# CONDITION ASSESSMENT OF BRIDGES

Session: 2019

PROJECT ADVISOR
DR. MUHAMMAD MAZHAR SALEEM
INDUSTRIAL ADVISOR: ENGR. FAROOQ NOVEED

SUBMITTED BY

| | |
|---|---|
| MUNEEB ASHRAF | 2019-Civ-68 |
| ATZAL UL REHMAN | 2019-Civ-72 |
| MUHAMMAD HAMZA | 2019-Civ-75 |
| YAHYA ZAFAR | 2019-Civ-81 |

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

# CONDITION ASSESSMENT OF BRIDGES

Session: 2019

GROUP MEMBERS

| | |
|---|---|
| MUNEEB ASHRAF | 2019-Civ-68 |
| ATZAL UL REHMAN | 2019-Civ-72 |
| MUHAMMAD HAMZA | 2019-Civ-75 |
| YAHYA ZAFAR | 2019-Civ-81 |

| INTERNAL EXAMINER | EXTERNAL EXAMINER |
|---|---|
| (DR. M MAZHAR SALEEM) | (DR. ALI MURTAZA RASOOL) |

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

**DEPARTMENT OF CIVIL ENGINEERING**

**UNIVERSITY OF ENGINEERING AND TECHNOLOGY**

**LAHORE, PAKISTAN**

# ACKNOWLEDGEMENTS

All praise and gratitude are due to ALLAH, the Lord of the universe. It is through His blessings and guidance that the authors have successfully completed this project. The authors are grateful to their project advisor, ***Dr. Muhammad Mazhar Saleem***, whose invaluable guidance and support were instrumental in undertaking and completing this work. His extensive knowledge and unwavering encouragement have been a constant source of inspiration for the authors.

The authors are deeply honored to extend their heartfelt thanks to ***Prof. Dr. Asad Ullah Qazi*** for his exceptional mentorship and invaluable assistance, which played a pivotal role in the successful completion of this project.

Special acknowledgement is extended to ***Mr. Syed Waqar*** for providing the E-Quake Arm Triaxial seismic accelerometer. His generous support and assistance have significantly contributed to the professional development and refinement of this project.

The authors would also like to express their gratitude to all the individuals who provided their time, expertise, and support during this project. Their contributions, both large and small, are deeply appreciated.

This project is a part of **HEC NRPU Project No. 15466** titled "Structural Health Monitoring of Critical Bridge Infrastructure: A sustainable, cost-effective and Multidisciplinary Approach". The authors acknowledge the Higher Education Commission of Pakistan for supporting this research endeavor.

Finally, the authors extend their sincere thanks to their families and friends for their unwavering support, understanding, and encouragement throughout this journey.

This work would not have been possible without the collective efforts and support of all those mentioned and the countless others who have played a part in shaping the authors' academic and personal development. May ALLAH reward them all with the best in this world and the Hereafter.

# ABSTRACT

This project provides a detailed study of Structural Health Monitoring (SHM) and its application in the condition assessment of bridges, aligning with the sustainable development goal of '***Sustainable Cities and Communities***'. The work covers a comprehensive study of SHM components, the importance of condition assessment, and various methods of monitoring structures. Old Ravi Bridge is considered as a case study in this project. Visual inspection of the bridge was performed and all of its components were evaluated according to FHWA scale. In addition to visual inspection, different types of sensors including mobilephone accelerometer, Extech Heavy Duty Vibration Meter, and E-Quake Arm Triaxial Seismic Accelerometer were deployed to acquire bridge vibration data against traffic loading. Girder vibrations were measured in all three orthogonal directions. The collected data were analyzed to compare bridge spans' behavior and identify any damage. The data showed that a couple of spans are in worse condition than the others exhibiting higher vibration levels. The findings shed light on key factors contributing to the deterioration of the Old Ravi Bridge, such as issues with expansion joints, bearings, and drainage system. These findings form the basis for suggested recommendations aimed at enhancing bridge maintenance practices and improving inspection techniques, maintenance of expansion joints, adoption of advanced monitoring technologies, and the establishment of integrated bridge management systems. Overall, this research project contributes to the field of SHM and provides valuable insights into the sustainable management of bridges, supporting the goal of sustainable infrastructure development.

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

## CHAPTER NO. 1

# 1. INTRODUCTION

## 1.1 STRUCTURAL HEALTH MONITORING:

Structural Health Monitoring (SHM) is the practice of consistently or periodically observing the state of a structure, like a bridge, in order to evaluate its well-being, detect any damage or decay, and guarantee its structural soundness. SHM systems employ an array of sensors, data collection systems, and analysis methods to gather and interpret information about the structure's behavior and performance over time. The process involves several steps:

### 1.1.1 Sensor Selection:

The initial stage of SHM involves choosing suitable sensors to monitor the bridge's behavior. Commonly used sensors include strain gauges, accelerometers, displacement transducers, and temperature sensors. These sensors are placed strategically at critical points on the bridge, such as structural components, joints, and supports.

### 1.1.2 Data Acquisition:

The sensors continuously or periodically collect data concerning the bridge's performance. Data acquisition systems convert the analog signals from the sensors into digital data, which can then be stored and analyzed. Wireless or wired communication networks transmit the collected data to a central monitoring station.

### 1.1.3 Structural Modeling:

A structural model of the bridge is developed to understand its response under different load conditions. The model incorporates information about the bridge's geometry, material properties, and boundary conditions. Analytical methods or numerical techniques, such as finite element analysis (FEA), simulate the bridge's reaction to external loads.

### 1.1.4 Baseline Monitoring:

The initial assessment of the bridge's condition involves monitoring its behavior under normal operational conditions. This baseline data serves as a reference for future comparisons. It helps identify any initial damage, changes in structural properties, or anomalies in the bridge's behavior.

### 1.1.5 Damage Detection:

Deviations from the baseline data can indicate the presence of damage or deterioration in the bridge. Damage detection algorithms are applied to the collected data to identify patterns or irregularities that may signify structural issues. These algorithms can range from basic statistical methods to advanced machine learning techniques.

### 1.1.6 Data Analysis:

The collected sensor data is analyzed to extract valuable information about the bridge's health. This analysis may involve examining the data in the time or frequency domain, conducting statistical analysis, performing pattern recognition, or conducting correlation studies. The goal is to identify changes in structural behavior, pinpoint potential damage, and assess its severity.

### 1.1.7 Decision-Making and Maintenance:

Based on the analysis results, decisions are made regarding the need for maintenance, repair, or further investigation. If damage is detected, engineers can evaluate its severity, prioritize repair or maintenance activities, and plan appropriate interventions to ensure the bridge's structural integrity.

### 1.1.8 Continuous Monitoring:

SHM is an ongoing process that involves continuous monitoring of the bridge's condition over time. Regular data collection and analysis allow for the early detection of changes in behavior or condition, enabling timely actions to prevent catastrophic failures and optimize maintenance strategies.

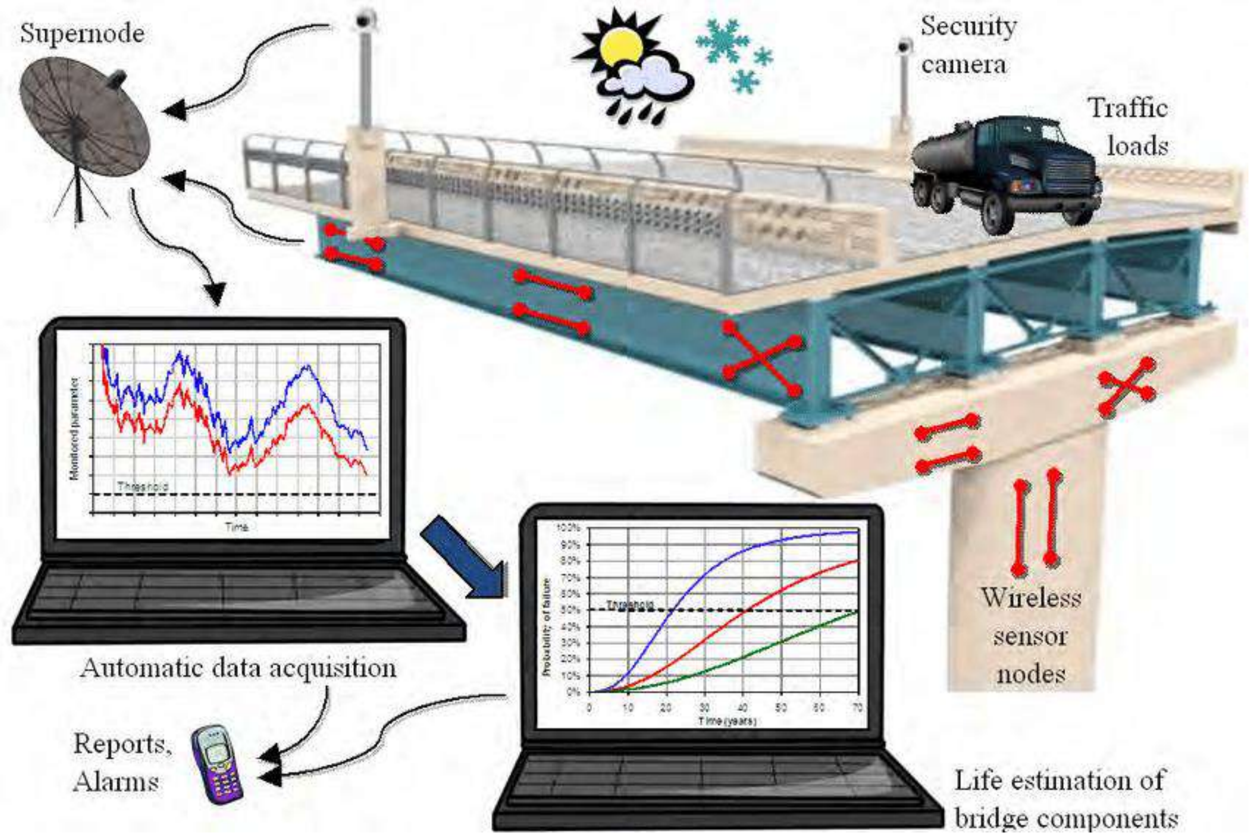


Figure 1.1: Continuous Monitoring

## 1.2 STRUCTURAL HEALTH MONITORING CATEGORIES:

In the field of Structural Health Monitoring (SHM) for bridges, there are several key categories to consider. Here are some common categories of SHM for bridges:

### 1.2.1 Load Monitoring:

#### *1.2.1.1 Monitoring Traffic Loads:*

This involves continuously tracking the dynamic loads exerted by vehicular traffic on the bridge. Load cells or pressure sensors are used to measure the forces or pressures applied to the bridge structure.

#### *1.2.1.2 Environmental Load Monitoring:*

This category focuses on monitoring the impact of environmental factors on the bridge, such as wind, temperature, and moisture. Sensors are utilized to measure parameters like wind speed, temperature variations, and humidity.

### 1.2.2 Structural Response Monitoring:

#### *1.2.2.1 Monitoring Displacement:*

This category involves measuring the movements or deflections of bridge components. Displacement transducers, inclinometers, or accelerometers are commonly used to monitor how the bridge responds to loads and environmental conditions.

#### *1.2.2.2 Strain Monitoring:*

Strain monitoring entails measuring the levels of deformation experienced by critical structural elements. Strain gauges or fiber optic sensors are employed to assess the distribution of stress and deformation within the bridge.

#### *1.2.2.3 Vibration Monitoring:*

Vibration monitoring focuses on evaluating the dynamic behavior of the bridge under different load conditions. Accelerometers or vibration sensors are utilized to measure the bridge's natural frequencies, mode shapes, and responses to external forces.

### 1.2.3 Condition Monitoring:

#### *1.2.3.1 Crack Detection:*

This category involves detecting and monitoring the presence and growth of cracks in bridge components. Visual inspections, acoustic emission monitoring, or non-destructive testing methods such as ultrasonic testing can be used.

#### *1.2.3.2 Corrosion Monitoring:*

Monitoring corrosion is crucial for bridges exposed to corrosive environments. Techniques like electrochemical sensors, corrosion potential measurements, or corrosion rate monitoring can be employed to assess the corrosion levels in bridge elements.

#### *1.2.3.3 Structural Deformation Monitoring:*

This category focuses on monitoring long-term structural deformations or movements that may occur due to factors like settlement, creep, or thermal expansion. Surveying techniques, GPS, or inclinometers can be used to monitor deformations.

### 1.2.4 Data Fusion and Integration:

This involves combining and integrating data from various sensors and monitoring techniques to gain a comprehensive understanding of the bridge's health. Data fusion techniques, such as statistical analysis or machine learning algorithms, can be applied to enhance the accuracy of damage detection and assessment.

### 1.2.5 Risk Assessment and Remaining Life Estimation:

Based on the collected data and analysis results, risk assessment methodologies and structural reliability models can be utilized to estimate the remaining lifespan of the bridge and prioritize maintenance or repair actions.

These categories highlight different aspects of SHM specifically for bridges, providing a framework for monitoring and evaluating their structural health, ensuring safety, and optimizing maintenance practices.

## 1.3 IMPORTANCE OF STRUCTURAL HEALTH MONITORING OF BRIDGES IN PAKISTAN:

Structural Health Monitoring (SHM) plays a crucial role in Pakistan's bridge infrastructure for several reasons:

### 1.3.1 Safety:

SHM continuously monitors the structural integrity of bridges, ensuring their safety. Given Pakistan's extensive bridge network, monitoring their health is essential to prevent accidents, loss of life, and property damage.

### 1.3.2 Aging Infrastructure:

Many bridges in Pakistan are aging and have faced heavy loads, harsh environmental conditions, and insufficient maintenance. SHM enables early detection of issues like corrosion, fatigue, or deterioration, facilitating timely repairs and maintenance to avoid major failures.

### 1.3.3 Seismic Activity:

Being located in a seismically active region, earthquakes pose a significant threat to bridges in Pakistan. SHM systems equipped with seismic sensors provide real-time data on the bridge's response to seismic events, enabling the assessment of seismic vulnerability and appropriate retrofitting measures.

### 1.3.4 Heavy Traffic Loads:

Bridges in Pakistan endure substantial traffic loads, including trucks and buses. Continuous monitoring of the bridge's response to these loads helps evaluate its load-carrying capacity, identify potential overloading, and implement weight restrictions or necessary repairs for sustained structural performance.

### 1.3.5 Extreme Weather Conditions:

Pakistan's diverse climate subjects bridges to extreme weather conditions like high temperatures, heavy rainfall, and floods. SHM allows for monitoring the bridge's structural health under such conditions, detecting issues like thermal expansion, water infiltration, or scour, and facilitating proactive maintenance and timely interventions.

### 1.3.6 Cost-Effective Maintenance:

SHM optimizes maintenance strategies by providing accurate and real-time information about the bridge's health. Instead of relying solely on scheduled inspections or reactive repairs, SHM enables condition-based maintenance, reducing overall maintenance costs through interventions based on the bridge's actual condition and performance.

