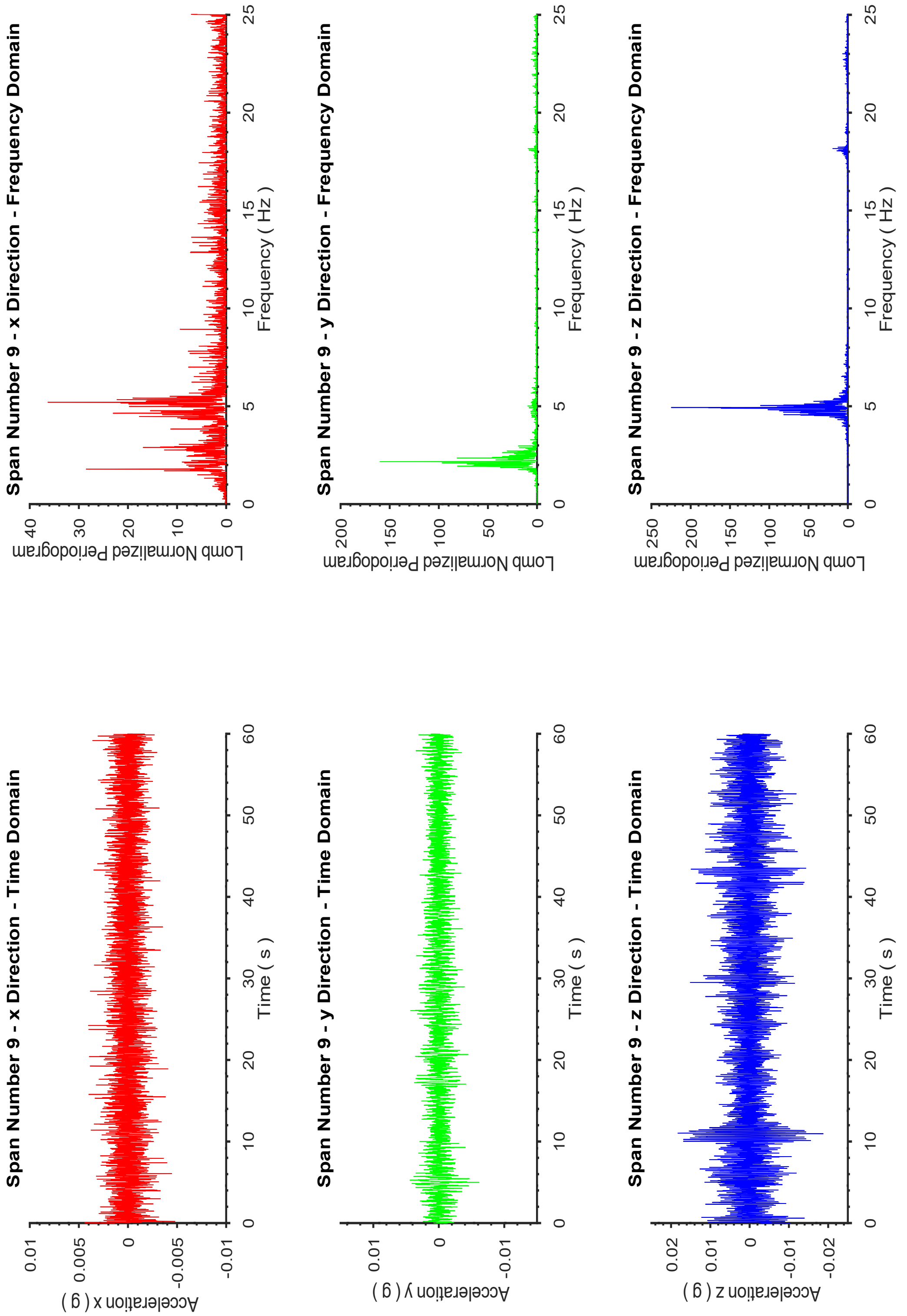

Figure A-9 Results of Span Number 9

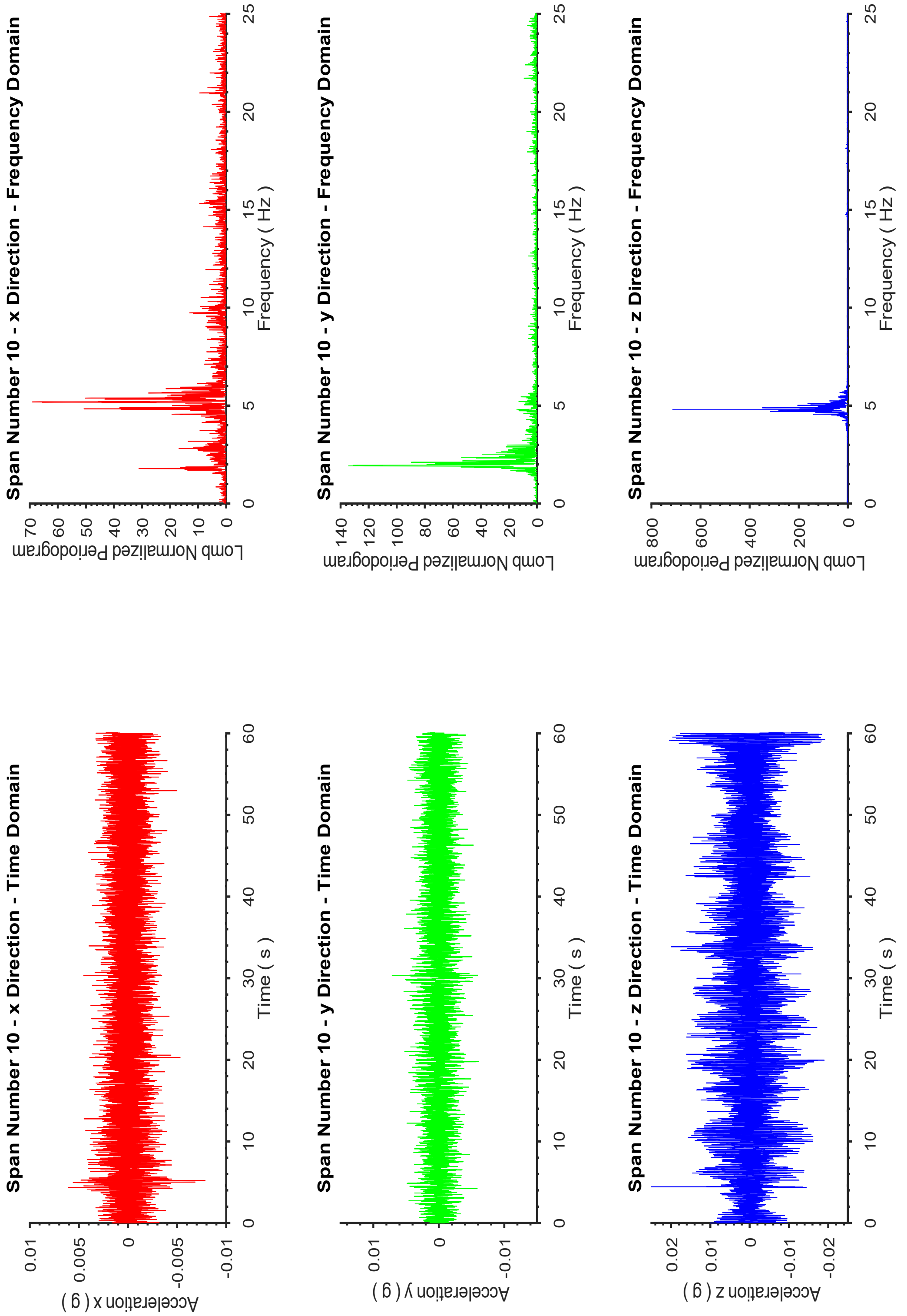

Figure A-10 Results of Span Number 10

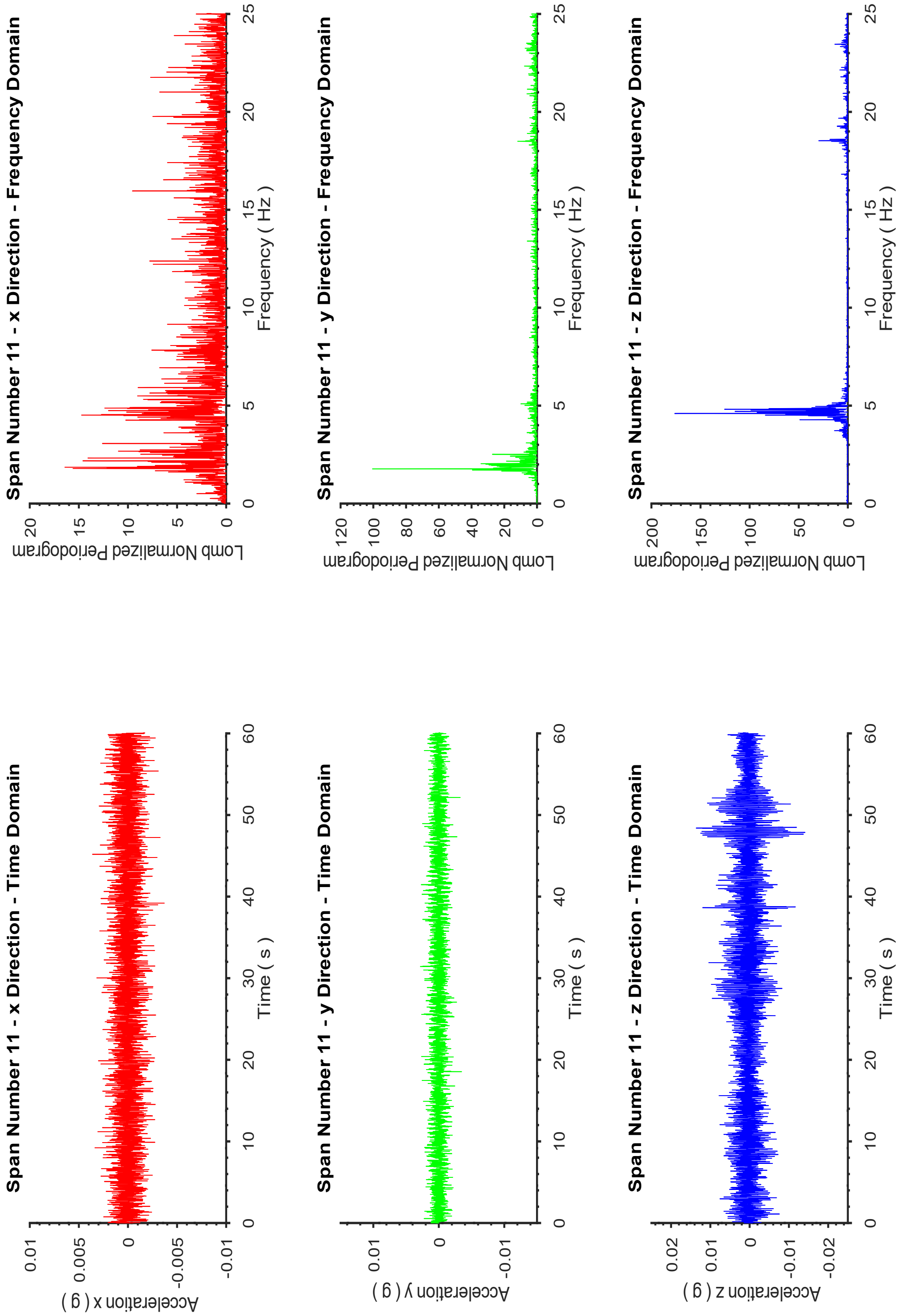

Figure A-11 Results of Span Number 11