### 1.3.7 Enhanced Service Life:

Proactive monitoring through SHM helps extend the service life of bridges. Timely detection of damage or deterioration enables prompt repairs or retrofitting, avoiding premature bridge replacements and optimizing their lifespan.

### 1.3.8 Sustainable Infrastructure Management:

SHM promotes sustainable infrastructure management practices by reducing the environmental impact associated with frequent inspections, unnecessary repairs, or premature bridge replacements. It allows for targeted interventions and resource allocation based on the actual condition and needs of the bridges.

## 1.4 CONDITION ASSESSMENT OF BRIDGES:

Condition assessment of bridges involves evaluating the physical state of a bridge structure and estimating its remaining service life. This process includes inspecting, evaluating, documenting, and reporting on the condition of various bridge components. Visual inspections, surveys, and performance tests are typically conducted as part of the assessment. This assessment is crucial for bridge maintenance and management as it helps identify and prioritize repair and rehabilitation needs.

Bridges are essential infrastructure assets that facilitate safe and efficient transportation of people and goods. They also hold cultural significance as landmarks within communities. However, bridges are susceptible to deterioration and damage over time, necessitating regular condition assessments to ensure their continued safety and reliability.

Various organizations provide definitions for condition assessment:

**American Society of Civil Engineers (ASCE):** The process of evaluating a bridge's condition to determine its safety and serviceability.

**Federal Highway Administration (FHWA):** The process of collecting and evaluating data on a bridge's condition to determine the need for maintenance, repair, or rehabilitation.

**Transportation Research Board (TRB):** The process of assessing a bridge's current condition and predicting its future condition based on current trends.

These definitions underscore the importance of assessing bridge condition to ensure safety and serviceability. The methods employed for condition assessment may vary depending on the bridge type, available resources, and desired level of detail. However, it is crucial that qualified professionals with the necessary expertise and experience conduct the assessments.

Factors considered during bridge condition assessment may include the bridge's age, design, materials, environment, usage, and maintenance history. Assessing these factors aids in understanding the overall condition and identifying specific areas requiring attention and maintenance.

### 1.4.1 Objectives of condition Assessment of bridges:

The main objectives of condition assessment are to:

- Identify and assess the condition of a bridge's components and systems.
- Determine the bridge's remaining service life.
- Identify any potential safety hazards.
- Develop a maintenance plan for the bridge.
- Prioritize maintenance and repair work.
- Reduce the risk of bridge failure.
- Improve the efficiency of bridge management.

### 1.4.2 Importance of condition assessment of bridges in Pakistan:

The condition of bridges in Pakistan is a matter of great concern, as highlighted by a recent study conducted by the Pakistan Bridge Authority. According to the study, more than half of the bridges in the country require repair or rehabilitation. The study also identified corrosion, cracking, and overloading as the most common issues faced by bridges in Pakistan.

The deteriorating condition of bridges poses a significant safety hazard. A tragic incident in 2017 in Karachi resulted in the collapse of a bridge, leading to the loss of 20 lives. This collapse was attributed to a combination of factors including corrosion, overloading, and insufficient maintenance.

The government of Pakistan has initiated measures to address the bridge safety problem. In 2018, a program was launched to repair or rehabilitate 1,000 bridges nationwide. However, the program faces challenges such as inadequate funding and a shortage of qualified personnel.

The poor condition of bridges in Pakistan demands urgent attention. The government must allocate increased funding for bridge repair and rehabilitation, and develop a comprehensive plan to ensure the safety of bridges throughout the country.

Additionally, non-governmental organizations are also playing a role in improving the condition of bridges in Pakistan. These organizations provide technical support, training, and funding to assist bridge owners and managers in the maintenance and repair of their bridges. Their efforts are contributing to the overall improvement of bridge safety in the country.

### 1.4.3 Scope of Condition Assessment of Bridges in Pakistan:

The scope of condition assessment of bridges in Pakistan includes the following:

- Visual inspection of the bridge's superstructure and substructure
- Non-destructive testing (NDT) of the bridge's materials and components
- Destructive testing of the bridge's materials and components
- Analysis of the bridge's structural behavior
- Development of a condition rating for the bridge
- Recommendations for bridge maintenance and rehabilitation

The initial stage of the condition assessment process involves a visual inspection, where an inspector examines the bridge for visible signs of damage like cracks, spalling concrete, and corrosion. Distress indicators such as leaning or tilting are also observed. Non-Destructive Testing (NDT) techniques are employed to evaluate the bridge's materials and components without causing damage. Examples of NDT methods include ultrasonic testing, radiography, and magnetic particle testing. On the other hand, Destructive Testing (DT) methods, such as core drilling and tensile testing, are used to assess the bridge's condition by intentionally damaging certain materials or components. The analysis of the bridge's structural behavior is conducted to determine its response to various loads, taking into account factors like geometry, materials, and components. A condition rating is then assigned to the bridge based on the results obtained from the visual inspection, NDT, and DT. This rating provides an overall assessment of the bridge's condition. Recommendations for bridge maintenance and rehabilitation are derived from the assessment findings, aiming to enhance the bridge's condition and prolong its service life. These recommendations may include repairs, strengthening measures, or even replacement. It is important to note that the condition assessment process is intricate and requires the expertise of a qualified engineer. The results obtained from the assessment serve as valuable insights for making informed decisions regarding the bridge's maintenance and rehabilitation activities.

## 1.5 Bridge Inspection Techniques:

Assessment of bridges can be done using different techniques. These are mainly classified as

- Non-Destructive Technique
- Destructive Technique

### 1.5.1 Non-Destructive Techniques

Non-destructive testing techniques are employed to evaluate the internal condition of bridge elements without causing damage. These techniques may include ultrasonic testing, ground-penetrating radar, magnetic particle inspection, impact echo testing, and other methods to assess the integrity of concrete, detect hidden defects, measure thickness, and identify potential structural issues.

The non-destructive techniques include

- Visual Inspection
- Ground Penetrating
- Acoustical technique
- Impact Echo
- Hammer Sounding
- chain dragging

#### *1.5.1.1 Visual Inspection:*

Visual inspection is a simple and direct approach for the inspection of bridges. In this technique only that parts of bridge can be visualized which can be seen through naked eye. Using this technique, only external condition of bridge can be observed and for internal assessment other destructive and non-destructive techniques can be used. It is most common technique and all other techniques are used after this technique. Mostly visual inspection is used for condition assessment reports and rating of different structural components. Through visual inspection potholes, cracks, spalling, delamination, pop out, efflorescence, collision damage can be observed. It is the most economical method for inspection of structural components.

#### 1.5.1.2 Ground Penetrating Radar

The most technical method for non-destructive testing is use ground-penetrating radar (GPR) which involves radar pulse for sub-surface image. In general, GPR can be used in rock, soil. ice, fresh water, pavements and other structures. Electromagnetic radiation in the microwave band, UHF/VHF frequencies are used in this technique, that bounce back from subsurface structures. The signals that are reflected help in the detection of objects, changes in material. voids and cracks. GPR can also be used for asphalt testing as well as for concrete highway surfaces. There are two common types of GPR for bridge surface measurement. Ground-coupled and air-launched. Ground-coupled systems rely upon an antenna that is placed very close to the road surface while in case of air-launched systems directional antennas placed at the surface from a height of around 30cm to 50cm. This technique shows the location and depth of rebar, tie bars and dowel bars.

#### 1.5.1.3 Acoustical Techniques

*Application of rebar locater device on concrete bridge pier wall*

This device is used for rebar locating inside the concrete. The rebar diameter and concrete cover of rebar can be determined by this device. For different tests such as ultrasound or penetration resistance, in order to obtain accurate results, it is necessary to locate rebar before applying these tests.

*Application of pin device*

It is generally known as Windsor pin device. It is a spring loaded device that pushes a steel pin into the concrete surface. The amount of penetration is inversely proportional to compressive strength of concrete. Greater the penetration, weaker is the concrete.

*Application of ultrasound pulse velocity device*

With the help of this device, the quality of concrete is identified by the ultrasonic pulses generated by device.

*Application of reinforcement corrosion resistivity (corrosion rate) device*

For determining the rate of corrosion of steel inside the concrete, resistivity measurement method is applied. Resistivity measurement is a fast, simple and cheap in situ non-destructive method to obtain information related to the corrosion hazard of embedded reinforcement.

#### *1.5.1.4 Impact Echo*

It is kind of pulse-echo technique which uses a mechanical impact to produce low frequency sound waves (around 2-20 KHZ). These transmitted stress waves travel through the material and will be reflected when they are encounter with discontinuities like internal. flaws and extemal surfaces. Applying a mechanical impact to produce stress waves for detection of flaws has had the greatest success in the practical application of stress waves. The impact echo method was developed and researched at the national institute of standards and technology in 1980's by Drs. Nicholas Carino and Mary Sansalone (Dennis A, Sack. L D. O. 1995). It is used for detection of flaws like cracks, delamination, voids, honeycombing and de bonding in plain, reinforced and post- tensioned concrete and it is also applicable for detection of cracks, voids and other defects in masonry structures where the block units are bonded using mortar.

#### *1.5.1.5 Hammer Sounding*

It is used to check the delamination of concrete. It is a type of physical inspection of bridge surface. The results of hammer sounding are based on pitch of sound. It gives better results to horizontal and vertical surfaces. When concrete surfaces are stuck with hammer, the damaged part produces dull sound while on the other hand a good concrete produces sharp ringing sound. The results may not be accurate due to hearing biases and this test cannot be performed on asphalt overlay. This method is applicable for short concrete deck and for long deck chain drag system is more accurate and practical method.

#### *1.5.1.6 Chain Dragging*

Chain dragging is used to detect delamination of concrete bridge deck. Over the deck the chains are swept audible response is noticed. Dull or hollow sound indicates that area over which test is performed, is faulty and referred for detailed inspection. This method is simple and economical.

In a noisy environment where traffic load is heavy this test may not give accurate results.

For example if this test is carried out on one lane and on other lane vehicles are moving with different velocities which can affect the chain dragging sound.

### 1.5.2 Destructive Techniques

Another type technique used for the assessment of concrete bridges is destructive. technique. In destructive techniques where inspection is required material is extracted from that part of bridge. Then the defects in the material and sometimes material properties are determined through tests. Various properties such as strength, permeability. moisture content etc. can be determined through these techniques. It is better to take material from damage as well as non-damage part of bridge so that comparison can be made. The size of sample is required according to test specifications. Field tests can also be performed on samples to check delamination or deterioration. Tests are carried out on drilled sample. Destructive tests which are generally used for the inspection are Carbonation, concrete

Permeability, concrete Strength, Endoscopes, Moisture Content, Chloride Test, Petrographic Examination and Reinforcing steel Strength.

#### *1.5.2.1 Core Sampling:*

In Core sampling a core of concrete is dig out from the in situ structure for the assessment of different characteristics of concrete. Care should be taken during drilling so that reinforcement in the structure do not damage otherwise reinforcement would also be checked either it is seriously damage or not. According to code the diameter of core should be three times the maximum aggregate size. The core sample is then used in various tests such as strength, porosity, permeability, density, carbonation, resistively. moisture content, chloride analysis, mix proportions, water absorption, gamma radiography and an estimation of damage due to sulfate attack and other chemical reactions. The Standard ASTM C-42 is used for drilling and testing of cores. The record of core samples should to taken for good evaluation.

#### *1.5.2.2 Test for Carbonization:*

The reaction of carbon dioxide with hydrated cement in the presence of moisture is called as carbonization. The reaction of these gases with alkaline ingredients of concrete diminishes concrete alkalinity. Carbonation causes oxidization of the steel by decreasing alkalinity of concrete near the reinforcement. The depth of carbonation can be measured by spraying two percent solution of phenolphthalein ethanol, which is a pH indicator, to a freshly uncovered concrete surface.

A change in color take place at a pH of just about 10 and after the test, the uncarbonated concrete color changes to magenta or pink color and the carbonated concrete remain colorless. The phenolphthalein is a guideless and low-cost method which is used to determine depth of carbonation in concrete.

#### *1.5.2.3 Material Testing:*

Material testing involves taking samples from bridge components, such as concrete, steel, or coatings, and subjecting them to laboratory testing. These tests assess material properties, strength, durability, corrosion resistance, and compatibility with design specifications. Material testing helps identify potential material deficiencies and degradation over time.

#### *1.5.2.4 Geotechnical Investigations:*

Geotechnical investigations focus on evaluating the soil conditions and foundation characteristics beneath the bridge. These investigations may involve soil sampling, laboratory testing, geophysical surveys, and analysis of groundwater conditions. Geotechnical information helps assess the stability and load-bearing capacity of the foundation and identifies potential risks, such as settlement or soil liquefaction.

### *1.5.2.5 Historical Data Analysis:*

Analyzing historical data and maintenance records of bridges provides insights into the past performance, maintenance practices, repair history, and identified issues. This information helps in identifying recurring problems, planning maintenance strategies, and understanding the overall condition of the bridge.

### *1.5.2.6 Bridge Management Systems:*

Implementing a comprehensive bridge management system facilitates effective condition assessment and maintenance planning. Bridge management systems utilize databases, software tools, and decision support systems to store and analyze bridge data, prioritize inspections, plan maintenance activities, and track the condition of each bridge within a network.

## 1.6 COMPONENTS OF BRIDGES:

- Deck Slab
- Stringer
- Floor Beam
- Diaphragm
- Bearing
- Piers
- Pile
- Pile Cap
- Pier Cap
- Drainage System
- Footpath
- Curb
- Expansion Joint
- Wearing Surface
- Abutment

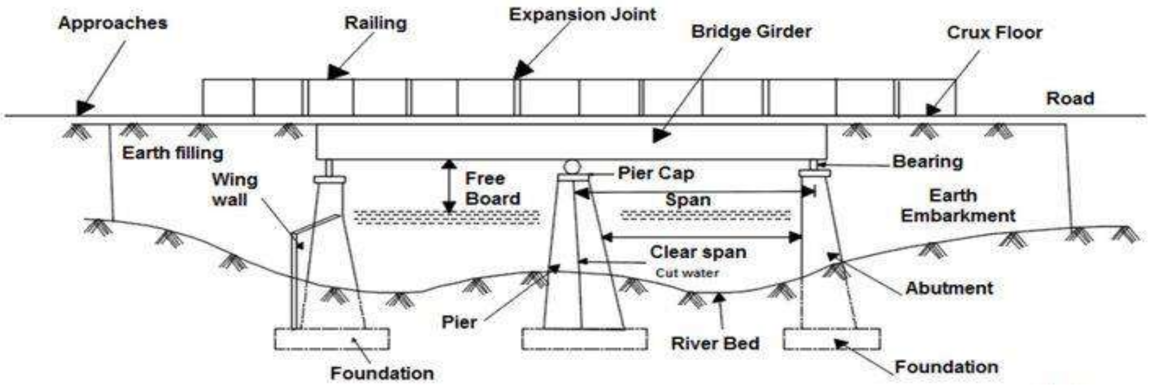


Figure 1.2: Components of the bridge structure

### 1.6.1 Deck Slab:

The deck slab is the upper surface of a bridge that serves as the roadway for vehicles and pedestrians. Usually made of reinforced concrete, it spans between supporting beams or girders. The deck slab carries the weight of traffic and transfers it to the underlying support elements. It is designed to withstand different types of loads, including vehicle weight, pedestrian loads, and environmental factors.

### 1.6.2 Stringer:

Stringers are longitudinal beams or girders that run parallel to the length of the bridge and provide support to the deck slab. Positioned beneath the deck slab, they distribute the load from the deck to the floor beams or other supporting elements. Stringers play a vital role in evenly distributing the load across the bridge structure, enhancing its strength and stability.

### 1.6.3 Floor Beam:

Floor beams are transverse beams that support the stringers and transfer the load from the stringers to the main girders or other supporting elements. Perpendicular to the stringers, they contribute to the overall structural integrity of the bridge. Floor beams play a crucial role in distributing loads from the stringers and deck slab to the primary support elements like piers or abutments.

### 1.6.4 Diaphragm:

Diaphragms are structural elements that reinforce and strengthen the bridge. They can be horizontal or vertical and are positioned between the main girders, stringers, or floor beams. Diaphragms provide lateral stability to the bridge, resisting forces such as wind, seismic loads, and vibrations caused by traffic. They help distribute loads, reduce deformations, and ensure the overall stability and integrity of the bridge structure.

### 1.6.5 Bearings:

Bearings are devices placed between the superstructure (deck slab) and the substructure (piers or abutments) of a bridge. They allow controlled movements and rotations of the superstructure, accommodating factors like thermal expansion, settlement, and seismic activity. Bearings provide support to the bridge and transfer loads from the superstructure to the substructure. They allow for necessary flexibility and movement while maintaining the bridge's stability and preventing excessive stress on the structure.

### 1.6.6 Piers:

Piers are vertical load-bearing structures that support the bridge deck. Typically constructed at regular intervals along the bridge span, they provide vertical support to resist the weight of the bridge and the loads it carries. Piers can take different forms such as solid columns, frames, or towers. They transmit loads from the superstructure to the foundation, which may be the ground or a pile foundation.

### 1.6.7 Pile:

Piles are long and slender columns made of concrete, steel, or timber that are driven or drilled into the ground to support the bridge substructure. Piles are used when the soil conditions are not suitable for direct foundation support. They transfer loads from the bridge to the underlying soil or rock, providing stability and preventing excessive settlement or lateral movement.

### 1.6.8 Pile Cap:

A pile cap is a reinforced concrete slab or beam that connects and transfers the load from a group of piles to the superstructure or pier. It is placed on top of the pile foundation, creating a stable platform for distributing loads from the bridge. Pile caps are designed to evenly distribute the loads among the piles and protect the top of the piles from environmental factors.

### 1.6.9 Pier Cap:

A pier cap is a horizontal structural element that rests on top of the piers. It acts as a connection point between the piers and the superstructure, distributing loads from the superstructure to the piers. Pier caps are typically made of reinforced concrete and designed to provide stability, load distribution, and support for the bridge structure.

### 1.6.10 Drainage System:

Drainage systems in bridges are essential for managing water runoff and preventing water accumulation on the bridge deck and substructure. Proper drainage helps prevent water-induced damage, such as corrosion, erosion, and deterioration of bridge components. It typically involves the design and installation of gutters, scuppers, downspouts, and drainage pipes that effectively collect and redirect water away from the bridge elements.

### 1.6.11 Footpath:

A footpath, also known as a sidewalk or pedestrian walkway, is a designated path on a bridge for pedestrians to safely cross or travel alongside vehicular traffic. Footpaths are separate from the roadway and are typically located on one or both sides of the bridge. They provide a safe space for pedestrians and are designed to meet specific width and accessibility requirements.

### 1.6.12 Curb:

A curb is a raised edge or barrier usually found on the sides of the bridge deck or footpath. It helps contain vehicles within their designated lanes and provides a visual and physical separation between vehicular and pedestrian areas. Curbs also assist in directing surface runoff towards drainage systems and preventing vehicles from accidentally driving off the bridge.

### 1.6.13 Expansion Joint:

An expansion joint is a flexible connection between two sections or elements of a bridge that allows for the expansion and contraction of the bridge due to temperature variations. Bridges experience thermal movements caused by temperature changes, and expansion joints accommodate these movements. They help prevent the development of excessive stresses and potential damage to the bridge structure by allowing controlled movement and reducing restraint.

### 1.6.14 Wearing Surface:

The wearing surface is the topmost layer of the bridge deck that directly encounters vehicle tires and pedestrian traffic. It is designed to withstand the abrasive action of traffic, provide a smooth and durable surface for vehicles to travel on, and protect the underlying structural components. Wearing surfaces can be made of materials like asphalt, concrete overlays, or specialized coatings that enhance skid resistance and reduce noise.

### 1.6.15 Abutment:

An abutment is a supporting structure located at the ends of a bridge, connecting the superstructure to the ground or to retaining walls. Abutments are typically made of reinforced concrete and provide vertical support to the bridge deck. They resist horizontal forces such as the weight of the bridge and loads transmitted to the supports. Abutments also serve to retain embankments or approach roads leading to the bridge.

## 1.7 TYPES OF SENSORS:

There are many different types of sensors that can be used for structural health monitoring (SHM) of bridges. Some of the most common types of sensors include:

### 1.7.1 Accelerometer:

Accelerometers are devices that measure acceleration or changes in acceleration. In the field of bridge structural health monitoring (SHM), they are used to measure the vibrations and dynamic movements experienced by the bridge.

#### *1.7.1.1 Function:*

The main purpose of accelerometers in bridge SHM is to gather data about the bridge's dynamic behavior. They help engineers assess the strength and stability of the structure, evaluate how the bridge responds to external loads, and detect potential issues like excessive vibrations or resonance.

#### *1.7.1.2 Principle:*

Accelerometers work based on the principle of inertia. They consist of a mass attached to a spring or a compliant element. When the accelerometer encounters acceleration or vibration, the mass moves relative to its surrounding frame. This movement creates a force or electrical signal that represents the acceleration.

Figure 1.3: Accelerometer

### 1.7.2 Strain Gages:

Strain gauges are devices employed to measure the strain or deformation occurring in materials. Within the field of structural health monitoring (SHM) for bridges, strain gauges are used to track the response of the structure to applied loads and detect any variations in strain levels.

#### *1.7.2.1 Function:*

The primary purpose of strain gauges in bridge SHM is to provide precise measurements of strain in different bridge components. They assist engineers in evaluating the structural integrity, assessing the impact of loads on the bridge, and identifying potential concerns like excessive strain or deformation.

#### *1.7.2.2 Principle:*

Strain gauges function based on the principle of electrical resistance. They consist of a thin wire or foil made of metal that is affixed to the surface of a structural element. As the element undergoes strain or deformation, the wire or foil experiences changes in its length and width, which in turn result in alterations in its electrical resistance.

### 1.7.3 Distributed Sensors:

Distributed sensors, also referred to as distributed sensing systems, are sensor devices employed in the structural health monitoring (SHM) of bridges. They offer continuous and spatially distributed measurements of various parameters. Unlike discrete sensors that provide measurements at specific locations, distributed sensors enable monitoring over large areas or extended lengths of the bridge structure.

#### *1.7.3.1 Function:*

The primary function of distributed sensors in bridge SHM is to gather data on different parameters, including strain, temperature, or vibration, at multiple points along the bridge. These sensors enable engineers to acquire a comprehensive understanding of the structural behavior, identify potential issues, and evaluate the overall health and performance of the bridge.

#### *1.7.3.2 Principle:*

Distributed sensing systems operate based on diverse principles depending on the specific sensor technology employed. One common principle is optical sensing, where optical fibers are utilized to measure the desired parameters. These optical fibers are either embedded within or attached to the bridge structure. Changes in the measured parameter induce alterations in the light transmitted through the fibers. These changes are then detected and analyzed to derive the necessary data.

### 1.7.4 Multiplexed Sensor:

Multiplexed sensors, also known as multiplexing sensors, are sensing devices used in structural health monitoring (SHM) of bridges to simultaneously measure and monitor multiple parameters at different locations. They provide a cost-effective and efficient solution for collecting data from multiple sensors using a single data acquisition system.

#### *1.7.4.1 Function:*

The main function of multiplexed sensors in bridge SHM is to enable the monitoring of multiple parameters at various points of the bridge using a single data acquisition system. By integrating multiple sensors into a single system, engineers can gather data on different parameters such as strain, temperature, displacement, or vibration from multiple locations on the bridge. This allows for a comprehensive assessment of the structural behavior and performance of the bridge.

#### *1.7.4.2 Principle:*

Multiplexed sensors operate based on the principle of sharing a common data acquisition system. Each sensor is equipped with a unique identifier that allows it to be individually addressed and differentiated within the system. The sensors are connected to a multiplexer or a switching mechanism, which sequentially connects each sensor to the data acquisition system, enabling data collection from each sensor in a sequential manner. This technique allows multiple sensors to be connected to a single system and eliminates the need for separate data acquisition units for each sensor.

### 1.7.5 Fiber Optical Sensors:

Fiber optic sensors are essential components in the monitoring of bridge structures for structural health purposes. These sensors operate on the principle of utilizing light propagation through optical fibers to measure and detect changes or irregularities in the structure. Their function involves gathering real-time data to enable early identification of potential structural issues, aiding in maintenance decision-making.

#### *1.7.5.1 Principle:*

The principle behind fiber optic sensors relies on the interaction between light and the optical fiber, which can be influenced by external stimuli such as strain and temperature. Among the commonly used types are fiber Bragg gratings (FBGs) and Fabry-Perot interferometers (FPIs).

#### *1.7.5.2 Function:*

FBGs are periodic variations in the refractive index along an optical fiber. When light passes through the fiber, a specific wavelength, known as the Bragg wavelength, is reflected due to the grating's periodicity. Changes in strain or temperature cause shifts in the Bragg wavelength, revealing the extent of strain or temperature experienced by the fiber and, consequently, the bridge.

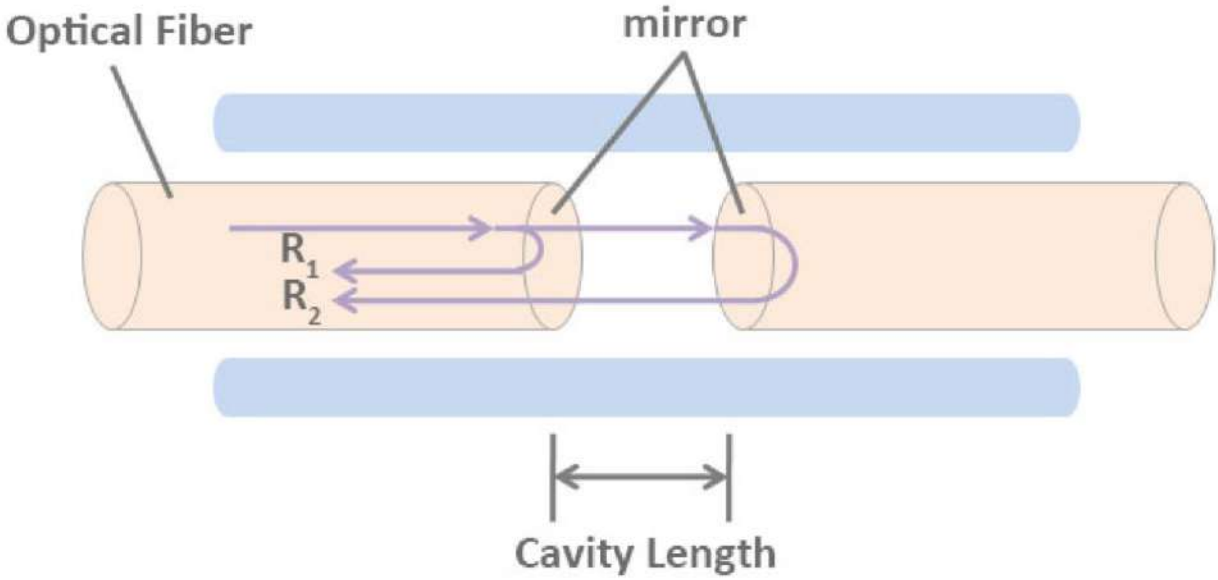


Figure 1.4: Fiber optical sensor

### 1.7.6 Linear Potentiometer:

A linear potentiometer is a device that converts the mechanical movement of a moving part into an electrical signal. The electrical signal is proportional to the movement of the moving part.

#### *1.7.6.1 Principle:*

Linear potentiometers are used in structural health monitoring (SHM) to measure the movement of bridge components. The movement of a bridge component can be influenced by a number of factors, such as stress, corrosion, and fatigue. By monitoring the movement of bridge components, SHM engineers can identify any potential problems before they cause damage to the bridge.

#### *1.7.6.2 Function:*

There are a number of ways to use linear potentiometers to measure the movement of bridge components. They can be embedded in the concrete, attached to the surface of the bridge, or mounted in a remote location. The type of linear potentiometer that is used will depend on the specific application.

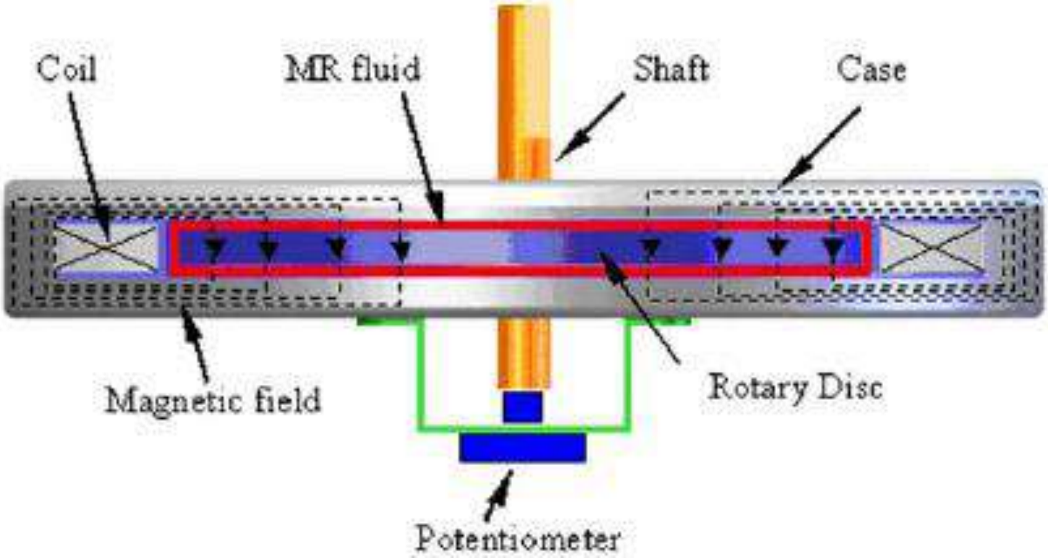


Figure 1.5: Linear potentiometer

# CHAPTER NO. 2

# CONDITION ASSESSMENT OF OLD RAVI BRIDGE

## 2.1 CONDITION RATING OF HIGHWAY BRIDGES:

The condition rating of a bridge is an evaluation of its overall structural soundness and maintenance needs. It is usually represented by a numerical or letter rating that reflects how well the bridge meets its design standards and anticipated lifespan. Factors such as age, materials, design, load capacity, and observed defects are taken into account when determining the rating. Higher ratings indicate better bridge conditions, while lower ratings suggest more significant defects or deterioration that may require repairs or replacement. Qualified engineers or inspectors conduct inspections to assess the bridge's condition and prioritize necessary maintenance and rehabilitation efforts for public safety and the bridge's longevity.