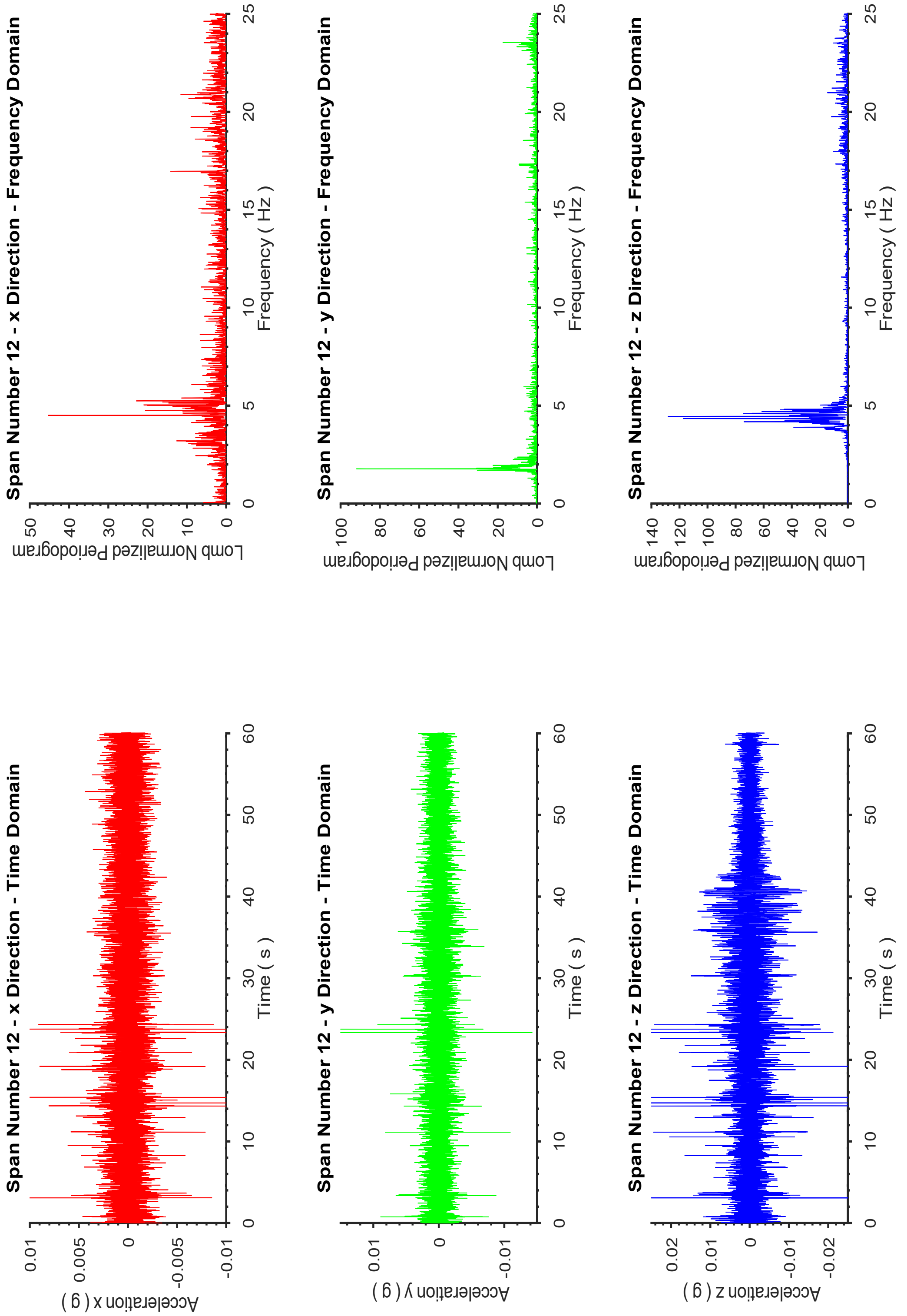

Figure A-12 Results of Span Number 12

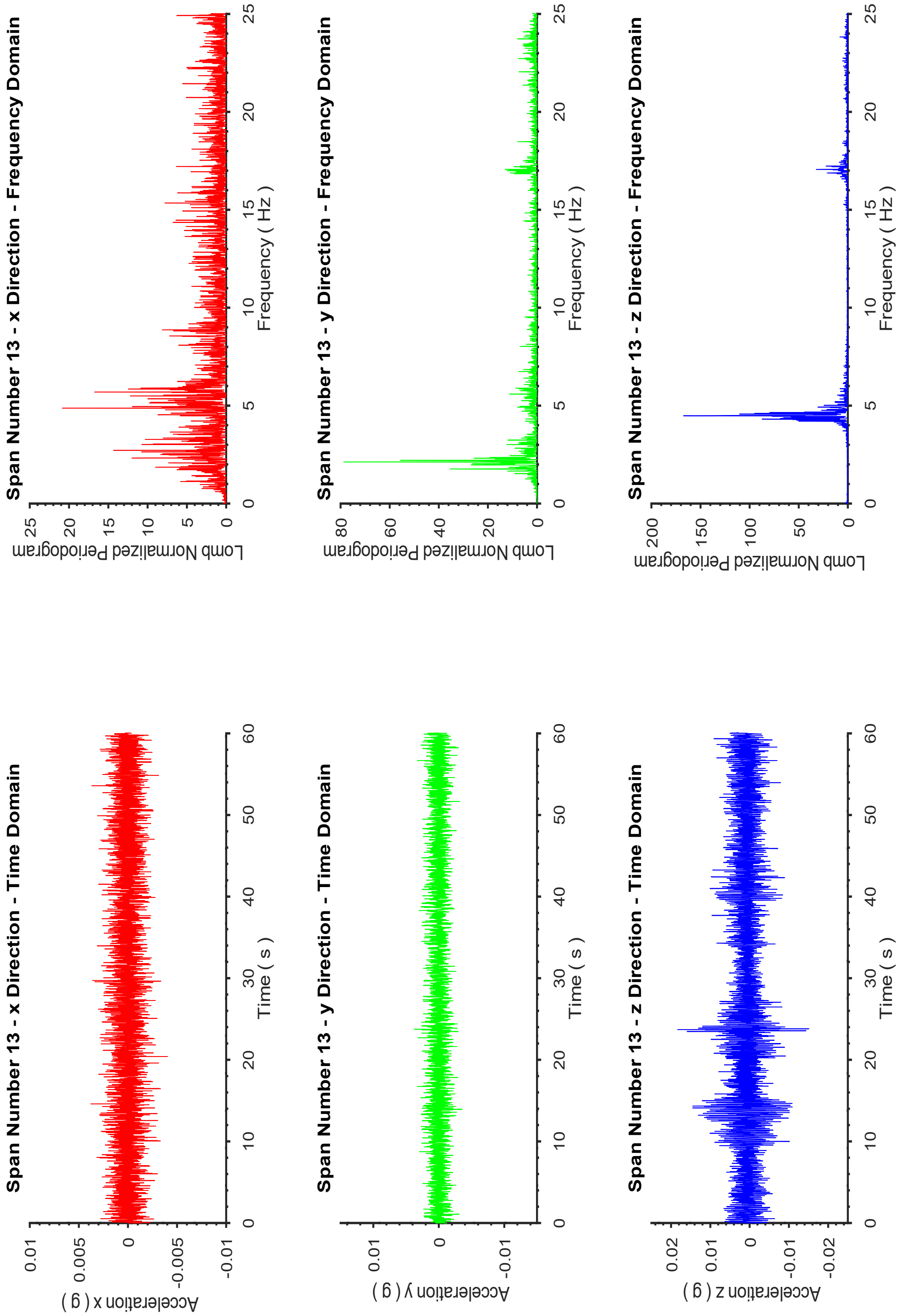

Figure A-13 Results of Span Number 13

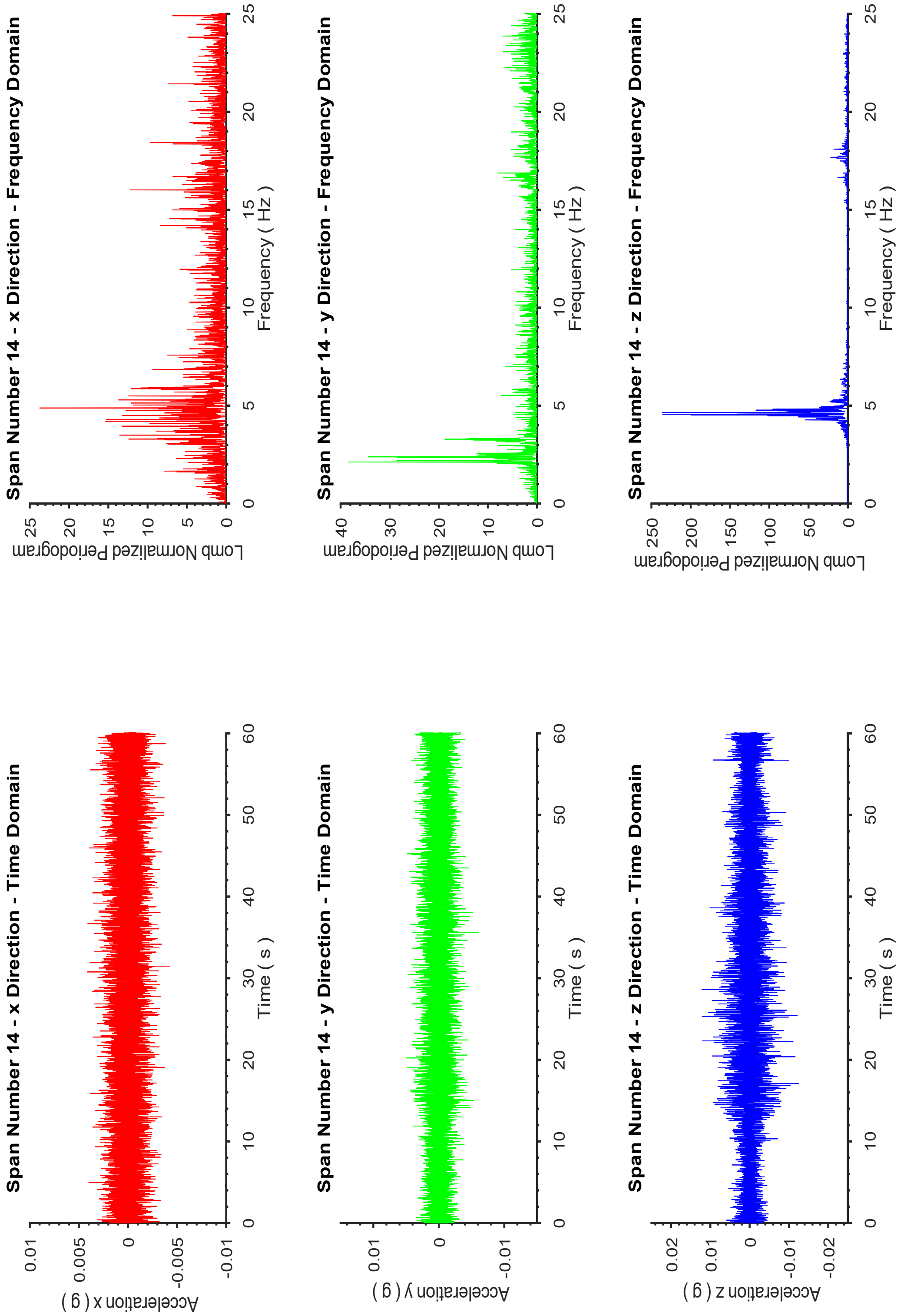

Figure A-14 Results of Span Number 14