### 2.1.1 Background related to Condition Rating of Highway Bridges:

Bridges pose significant challenges in civil engineering structures due to the various factors involved in their maintenance, such as traffic disruptions, costly machinery, special materials, and accessibility issues.

It is crucial to carefully maintain bridges throughout their lifespan. Many countries around the world are currently grappling with problems related to bridge maintenance and rehabilitation. According to a report published by the American Society of Civil Engineers in 2017, 9.1% of bridges in the United States were deemed structurally deficient, while 13.6% were considered non-operational due to their poor condition out of a total of 614,387 bridges. The rehabilitation of these bridges requires a substantial investment of $123 billion. Differentiating between structurally deficient and functionally obsolete bridges is important. A bridge is classified as structurally deficient if its main components have significant damage, while a bridge is considered functionally obsolete if it fails to meet public safety standards

The rating and evaluation system for bridges originated in the United States in 1967 after the failure of the Silver Bridge on the Ohio River, which resulted in 46 casualties. The National Inspection Bridge Program was introduced to develop a rating and inspection system to assess the remaining service life of bridges in the country. The American Association of State Highway and Transportation Officials (AASHTO) issued the first inspection manual in 1970, providing essential information for recording, rating, and evaluating the load capacity of bridges.

In 1971, the National Bridge Inspection Standards were established to define inspection criteria for highway agencies. These standards mandated the presence of a bridge inspection organization in each state, requiring bridges to be inspected every two years and the National Bridge Inventory (NBI) to be regularly updated. Condition ratings in the NBI are determined using a numeric scale from 0 to 9, with 9 indicating excellent condition and 0 indicating failure. Following the failure of several bridges in 2007, a joint group formed by the ASCE recommended adopting a periodic inspection approach instead of the biennial inspections, and Risk-Based Inspection (RBI) was proposed for highway bridge inspection. This technique was successfully implemented on two highway bridges, demonstrating its effectiveness

In Pakistan, the approach to bridge maintenance has traditionally been reactive, with officials addressing problems as they arise. However, there is a need to transition to a proactive approach that anticipates and prepares for future issues. Inspecting the old Ravi Bridge in Lahore aimed to develop a Bridge Management System (BMS) in the country. Condition ratings serve to compare the current state of bridges with their condition at the time of construction. The initial step in bridge inspection involves visual observation, which includes:

i. Cracking
ii. Scaling
iii. Spalling
iv. Delamination
v. Corrosion

Following a visual inspection, Non-Destructive Techniques (NDT) can be employed to assess the magnitude of damage. Bridge condition rating systems have been established to evaluate the overall condition of bridges. Different countries worldwide have devised their own rating systems according to their specific conditions and situations. For instance, the Japanese have categorized deterioration levels from I to V, while the FHWA employs a scale ranging from 0 to 9. New York utilizes a formula to inspect bridges.

$$\textbf{Bridge Condition Rating (BCR)} = \frac{\Sigma(\boldsymbol{component\ ratingxweight})}{\Sigma \boldsymbol{Weights}}$$

Different Bridges have different inspection criteria based on:

- Type of element used
- Weight
- Age
- Function of bridge to be performed

**Table 2.1: FHWA Element Condition Rating**

| | |
|---|---|
| **N** | **Not Applicable** |
| **9** | **Excellent Condition** |
| **8** | **Very Good Condition** |
| **7** | **Good Condition** |
| **6** | **Satisfactory Condition** |
| **5** | **Fair Condition** |
| **4** | **Poor Condition** |
| **3** | **Serious Condition** |
| **2** | **Critical Condition** |
| **1** | **Imminent Failure Condition** |
| **0** | **Failed Condition** |

**Table 2.2: Moscow Bridge Rating System**

| Condition | Assessment | Wear | Type of Repair Required |
|---|---|---|---|
| 1 | Good | Less than 20% | Cleaning scheduled maintenance |
| 1.5 | Not very Good | 20-40% | Preventing maintenance |
| 2 | Poor | 40-60% | Current (local repair) |
| 2.5 | Very Poor | 60-80% | Major repair |
| 3 | Unacceptable | 80-100% | Replacement or restoration repair |

Ministry of Transportation Organization (MTO) has contributed its role in development of bridge Condition Index (BCI). The inspector is guided to measure the quantities like area and lengths. The measured quantities are used to calculate Bridge Element Condition Index (BECI) on the basis of remaining value of deteriorating element. This index varies from 0 to 100. BECI is calculated as:

$$\textbf{Bridge Element Condition Index (BECI)} = \frac{Current\ Element\ Value}{Initial\ Element\ Value} x100$$

Bridge condition index (BCI) is then modified to Element Structural Condition Index (ESCI). It is used to calculate the Overall Structural Condition (OSCI). OSCI is a number from 1 to 4, where 4 is worst condition and 1 indicates the new bridge.

Summary of present and past Indices used around the globe is mentioned in table:

**Table 2.3: Summary of Indicis used around the Globe**

| **Country** | **Index** | **Basic** |
|---|---|---|
| Australia | Overall Structural Condition (OSCI) | Based on element structural condition index |
| U. K | Bridge Condition Index (BCI) | - |
| New York | Bridge Condition Index (BCI) | - |
| Ontario | Bridge Condition Index (BCI) | Based on remaining economic worth |
| Japan | Deterioration level I to V | Deficiency rating based on defects |
| Russia | Rating scale 1 to 3 | - |
| Pakistan | Bridge Performance Index (BPI) | Based on weighted element condition rating |

## 2.2 OLD RAVI BRIDGE (Shahdara Bridge)

### 2.2.1 Introduction:

River Ravi runs across the Lahore in a water course of length of approximately 26 Kilometers. There are three bridges on river Ravi (Railway, Old Ravi Bridge and new Ravi bridge). All these three bridges are parallel to each other. Old Ravi bridge **(Fig. 3.1)** was originally constructed in 1915. After serving for about half a century the old bridge started giving problems posing risk for the safe use of vehicular traffic in the year 1966. The study conducted at that time did not support the retention of the superstar-structure of the bridge, which had incapacitated to sustain the induced stresses the induced stresses and effects by incoming traffic. Consequently, the bridge was demolished but its well foundations were retained below the river bed.

It was decided to reconstruct the bridge above the existing foundations. Keeping in view the load carrying capacity of existing foundations design of a two-lane wide new bridge was carried out. The reconstruction was carried out in the year 1966-67.

For the purpose of inspection and evaluation, old Ravi Bridge was visited on October 2, 2022. Old Ravi bridge is not being used for heavy traffic now-a-days due to its improper condition to support heavy traffic. The following are the features with regard to its sub-structure and super-structure components.

**Table 2.4: OLD RAVI BRIDGE (Shahdara Bridge)**

| | |
|---|---|
| Length | No change, a 1462’-6” long bridge with 15 number of spans of 97’-6” each. |
| Roadway | 24’ wide with 9” RCC curb on either side |
| Main Beams | 6’ high pre-stressed post tensioned concrete girders |
| Bracers | Pre stressed post tensioned concrete diaphragms |
| Deck | 7” thick RCC Slab |
| Pier transoms | 5’-9”x2’-9”x21’ RCC cap over columns |
| Pier Columns | 3’-3” diameter RCC columns over RCC footing / transom slab |
| Foundation | The existing well/ caissons of old Ravi bridge were used |

**Figure 2.1**

Following components were inspected during our visit to old Ravi Bridge:

- Light Poles
- Sign Boards
- Expansion Joints
- Wearing Surface
- Deck Slab
- Drainage System
- Girder and Diaphragm
- Bearings
- Pier Caps
- Piers
- Pile Caps
- Abutments

### 2.2.2 Light Poles:

Light Poled of Shahdara Bridge were in good condition. Most of the light poles were straight **(Fig. 2.2).** Some of the light poles did not have light bulbs and the safety glasses were missing. Some of the light's poles were buckled and were aligned in dangerous condition which can fall down any time and can cause serious accidents **(Fig. 2.3)**

**Figure 2.2 Straight light poles**

**Figure 2.3 Tilted light poles**

### 2.2.3 Signs:

On Shahdara bridge were no sign boards indicating about speed limits or other warnings were missing. The sign board indicating about load wanning was also missing but a barrier was installed at the start of bridge to indicate about the load warning **(Fig. 2.4)**

**Figure 2.4 Barrier to indicate about load warning**

### 2.2.4 Barriers:

Barriers of Shahdara bridge were not in good condition. Some of the barriers were bent due to traffic accidents in the past years. The grills were missing due to rusting in some part of barriers. The rail part of the barrier was completely missed in some spans of the bridge. The steel surface in the barrier rail and support were exposed to atmosphere causing corrosion and deterioration **(Fig. 2.5)**. Joints of the barrier rails were not properly welded. The bolts in the joining plates were not present **(Fig. 2.6)**.

**Figure 2.5 Corrosive surface of barrier**

**Figure 2.6 Missing Bolts at joints**

### 2.2.5 Expansion Joints:

Expansion joints of Shahdara bridge were in a very critical condition. The steel plates and anchor of expansion joints were free due to the removal of concrete from wearing surface from sides of expansion joint **(Fig.2.7).** This causes a lot of movement of the bridge when traffic pass over the expansion joints and also disturbing noise were produced. At some places, the steel plates of expansion joint moved up and some places were move down up to some inches. The unleveled joints can cause serious accidents. Water can also enter into the expansion joints and can cause damage to the inner side of deck slab. The joints were distorted badly. Most of the expansion joints were filled with concrete **(Fig. 2.8)**.

**Figure 2.7 Exposed anchorage**

**Figure 2.8 Joint filled with concrete**

### 2.2.6 Wearing Surface:

Wearing surface of Shahdara Bridge was not in good condition. Wearing surface was excessively damaged near the expansion joints **(Fig. 2.9)**. The wearing surface damage was also observed near the support of barriers. The wearing surface was excessively damaged due to traffic loading and hammering like actions. There were holes in the wearing surface for drainage purpose **(Fig. 2.10)**.

**Figure 2.9 Damaged surface near joints**

**Figure 2.10 Holes in the wearing surface**

### 2.2.7 Deck Slab:

The deck slab at the Shahdara bridge was not in good condition due to the defects in the expansion joints. There were stones on the deck slab to fill the deteriorated surface at the expansion joints **(Fig. 2.11)**. The deck slab was not levelled due to the pouring of concrete at the expansion joints **(Fig. 2.12)**. Water can easily penetrate to the deck through distorted joints and can cause problem due to improper drainage.

**Figure 2.11 Stones on the deck slab**

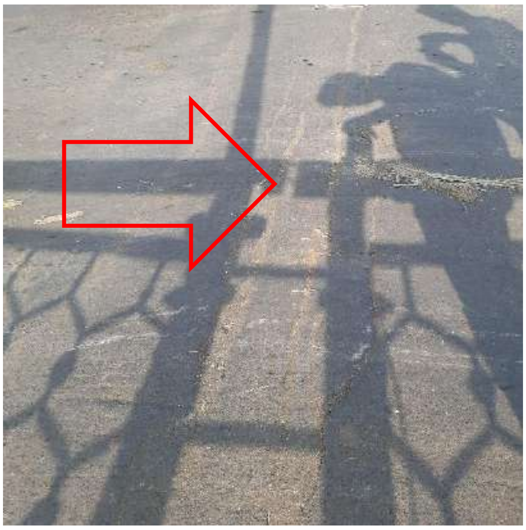


**Figure 2.12 Extra Pouring of concrete**

### 2.2.8 Drainage System:

There was no proper drainage system in the inspected bridge. The holes were drilled from wearing surface through the deck for the drainage purposes **(Fig. 2.13)**. Most of the drain holes get blocked due to the trash around them **(Fig. 2.14)**.

**Figure 2.13 Holes drilled on wearing surface**

**Figure 2.14 Trash inside holes**

### 2.2.9 Girder and Diaphragm:

All the girders and diaphragm of Shahdara bridge were in good condition **(Fig. 2.15)**. Girders and diaphragm were inspected from the bottom of the bridge. No physical defect was found from visual inspection.

**a) Diaphragm surface** **b) Bottom view of Girders and floor beams**

**Figure 2.15 Girders and Diaphragm Inspection**

### 2.2.10 Bearings:

Bearings of Shahdara bridge were not visible by naked eye. Trashes were observed below the floor beam around bearing **(Fig. 2.16)**. Unwanted and damaged pipes were found below the floor beam **(Fig. 2.17)**.

**Figure 2.16 Accumulated Trash**

**Figure 2.17 Unwanted and damaged pipes**

### 2.2.11 Pier Caps:

Pier caps of Shahdara bridge were in good condition **(Fig. 2.18)**. These were not inspected properly due to river course.

**Figure 2.18 Pier Cap Inspection**

### 2.2.12 Piers:

Piers of Shahdara bridge were in good condition **(Fig. 2.19)**. Only few of piers were inspected properly. Remaining piers were not inspected properly due river course obstacle. Unwanted material was compiled on the pier stems.

**a) Bottom view of piers** **b) Unwanted material on pier stem**

**Figure 2.19 Piers Inspection**

### 2.2.13 Pile Caps:

Piles caps of Shahdara bridge were in good condition. These were not inspected properly due to river course. However, by visual inspection, the dampness was found in most of pile caps **(Fig. 2.20)**.

**a) Pile caps having dampness**

**Figure 2.20 Pile Cap inspection**

### 2.2.14 Abutments:

Some physical defects around abutment area of old Ravi bridge were found by visual inspection such as removal of concrete from surface and accumulation of trash **(Fig. 2.21)**.

**a) Removal of concrete from surface** **b) Accumulation of Trash**

**Figure 2.21 Abutments Inspection**

## 2.3 EVALUATION OF BRIDGE COMPONENTS:

Following bridge rating criteria was used for rating of components of inspected bridge.

**Table 2.5: FHWA Bridge Condition Rating Categories**

| Rating | Condition Category | Description |
|---|---|---|
| **9** | **Excellent** | A new Bridge |
| **8** | **Very Good** | No problem noted |
| **7** | **Good** | Some minor problems |
| **6** | **Satisfactory** | Some minor deterioration in structural elements |
| **5** | **Fair** | All primary structural elements are sound but may have minor section loss, cracking, spalling or scour |
| **4** | **Poor** | Advanced section loss, deterioration, spalling or scour |
| **3** | **Serious** | Loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present. |
| **2** | **Critical** | Advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may be removed sub-structure support. Unless closely monitored, it may be necessary to close the bridge until corrective action is taken. |
| **1** | **Imminent Failure** | Major deterioration or section loss present in critical structural components, or obvious vertical or horizontal movement affecting structural stability. Bridge is closed to traffic, but corrective action may put bridge back in light service. |
| **0** | **Failed** | Out of service; beyond corrective action. |

### 2.3.1 Evaluation of Old Ravi Bridge:

- Date of Evaluation 02-Oct-2022
- Number of spans 15

**Table 2.6: Bridge Details**

| | |
|---|---|
| **Total Length/span of bridge** | **450 m** |
| **Number of spans** | **15** |
| **Total number of floor beams in each span** | **4** |
| **Total number of floor beams** | **60** |
| **Number of stringer beams** | **3** |
| **Total number of girders** | **45** |
| **Total number of piers** | **26** |
| **Total number of expansion joints** | **16** |
| **Total number of light poles** | **17** |
| **Width of deck** | **8 m** |

**Table 2.7: Condition Rating of bridge components**

| **Span** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Barrier** | 7 | 4 | 5 | 5 | 4 | 3 | 5 | 6 | 4 | 5 | 3 | 5 | 6 | 4 | 5 |
| **Wearing Surface** | 6 | 6 | 6 | 6 | 5 | 5 | 6 | 5 | 4 | 3 | 5 | 4 | 6 | 6 | 6 |
| **Expansion joints** | 4 | 4 | 4 | 3 | 3 | 4 | 2 | 2 | 3 | 4 | 5 | 3 | 6 | 4 | 6 |
| **Drainage** | 7 | 5 | 5 | 3 | 3 | 3 | 7 | 6 | 4 | 6 | 7 | 5 | 6 | 5 | 6 |
| **Light poles** | 7 | 6 | 6 | 5 | 4 | 6 | 4 | 5 | 4 | 7 | 5 | 6 | 6 | 4 | 7 |
| **Signs** | 8 | - | - | - | - | - | - | - | - | - | - | - | - | - | 8 |
| **Deck** | 7 | 5 | 5 | 6 | 4 | 6 | 4 | 4 | 5 | 5 | 6 | 5 | 5 | 6 | 7 |
| **Girders** | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| **Bearings** | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| **Pier caps** | - | 7 | 7 | 7 | 7 | 7 | 5 | 5 | 7 | 7 | 7 | 7 | 7 | 7 | - |
| **Piers** | 7 | 7 | 7 | 7 | 7 | 7 | 5 | 5 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| **Piles** | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |

**Remarks:**

Detailed inspection is not required and the bridge must be replaced.

### 2.3.2 Causes and Remedial Measures:

During the assessment of bridge, different defects were found in the bridges. Each defect has its own causes and remedial measures which are discussed below:

**Table 2.8: Causes and Remedial Measures for Bridge**

| PROBLEM | CAUSES | REMEDIAL MEASURES |
|---|---|---|
| **Damaged Barriers** | • Weathering Effects<br>• Accidents | • Proper sign boards should be installed warning the passengers about speed limit and other cautions to avoid accidents<br>• Maintenance after particular time period is must |
| **Deteriorated wearing surface** | • Accidents (Impact loading)<br>• Heavy Traffic<br>• Poor maintenance | • New layer of wearing surface should be applied after certain time duration |
| **Damaged Expansion Joints** | • No proper bond between steel and wearing surface<br>• No design for joints<br>• Exposed reinforcement of joints | • Special binders should used to develop strong bond between steel and wearing surface<br>• Expansion joints should be replaced after certain time period |

| | | |
|---|---|---|
| **Drainage Problem** | • Drainage holes are filled with garbage<br>• No proper outlet for drainage | • Drainage holes must be cleaned on weekly basis<br>• A proper outlet must be there so that water/waste may not damage deck or column underneath deck. |
| **Broken/damaged Light poles** | • Accidents<br>• No maintenance | • Light bulbs should be replaced when fused or broken<br>• Broken or tilted should be taken care of |
| **Missing or wrapped Sign Boards** | • Mostly sign boards are not there which cause accidents<br>• Wrapped with advertising posters if sign board is there | • Sign boards with proper cautions should be there<br>• Legal action should be taken against those who paste poster on sign boards |
| **Deteriorated Deck** | • Exposed Reinforcement<br>• Weathering effects | • Thickness of concrete cover should be sufficient<br>• Concrete cover should be immediately applied where needed |
| **Deteriorated Girders** | • Dampness<br>• Concrete spalling<br>• Exposed reinforcement | • There should not be any drainage problem to avoid dampness<br>• Concrete cover should be sufficient<br>• It should be designed under-reinforced |

### 2.3.3 Summary:

In summary, this chapter extensively examined the condition assessment of old Ravi bridge to enhance our understanding of the factors that impact bridge health and propose effective maintenance and management strategies. Through thorough research and empirical studies, several important findings have emerged.

The analysis of the collected data revealed that bridges are vulnerable to various deterioration mechanisms, including corrosion, fatigue, and excessive loading. These factors, along with environmental conditions and traffic demands, pose significant challenges to the durability and structural integrity of bridges.

Additionally, the study highlighted the significance of adopting a proactive approach to bridge management. Implementing preventative maintenance measures such as routine cleaning, timely repairs, and regular inspections can considerably extend the service life of bridges and reduce long-term maintenance costs.

Based on these findings, several recommendations can be made. Firstly, it is advisable for bridge authorities to invest in advanced technologies for condition assessment to improve accuracy and efficiency. Secondly, encouraging collaboration and knowledge sharing among researchers, practitioners, and policymakers can lead to the development of standardized assessment methodologies and guidelines. Lastly, ongoing research and development efforts should focus on designing and constructing more durable and resilient bridge structures.

Overall, this chapter contributes valuable insights to the field of bridge engineering by shedding light on the condition assessment process and providing practical recommendations for enhancing bridge management practices. It is hoped that the findings presented in this study will contribute to the sustainable and safe operation of bridges, ensuring an efficient transportation network and promoting public safety for years to come.

## CHAPTER NO. 3

# STUDY OF VARIOUS SENSORS

This chapter deals with the study of different sensors readily available for the vibration measurements. In order to select the type of sensors to be used in taking measurements, the authors learned the following 3 devices to understand their pros and cons:

- Mobile Accelerometer
- Extech Heavy Duty Vibration Meter
- E-Quake Arm Triaxial seismic Accelerometer

## 3.1 MOBILE ACCELEROMETER

The field of bridge condition assessment plays a crucial role in ensuring the structural integrity and safety of bridges. To accurately monitor the behavior and detect potential issues in bridges, the use of advanced sensing technologies has become increasingly important. One such technology is the mobile accelerometer, which offers a convenient and cost-effective solution for bridge monitoring. This one-page description focuses on the mobile accelerometer as a device for condition assessment of bridges, specifically its features, advantages, and limitations.

### 3.1.1 Features and Capabilities

The mobile accelerometer, utilized in this study through the "Physics Toolbox Suite" app, is a portable and widely accessible device capable of measuring acceleration forces exerted on a structure. With a sampling frequency of 200 Hz, it provides high-resolution data that enables accurate monitoring of dynamic responses. The accelerometer is designed to capture vibrations induced by various sources, including traffic loads, environmental factors, and seismic activities. Its user-friendly interface and ease of operation make it an attractive option for bridge engineers and researchers alike.

### 3.1.2 Advantages

The advantages of mobile accelerometer are numerous. Following points summarize the advantages of mobile sensors:

- ***Portability:*** The mobile accelerometer offers the advantage of portability, allowing users to carry out measurements conveniently at multiple locations within a bridge structure.

This feature facilitates extensive data collection and improves the accuracy of the condition assessment.

- ***Cost-effectiveness:*** Compared to traditional and specialized monitoring equipment, the mobile accelerometer is a cost-effective alternative. It leverages the widespread availability of smartphones, eliminating the need for expensive proprietary devices and reducing overall monitoring costs.
- ***Real-time monitoring:*** With its high sampling frequency and real-time data acquisition capabilities, the mobile accelerometer enables continuous and immediate monitoring of bridge behavior. This real-time data stream aids in detecting and analyzing transient events or sudden changes in structural response, allowing for timely intervention if necessary.
- ***Versatility:*** The mobile accelerometer can be used for a wide range of applications beyond bridge monitoring. Its versatility extends to other civil engineering structures, such as buildings, dams, and tunnels, making it a valuable tool for professionals in various fields.

### 3.1.3 Limitations

- ***Accuracy:*** While the mobile accelerometer provides valuable data, its accuracy may be affected by inherent limitations of smartphone sensors, such as sensitivity and calibration issues. Calibration verification and comparison with reference sensors should be performed to ensure reliable measurements.
- ***Mounting and positioning:*** Proper mounting and positioning of the mobile accelerometer on the bridge structure are critical for obtaining accurate results. Challenges may arise when trying to achieve consistent and standardized sensor placement across different spans or sections of the bridge.

In conclusion, the mobile accelerometer offers a portable, cost-effective, and versatile solution for bridge condition assessment. Its features, including high sampling frequency, real-time monitoring capabilities, and user-friendly interface, make it an attractive choice for bridge engineers and researchers. However, careful attention must be given to accuracy and proper sensor placement. By considering these factors, the mobile accelerometer can provide valuable insights into the behavior and health of bridges, contributing to enhanced maintenance strategies and increased overall safety.

## 3.2 EXTECH HEAVY DUTY VIBRATION METER

The Extech Heavy Duty Vibration Meter is a robust and professional-grade device that provides precise measurements of vibration levels in various units, including acceleration, velocity, and displacement. Equipped with a high-quality accelerometer, it offers a wide frequency range and can accurately capture vibrations induced by different sources such as traffic, wind, and structural responses. Unfortunately, the acceleration feature of the vibration meter used in the project was out of order.

### 3.2.1 Meter Description

1. Probe connector
2. RS-232 Connector
3. LCD Display
4. Function switches and pushbuttons
5. Probe
6. Magnetic base
7. Protective rubber meter jacket
8. Battery compartment (on rear)

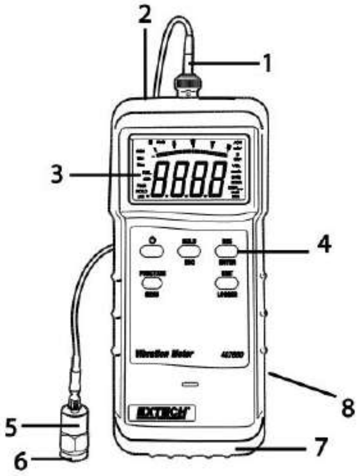


Figure 3.1: Vibration Meter

### 3.2.2 General Specifications

| | |
|---|---|
| Display | 3-1/2 digit LCD with bargraph |
| Frequency range | 10Hz to 1KHz (frequency sensitivity meets ISO-2954) |
| Sampling time | One (1) second approx. |
| Data output | Isolated serial RS-232 PC Interface |
| Min/Max Memory | Meter stores highest and lowest readings for later recall |
| Data Logger | Store up to 500 readings |
| Data logger Sample Time | 0 (manual), 1, 2, 5, 10, 30, 60, 600, 1800 and 3600 sec. |
| Power supply | 9V Battery |
| Power consumption | 8mA DC approx. |

### 3.2.3 Procedures for using a heavy-duty vibration meter

- ***Connecting the probe to meter:*** Plug the BNC connector end of the probe cable onto the BNC connector at the top of the meter.
- ***Connecting to machinary:*** The probe can then be connected to the tested machinery by attaching the magnetic end of the probe to a ferrous material on the equipment under test.

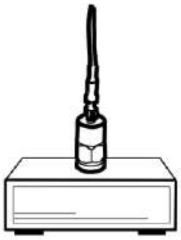
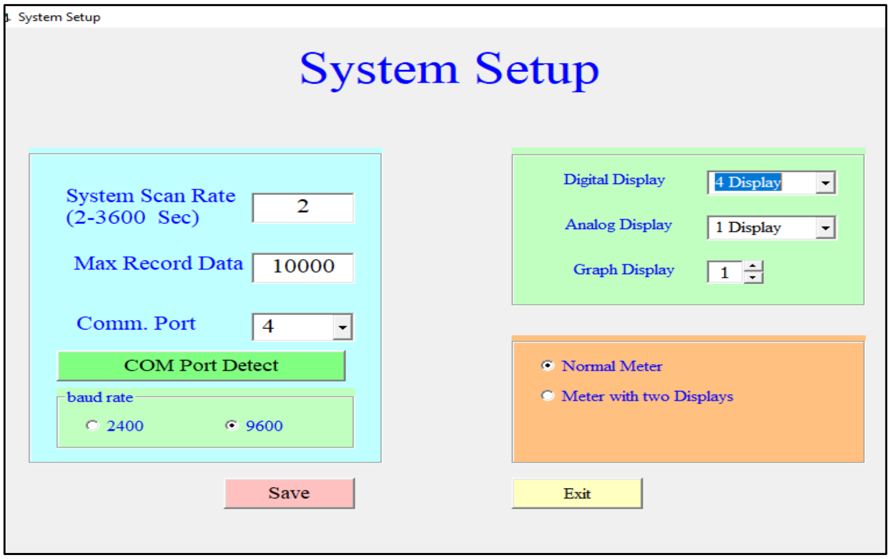


Figure 3.2: Connecting probe to machinery

- ***Power ON:*** Press the power button to turn the meter on.
- ***Function Button:*** Press the FUNCTION button to select RMS, PEAK or MAX-HOLD.
  1. RMS - Typical selection for vibration measurements
  2. PEAK – For measurement of the peak value. Not available in the Displacement mode.
  3. MAX_HOLD – Holds and displays the maximum value. The display will update only when a new maximum is measured. Not available in the Displacement mode.
- ***Units of measurement:*** Press the unit button to select the desired units of measurement. (Metric or Imperial Units).
- ***Connecting to PC:*** Now connect the vibration meter to a laptop using a cable.
- ***System Setup:*** Install the software given by the manufacturer of the vibration meter. Run the software and open system setup.