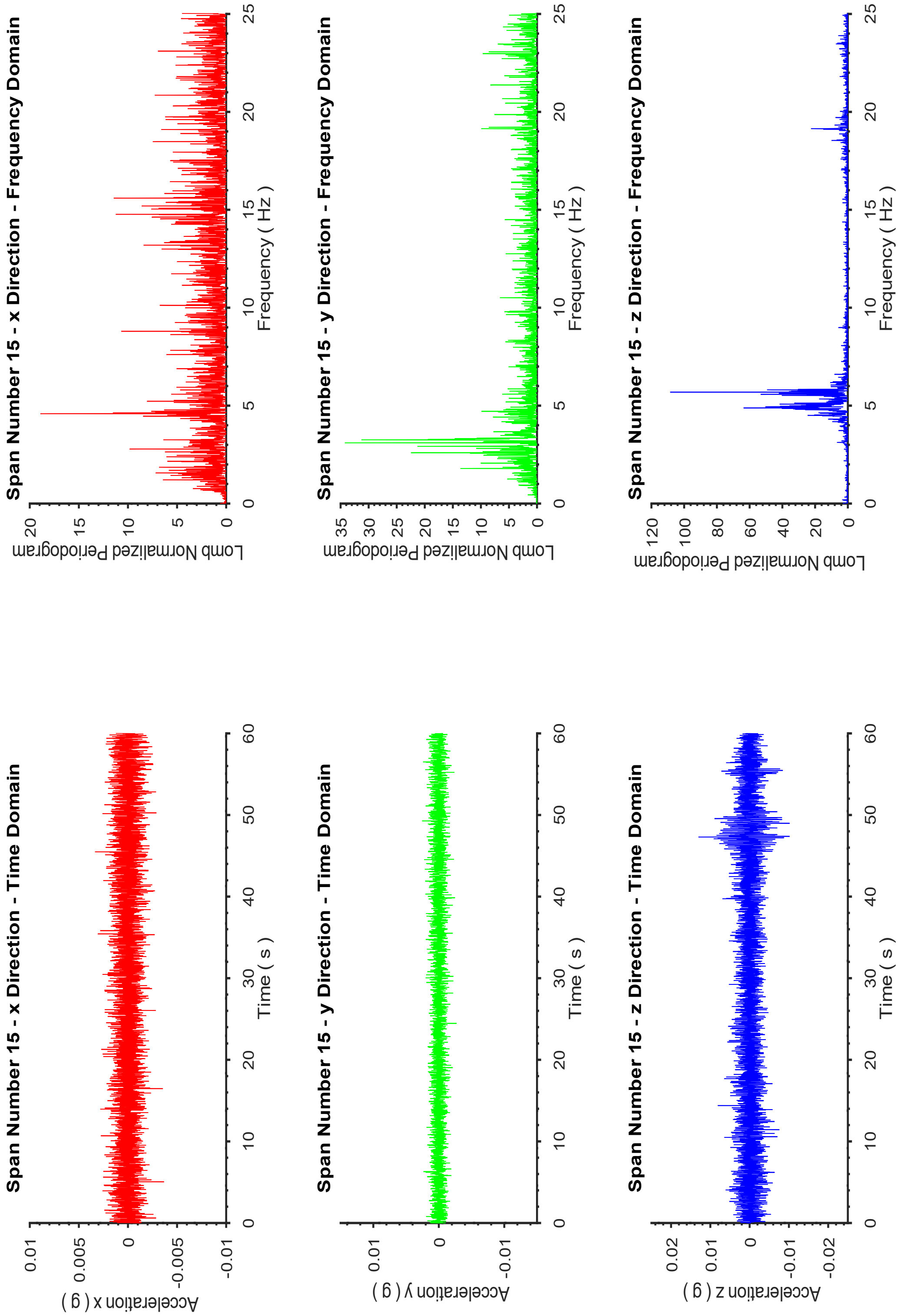

Figure A-15 Results of Span Number

SIMILARITY INDEX UNDERTAKING

We solemnly declare that project work presented in the thesis titled "A STUDY OF STRUCTURAL HEALTH MONITORING OF BRIDGES" is solely our project work with no significant contribution from any other person. Small contribution/help wherever taken has been duly acknowledged and that complete thesis has been written by us.

We understand the zero-tolerance policy of the HEC and University of Engineering and Technology Lahore towards plagiarism. Therefore, we as authors of the above titled thesis declare that no portion of our thesis has been plagiarized and any material used as reference is properly referred/cited. Also, the similarity index of above title thesis is less than 19%.

Student /Author Signatures:

1. Name: Nouman Mustafa Signatures: ___________________

2. Name: M. Haider Imran Signatures: ___________________

3. Name: Hasham Ahmed Khan Signatures: ___________________

4. Name: Rehman Awan Signatures: ___________________

Project Supervisor Signature:

Name Prof. Dr. Asad Ullah Qazi Signatures: ___________________