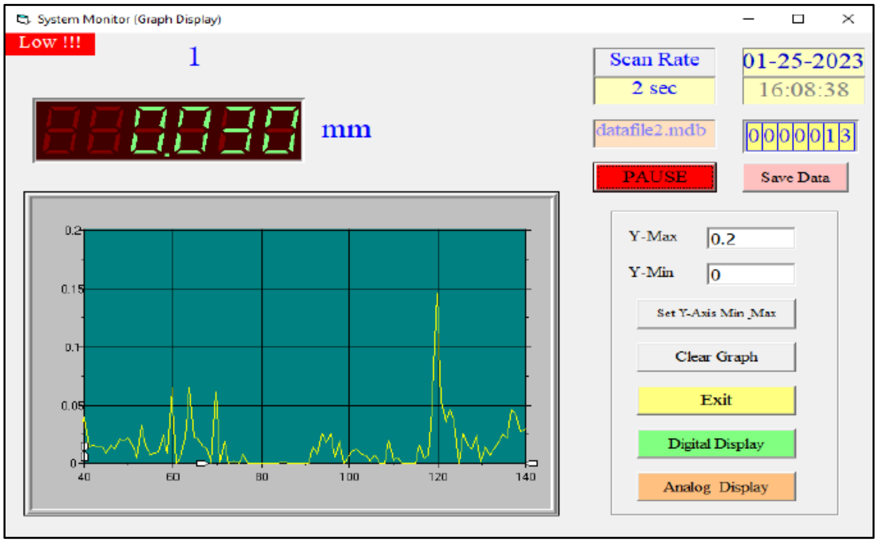


System Scan Rate (2-3600 Sec): 2
Max Record Data: 10000
Comm. Port: 4
baud rate: ○ 2400 ● 9600
Digital Display: 4 Display
Analog Display: 1 Display
Graph Display: 1
● Normal Meter
○ Meter with two Displays

Figure 3.3: System setup for heavy duty vibration meter

- ***System Setup:*** Select the system scan rate, max data record and display type from the system setup.

- ***Data Monitoring:*** Now start the program. You can monitor the values being recorded by the vibration meter.



System Monitor (Graph Display)

Low !!!

1

0.030 mm

Scan Rate 2 sec

01-25-2023

16:08:38

datafile2.mdb

000013

Y-Max 0.2

Y-Min 0

Figure 3.4: System Monitor for vibration meter

User can also manually save the values by clicking the button “Save Data” on system monitoring screen.

- ***Generating Excel Files:*** Recorded data can be exported in the form on an excel file.

### 3.2.4 Advantages

- ***Multiple Measurement Parameters:*** With its ability to measure acceleration, velocity, and displacement, the Extech Vibration Meter provides comprehensive data that allows for a thorough analysis of bridge behavior. This versatility enables engineers to gain a comprehensive understanding of the vibration characteristics of the bridge and make informed decisions regarding maintenance and structural modifications.
- ***Robust Construction:*** Designed to withstand challenging environmental conditions, the Extech Vibration Meter features a heavy-duty build. Its rugged construction ensures durability and longevity, making it suitable for field applications in various weather and site conditions.
- ***Data Logging and Analysis:*** The vibration meter includes built-in memory or storage capabilities, allowing for data logging over extended periods.

### 3.2.5 Limitations

- ***Scanning Rate:*** The scanning rate of Extech Heavy duty vibration meter is not very much suitable for bridge monitoring. It’s minimum scanning rate is 2 seconds. It means it’ll scan and record a value after 2 seconds. In SHM, we prefer a device which has frequency range of around five times the natural frequency of the structure, whose inspection is planned. So this device is not suitable for bridge monitoring. If we use this device, probability of losing some useful data is very high.

- ***Acceleration sensor out of order:*** The acceleration sensor of the available vibration meter was out of order. So this point makes this sensor not suitable option for the planned inspection.
- ***Cost and Accessibility:*** The Extech Heavy Duty Vibration Meter, being a professional-grade device, may have a higher cost compared to other vibration monitoring solutions. This factor could limit its accessibility for small-scale projects or budget-constrained applications.
- ***Specialized Training:*** Effective utilization of the Extech Vibration Meter may require specialized training or experience in vibration measurement techniques. Users should be familiar with the device's operation and understand the interpretation of vibration data to derive meaningful conclusions.

The Extech Heavy Duty Vibration Meter offers accurate and precise measurements of vibrations, making it a valuable tool for bridge condition assessment. But due to some problems with its acceleration sensor and undesired sensing rate, this Extech heavy duty vibration meter was not used in this project.

## 3.3 E-QUAKE ARM TRIAXIAL SEISMIC ACCELEROMETER

The e-Quake arm triaxial seismic accelerometers, originally developed as part of the e-Quake smart earthquake early warning system, are sophisticated sensors designed to record acceleration in three axes. This accelerometer can be connected with a PC using ethernet cable.

Figure 3.5: E-Quake Arm Triaxial Seismic Accelerometers

### 3.3.1 E-Quake Smart System

E-Quake smart is an earthquake early warning system. When earthquake waves start propagating from the center and reach to a certain location on earth, they are sensed in 2 different types, called P waves and S waves. As P waves move faster, they arrive at a certain location earlier than the S waves. So e-Quake arm triaxial seismic accelerometer is designed to sense the small amplitude P waves, seconds before the higher amplitude S waves arrive, and then e-Quake smart system generates a warning in terms of seconds before the main shock strikes, which may be very important for taking a precaution.

Generally, 4 e-Quake arm triaxial seismic accelerometers are installed in a typical high-rise building. One is located at the topmost floor of the building. 1 at one of the middle floors and 2 at the basements. Up to 16 sensors may be located.

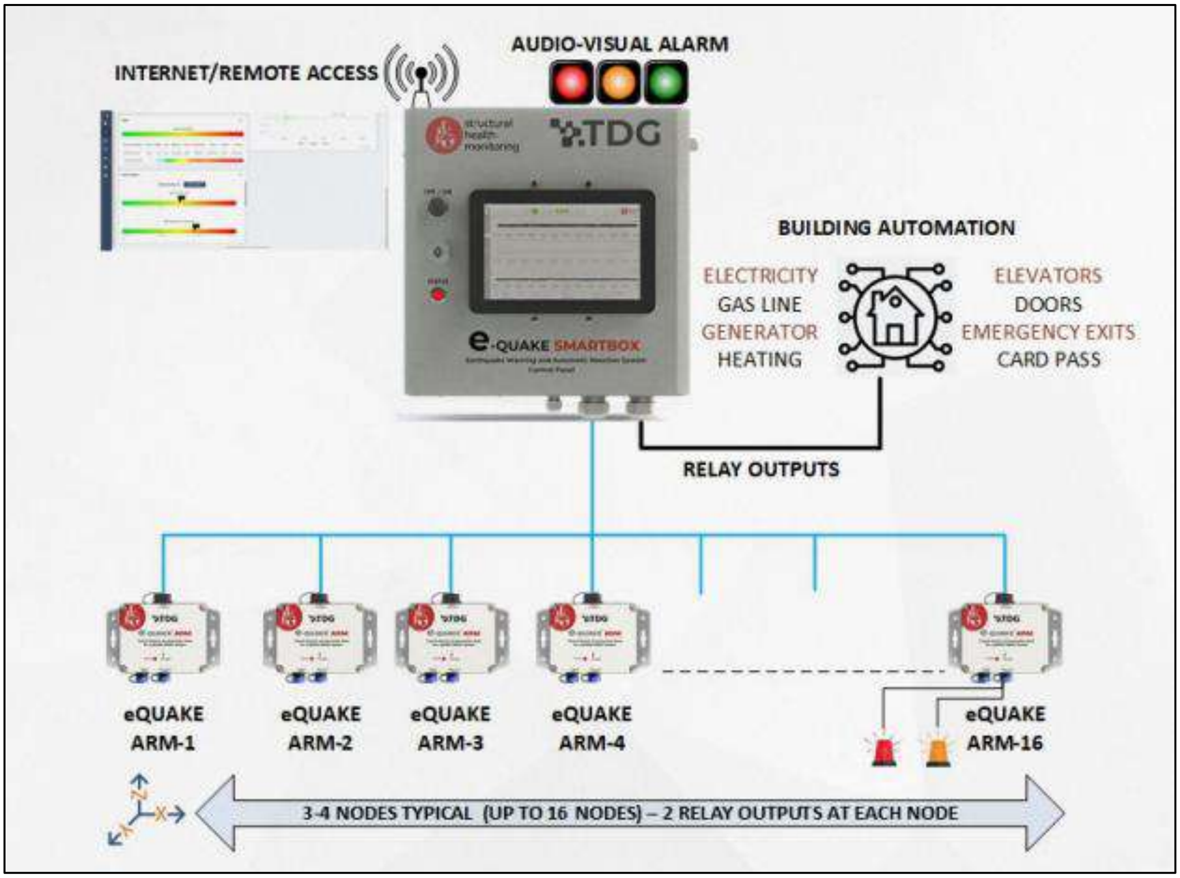


Figure 3.6: E-Quake Smart System

### 3.3.2 E-quake arm triaxial seismic accelerometer PC setup

E-Quake arm devices can be used with e-Quake smart software. This software analyzes the data coming from the devices real-time. After this analysis, PGA (peak ground acceleration) values are obtained. Beside these analyses, FFT (Fast Fourier Transform) analysis is also made.

### 3.3.2.1 *IP Address Configuration*

E-Quake Arm devices are communicating over ethernet. Hence, static IP address must be given to the computer that they are connected. For this, the steps below can be followed:

1. In the network connections page, ethernet connection is selected

2. By right clicking on that ethernet connection and selecting properties, Internet protocol version 4 (IP v4) menu is selected.

3. The important remark regarding the IP address is following:

The IP address must be in the same block with the e-Quake Arm. i.e. if the device’s IP address is 192.168.2.230, PC’s IP block must start with 192.168.2 but the end must be different than the ARM’s.

## 3.3.3 *Software Interface and First Screen*

After the configurations mentioned in previous sections, the electrical and ethernet connections of the devices will be cautiously controlled and then the software will be turned on. In the main window of the software, there exist four tabs: Acceleration, Intensity, FFT and Channels. At the bottom of the window, the status of the connected relays can be seen. The data coming from these devices can also be seen in the graph.

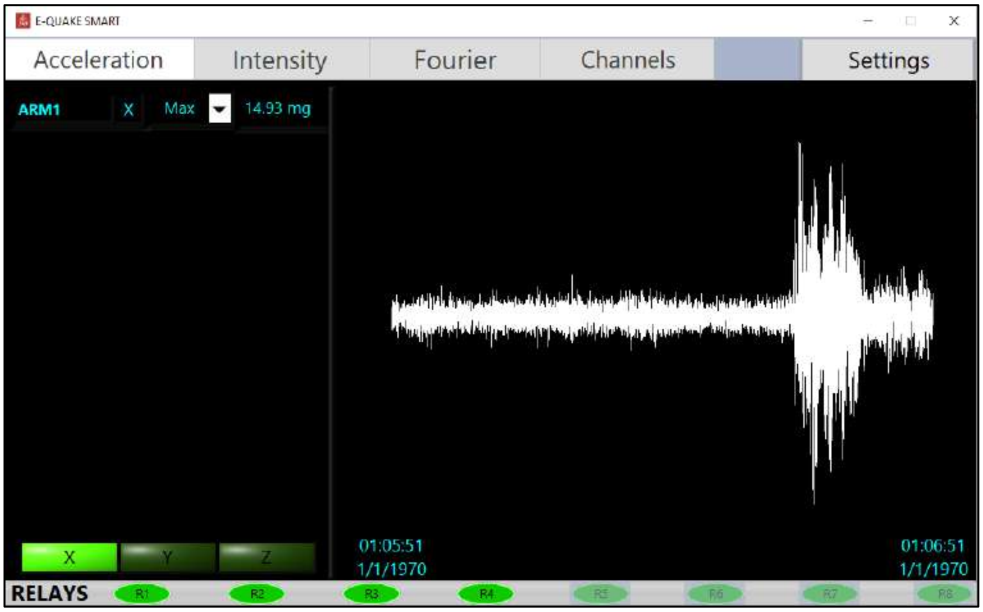


Figure 3.7: E-Quake Smart Software

Similarly, Fast Fourier Transform (FFT) analysis of the real-time data can also be seen in the Fourier tab. This analysis shows which specific frequency is dominant in the structure.

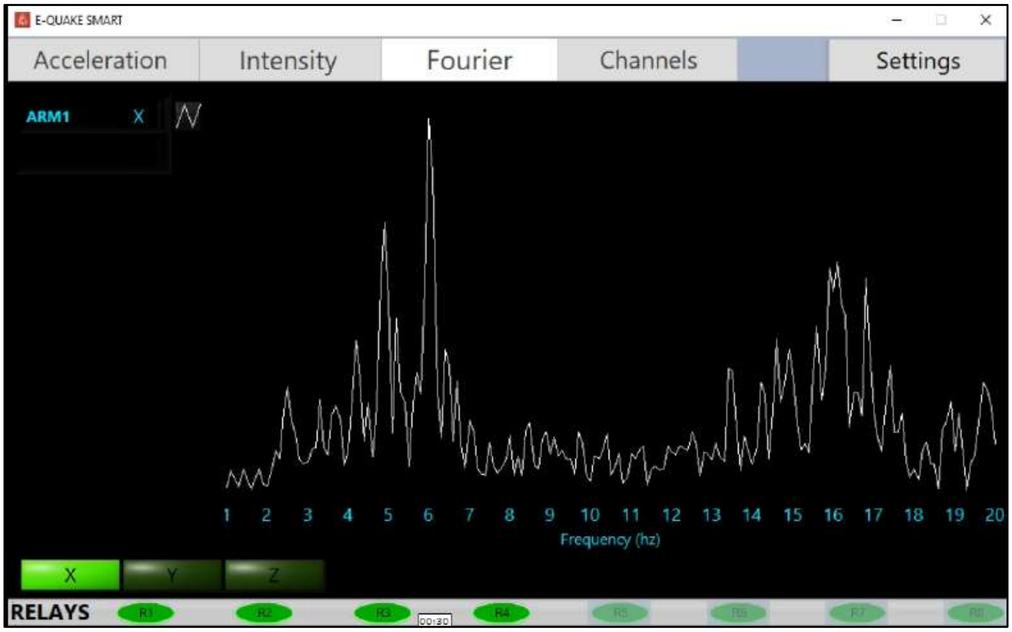


Figure 3.8: Fourier Analysis by E-Quake Smart

### 3.3.4 Data Recording

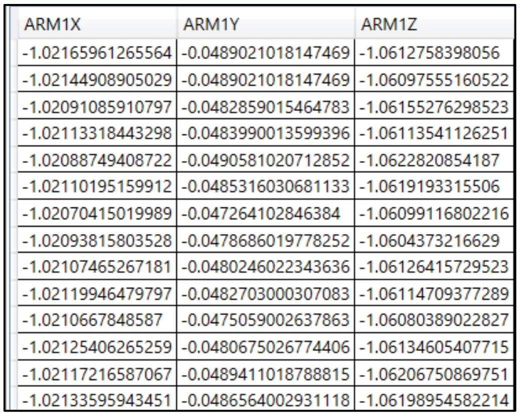
Record Day in the settings panel determines number of days of record that will be kept. If it is 1, it means only there will be 24 files in the folder at most. The sensor will generate a TDMS format file of the recoded data on the desktop.

#### 3.3.4.1 *TDMS Format*

The TDMS (Technical Data Management Streaming) format is a file format developed by National Instruments specifically for managing and storing measurement data. It is commonly used in applications that require high-speed data acquisition and logging, such as scientific research and industrial monitoring.

TDMS provides a structured and efficient way to store large volumes of time-based data, along with associated metadata. One notable feature of the TDMS format is its hierarchical structure, which allows data to be organized into groups, channels, and sub-channels. This hierarchical arrangement facilitates the management of complex datasets and makes it easier to retrieve specific data when working with large amounts of information. TDMS supports a wide range of data types, including numerical data, waveforms, strings, arrays, and more. This versatility enables the storage of various types of measurement data, accommodating the diverse requirements of different applications.

Different software tools and programming environments like DIAdem, LabVIEW, MATLAB, TSMD Viewer and Python are used to view and process TDMS format data.

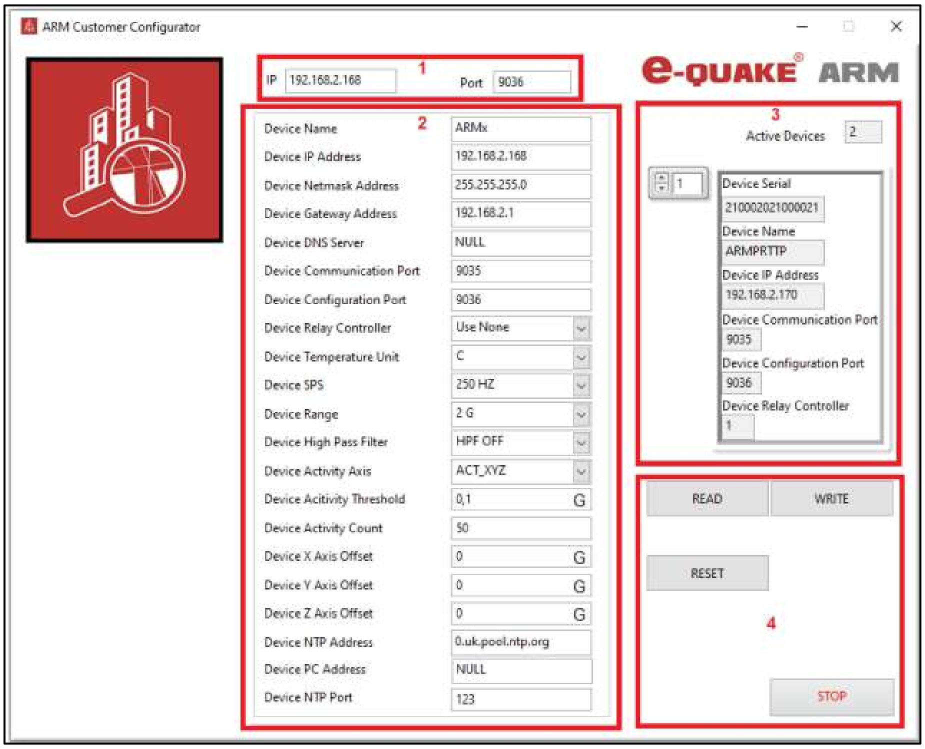


| ARM1X | ARM1Y | ARM1Z |
|---|---|---|
| -1.02165961265564 | -0.0489021018147469 | -1.0612758398056 |
| -1.02144908905029 | -0.0489021018147469 | -1.06097555160522 |
| -1.02091085910797 | -0.0482859015464783 | -1.06155276298523 |
| -1.02113318443298 | -0.0483990013599396 | -1.06113541126251 |
| -1.02088749408722 | -0.0490581020712852 | -1.0622820854187 |
| -1.02110195159912 | -0.0485316030681133 | -1.0619193315506 |
| -1.02070415019989 | -0.047264102846384 | -1.06099116802216 |
| -1.02093815803528 | -0.0478686019778252 | -1.0604373216629 |
| -1.02107465267181 | -0.0480246022343636 | -1.06126415729523 |
| -1.02119946479797 | -0.0482703000307083 | -1.06114709377289 |
| -1.0210667848587 | -0.0475059002637863 | -1.06080389022827 |
| -1.02125406265259 | -0.0480675026774406 | -1.06134605407715 |
| -1.02117216587067 | -0.0489411018788815 | -1.06206750869751 |
| -1.02133595943451 | -0.0486564002931118 | -1.06198954582214 |

Figure 3.9: Recorded values by e-Quake Arm

### 3.3.5 ARM Customer Configurator

In order to change the settings of the e-Quake Arm, the user can use the e-Quake ARM Configurator. The devices in the network can be seen in the 3rd box. The software overview is as following:



IP 192.168.2.168
Port 9036

| | |
|---|---|
| Device Name | ARMx |
| Device IP Address | 192.168.2.168 |
| Device Netmask Address | 255.255.255.0 |
| Device Gateway Address | 192.168.2.1 |
| Device DNS Server | NULL |
| Device Communication Port | 9035 |
| Device Configuration Port | 9036 |
| Device Relay Controller | Use None |
| Device Temperature Unit | C |
| Device SPS | 250 HZ |
| Device Range | 2 G |
| Device High Pass Filter | HPF OFF |
| Device Activity Axis | ACT_XYZ |
| Device Acitivity Threshold | 0,1 G |
| Device Activity Count | 50 |
| Device X Axis Offset | 0 G |
| Device Y Axis Offset | 0 G |
| Device Z Axis Offset | 0 G |
| Device NTP Address | 0.uk.pool.ntp.org |
| Device PC Address | NULL |
| Device NTP Port | 123 |

Active Devices 2

1

| | |
|---|---|
| Device Serial | 210002021000021 |
| Device Name | ARMPRTTP |
| Device IP Address | 192.168.2.170 |
| Device Communication Port | 9035 |
| Device Configuration Port | 9036 |
| Device Relay Controller | 1 |

Figure 3.10: Arm Customer Configurator

### 3.3.6 Features and Capabilities

The e-Quake arm triaxial seismic accelerometers offer advanced features and capabilities that enable precise measurement and analysis of bridge vibrations and seismic events. Key features of this sensor include:

- ***Triaxial Measurement:*** The e-Quake arm triaxial seismic accelerometers are equipped to record acceleration in three axes (X, Y, and Z). This triaxial measurement capability allows for a comprehensive understanding of the bridge's dynamic behavior, including lateral, longitudinal, and vertical movements.
- ***High Sensitivity and Range:*** These accelerometers are designed with high sensitivity and a broad measurement range, enabling the detection and measurement of subtle to strong vibrations and seismic events. This range provides valuable data for assessing the structural response of the bridge under various loading conditions. The frequency of e-Quake arm can be set between 125 Hz to 1000 Hz.
- ***Real-time Monitoring:*** The e-Quake arm accelerometers provide real-time monitoring capabilities, allowing for immediate detection and analysis of vibrations and seismic activities. The data collected in real-time provides timely insights into the dynamic behavior of the bridge, enabling quick responses and appropriate interventions if necessary.
- ***Graphical Representation:*** The accompanying software of the E-Quake Arm accelerometers offers visual representation of acceleration data. The software displays acceleration graphs, illustrating the time domain behavior of the vibrations. Additionally, it presents frequency domain graphs, providing insights into the spectral characteristics of the vibrations and aiding in identifying dominant frequencies and potential resonance issues.

### 3.3.7 Limitations

One limitation of the e-Quake arm triaxial seismic accelerometers is that they store data only for peak ground accelerations. This means that while they provide crucial information about the maximum acceleration values experienced during vibrations or seismic events, they do not offer the user access to the complete time-acceleration history. Consequently, a detailed analysis of the acceleration time history, including waveform characteristics and temporal variations, may not be available using this specific sensor.

### SUMMARY

The e-Quake arm triaxial seismic accelerometers provide advanced capabilities for bridge structural monitoring. With their triaxial measurement, high sensitivity, real-time monitoring, and graphical representation features, they offer valuable insights into the dynamic behavior of bridges. However, it is important to consider the limitation that these accelerometers store data only for peak ground accelerations, without providing access to the complete time-acceleration history. Nonetheless, by leveraging the comprehensive data captured by these accelerometers, bridge engineers and researchers can make informed decisions regarding maintenance, retrofitting, and overall safety enhancements, ultimately contributing to the longevity and resilience of bridge structures.

## CHAPTER NO. 4

# SENSOR MEASUREMENTS ON THE OLD RAVI BRIDGE

This chapter focuses on the sensor measurements conducted on the Old Ravi Bridge in Lahore, Pakistan, utilizing the two aforementioned sensors: the Mobile Accelerometer, and e-Quake arm triaxial seismic accelerometers. The objective of this chapter is to provide a comprehensive overview of the location and methodology employed for data collection, as well as highlight the significance of these measurements in assessing the condition of the bridge. By understanding the location and approach used for taking readings, the validity and reliability of the subsequent analysis and findings can be established.

## 4.1 DATA ACQUISITION

Data acquisition is a fundamental process in sensor measurement, encompassing the capture, conversion, and storage of raw data generated by sensors. This process plays a crucial role in various fields, including scientific research and structural health monitoring. In this section, we will explore the key aspects of data acquisition from a sensor, highlighting its importance and the steps involved in the process.

### 4.1.1 Selection of Sensors

The initial stage of data acquisition involves carefully choosing a sensor that is suitable for the particular application at hand. The selection of the sensor depends on the specific type of measurement that needs to be performed, which could range from temperature and pressure to vibration or acceleration. Various factors come into play during the sensor selection process, including accuracy, measurement range, sensitivity, and compatibility with the environment in which it will be deployed. Considering these factors ensures that the chosen sensor is capable of providing reliable and accurate data for the intended purpose.

### 4.1.2 Sensor Installation and Placement

When installing sensors for structural monitoring, it is crucial to ensure that the installation process does not alter the behavior of the structure. Non-intrusive methods such as surface-mounted sensors or adhesive attachments should be utilized to minimize disruption. Additionally, it is important to consider the incorporation of sensor wiring, conduit, junction boxes, and other accessories in the initial structural design. By accounting for these element from the outset, the design can accommodate the sensors without compromising the structural integrity or aesthetics of the structure.

Strategic sensor placement is essential to capture relevant data and monitor critical areas of the structure. Sensors should be positioned in locations that provide valuable insights into the structural performance, such as areas with potential stress concentrations or critical connections. Furthermore, considering wiring and conduit requirements, as well as providing access for maintenance and calibration, ensures the smooth operation and longevity of the monitoring system. By carefully addressing these aspects, the sensor installation process can be seamlessly integrated into the structure, enabling effective structural monitoring without compromising the integrity of the monitored system.

### 4.1.3 Transfer to Data Acquisition System

There are two primary methods for transferring data from a sensor to a data acquisition unit (DAS): lead wire and wireless transmission. The lead wire method involves a direct physical link between the sensor and the DAS. This method is the least expensive and most commonly used. However, it may not be practical for large structures due to the limitations of long lead wires, which can introduce noise into the signal.

On the other hand, wireless transmission offers the advantage of eliminating the need for physical wiring between the sensor and the DAS. However, it is a more expensive option compared to lead wires. Wireless transmission can be slower and may not provide the same level of data security as a wired connection. Despite these drawbacks, the use of wireless transmission is expected to increase in the future as technology advances and the demand for wireless sensor networks grows.

### 4.1.4 Data Sampling and Collection

Sampling and collecting data in a monitoring system require a careful balance between data volume and usability. The amount of collected data should neither be too limited to compromise its usefulness nor so extensive that it becomes overwhelming to interpret. This balance can be achieved by considering factors such as the number of sensors and data sampling rates. The selection of sensors and their placement should align with the specific monitoring objectives, while the sampling rate needs to capture relevant information without generating an excessive amount of data. Efficient strategies for data organization and storage are also crucial to facilitate easy access and retrieval of information, particularly when dealing with large data volumes. Implementing data compression techniques, effective file naming conventions, and appropriate storage solutions can optimize the manageability and usefulness of the collected data.

The ultimate goal of efficient data sampling and storage strategies is to support data analysis and interpretation. By carefully addressing the number of sensors, sampling rates, and data sorting methods, monitoring systems can provide valuable insights into various fields such as structural health monitoring.

## 4.2 DATA ACQUISITION FROM OLD RAVI BRIDGE

In order to gain insights into the structural behavior of the Old Ravi Bridge, data acquisition was carried out using two different types of accelerometers: a mobile accelerometer and an e-quake arm triaxial seismic accelerometer. The data acquisition process aimed to provide a comprehensive understanding of the bridge's dynamic response and to assess its condition.

### 4.2.1 Selection of Sensors for Old Ravi Bridge

The selection of appropriate sensors for acceleration measurement on the Old Ravi Bridge was a critical decision in our monitoring process. After careful consideration, we opted to utilize a mobile accelerometer and an e-quake arm triaxial seismic accelerometer for data collection. The mobile accelerometer, utilized through the "Physics Toolbox Suite" app, offered a convenient and cost-effective solution. With a scanning rate of 200 Hz, it provided real-time acceleration data, allowing us to capture rapid changes in the bridge's behavior.

Additionally, we chose the e-quake arm triaxial seismic accelerometer due to its advanced capabilities. This sensor was specifically designed for seismic applications and had the ability to record acceleration in three axes simultaneously. Its software provided comprehensive visualization tools, including acceleration and frequency domain graphs, enabling a more detailed analysis of the bridge's dynamic response. The selection of these sensors was based on their compatibility with our monitoring objectives, accuracy requirements, and the need for real-time data acquisition.

However, it is worth noting that we did not utilize the Extech heavy duty vibration meter for our measurements. We encountered limitations with this device, as its scanning rate was too slow for our monitoring needs. Furthermore, the acceleration sensor on the Extech device was not functioning properly. These issues rendered it unsuitable for our data acquisition purposes. As a result, we relied on the mobile accelerometer and e-quake arm triaxial seismic accelerometer, which proved to be reliable and effective in capturing the necessary acceleration data from the Old Ravi Bridge.

### 4.2.2 Sensor Installation and Placement on Old Ravi Bridge

During the placement of the e-quake arm triaxial seismic accelerometer on the Old Ravi Bridge, the research team encountered a significant challenge. The sensor required a 12V DC power supply to operate effectively, but supplying power on the bridge proved to be a difficult task. To address this issue, a battery system was developed specifically for powering the sensor. This battery system served as a reliable and portable solution, providing the necessary power supply to ensure the continuous operation of the e-quake arm triaxial seismic accelerometer. The team's ingenuity in developing this battery system allowed them to overcome the obstacle of limited power availability on the bridge and successfully gather the essential acceleration data for their monitoring purposes.

During the sensor placement and installation phase, the research team took readings using a mobile sensor on all 15 spans of the Old Ravi Bridge. This approach ensured comprehensive data collection across the entire bridge structure. Additionally, the team utilized the E-Quake arm triaxial seismic accelerometer to capture readings on specific critical sensors where subtle variations in behavior were observed in the data collected from the mobile accelerometer. By incorporating the use of the E-Quake arm, the team aimed to gain deeper insights into the bridge's structural dynamics and identify any potential anomalies or variations in the measured data.

In conjunction with the mobile sensor readings, the data collected from the E-Quake arm provided a more comprehensive understanding of the bridge's behavior. This combination of sensors allowed for comparative analysis and verification, enhancing the accuracy and reliability of the acquired data. By employing both sensors, the research team could effectively monitor and evaluate the structural performance of the Old Ravi Bridge, ensuring a thorough assessment of its condition and facilitating informed decision-making for maintenance and safety measures.

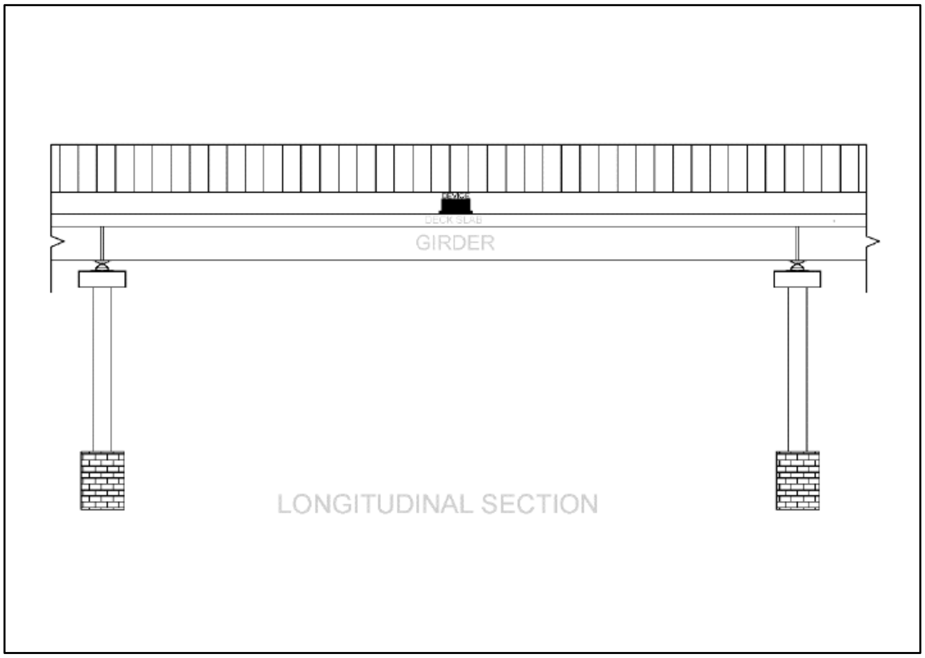


Figure 4.1: Position of sensor in longitudinal direction

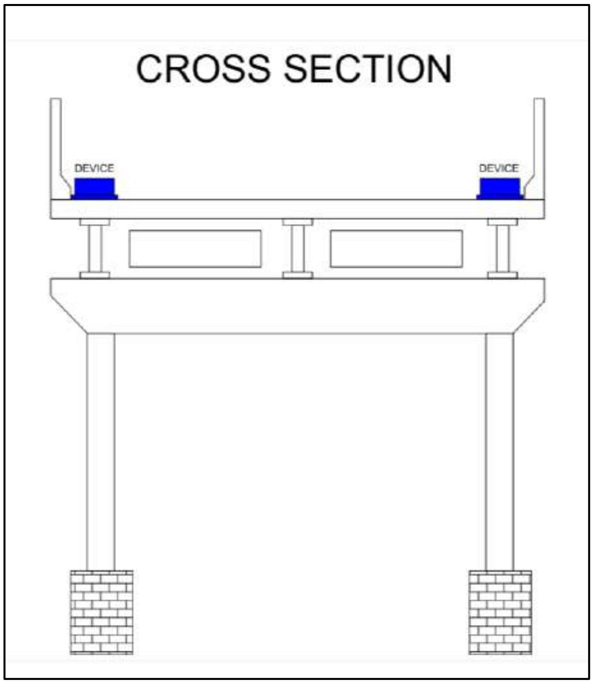


Figure 4.2: Position of sensor in transverse direction

#### 4.2.2.1 Placement of sensor at the bottom of Bridge girders

To facilitate a detailed comparison between the mobile sensor and the e-quake arm triaxial seismic accelerometer, both sensors were placed at the bottom of all three bridge girders of span 1. The placement of the sensors side by side allowed for simultaneous data collection, enabling a direct and immediate comparison of the values obtained. This setup was carefully designed to provide valuable insights into the consistency and accuracy of the measurements obtained from both sensors.

By placing the sensors in close proximity to each other, the research team aimed to identify any discrepancies or variations in the data recorded by the mobile sensor and the e-quake arm triaxial seismic accelerometer. This comparative analysis was crucial in understanding the reliability and performance of each sensor and their suitability for the monitoring objectives. The side-by-side placement allowed for a comprehensive assessment of the sensors' performance, highlighting any potential differences in the measured values and shedding light on the factors that might influence their readings.

Overall, this approach provided valuable information for evaluating the performance of both sensors, enabling the research team to make informed decisions regarding the reliability and accuracy of the collected data. The direct comparison between the mobile sensor and the e-quake arm triaxial seismic accelerometer served as a crucial step in the data analysis process, enhancing the overall integrity and comprehensiveness of the research findings.

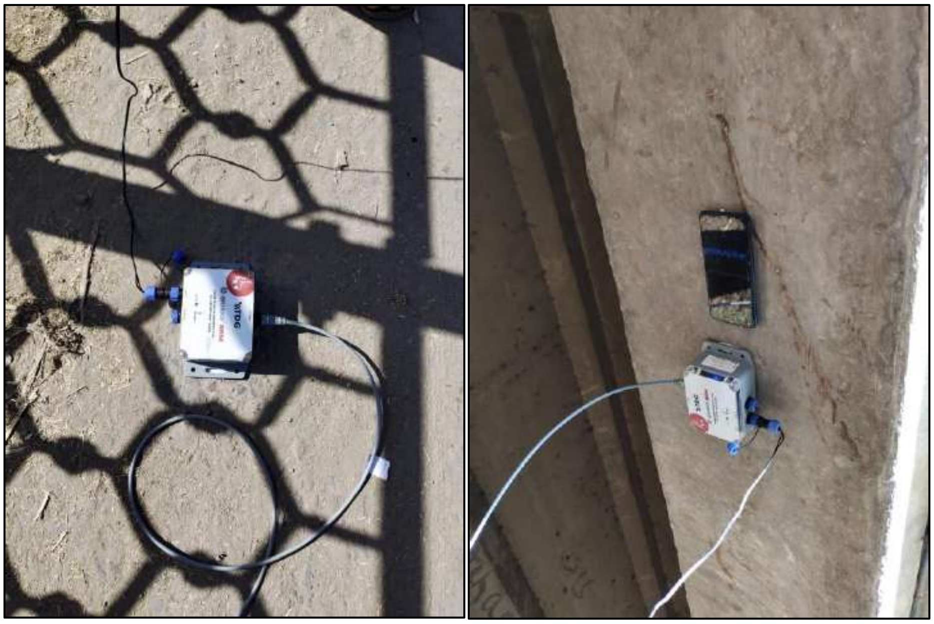


Figure 4.3: Placement of Sensor on wearing surface and bridge girder

### 4.2.3 Transfer to Data Acquisition System

The e-quake arm triaxial seismic accelerometer utilizes an Ethernet cable for the seamless transfer of data from the sensor to a laptop or computer. This method ensures a reliable and high-speed connection between the two devices, enabling efficient data transmission and analysis. The Ethernet cable serves as a conduit for the digital data generated by the accelerometer, allowing it to be directly streamed to the laptop for further processing.

Figure 4.4: Data transfer to the laptop

### 4.2.4 Data Sampling and Collection

Normally the general principal is that the sampling frequency of your device must be at least five times the natural frequency of the structure. Normally 100 Hz frequency of the sensor is sufficient to capture the natural frequency of the structures.

During the data sampling process, the mobile sensor was set to a frequency of 200 Hz, while the e-Quake arm triaxial seismic accelerometer operated at a frequency of 250 Hz. To ensure an adequate duration for data collection, readings were gathered for a period of 3 minutes when the sensors were placed on the wearing surface of the bridge. This time interval was chosen to capture sufficient data points for analysis and provide a representative sample of the bridge's behavior under normal operating conditions.

However, when the sensor was positioned on the girder, a longer data collection duration of 5 minutes was implemented. This extended time period accounted for potential variations in the structural response and allowed for a more comprehensive understanding of the bridge's performance in that specific location. By acquiring data for these specified durations, the research team aimed to strike a balance between capturing an adequate number of data points without overwhelming the analysis process, thereby ensuring that the collected data was both reliable and manageable for subsequent interpretation and evaluation.

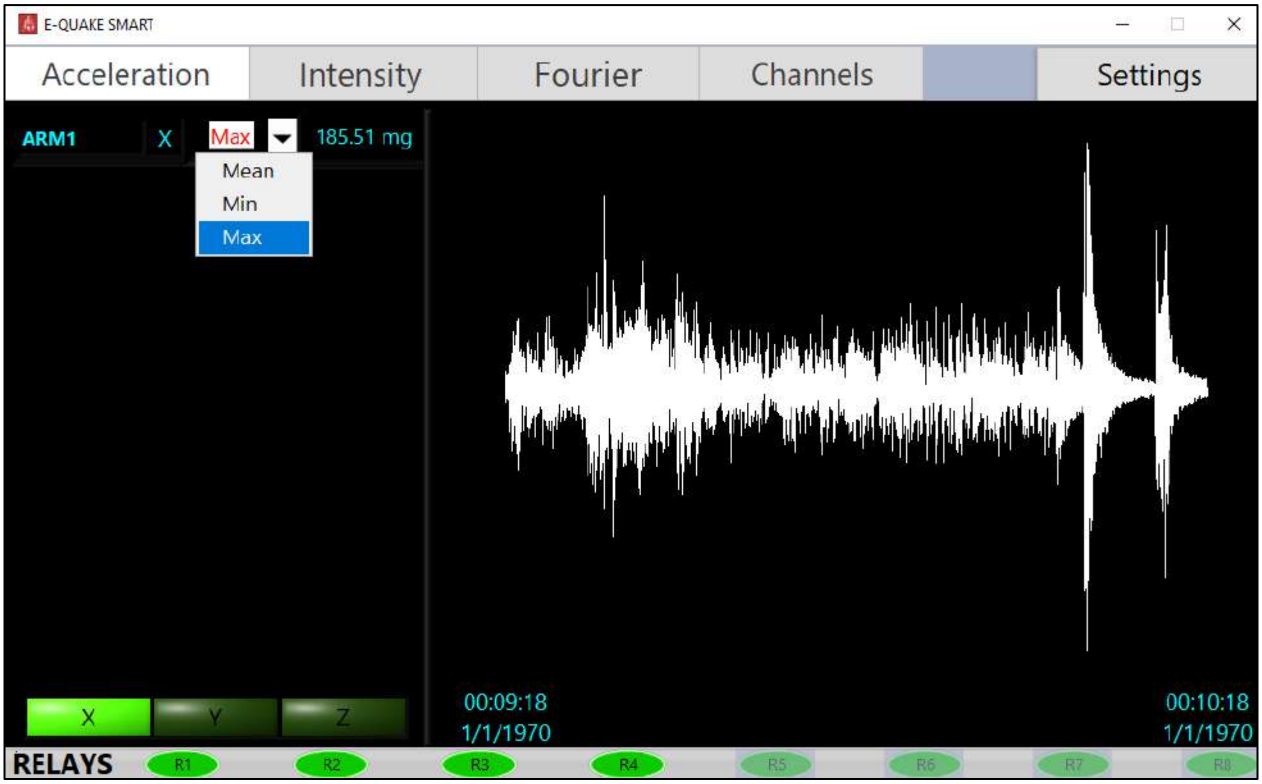


Figure 4.5: Collection of Data from Sensor to laptop

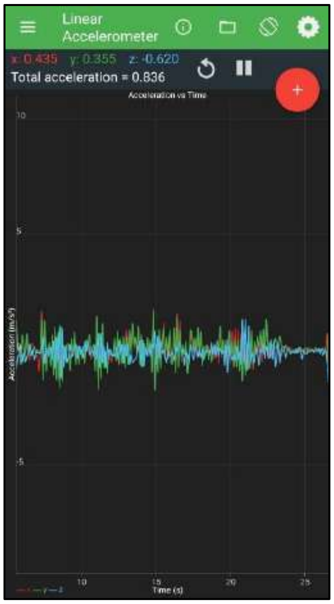


Figure 4.6: Collection of data from mobile sensor

## 4.3 DATA PROCESSING

In the data processing step, the collected data from all 15 spans of the bridge underwent a series of analyses to extract valuable insights.

### 4.3.1 Acceleration Time History

Initially, time vs. acceleration curves were plotted for each span, providing a visual representation of the structural response over time. This allowed for a comprehensive comparison between the spans, identifying any notable differences or patterns in their behavior.

### 4.3.2 Time Domain to Frequency Domain

To further analyze the data, a transformation from the time domain to the frequency domain was performed using the Fast Fourier Transform (FFT) and Fourier functions in MATLAB. This conversion enabled a deeper exploration of the frequency components present in the data. By analyzing the frequency domain representation of the data, it became possible to identify specific frequencies or vibration modes that might be significant for the bridge's structural behavior.

### 4.3.2.1 *Advantages of Frequency Domain*

Converting data from the time domain to the frequency domain offers several advantages:

- It allows for a more detailed examination of the frequency content and distribution within the measured data. This can help in identifying dominant frequencies or specific vibration modes that may be critical for understanding the bridge's response to external forces or environmental conditions.
- The frequency domain representation facilitates the detection of hidden patterns or anomalies that might not be readily apparent in the time domain. By isolating and analyzing specific frequency components, it becomes easier to identify and investigate unusual or unexpected behavior within the structural response.
- The data in frequency domain can be used to check the change in frequency of the structure with time which can also be related with the stiffness of the structure.

Overall, the conversion from the time domain to the frequency domain provides a powerful tool for analyzing and interpreting the collected data, enabling a deeper understanding of the bridge's dynamic behavior and aiding in the identification of potential issues or areas of concern.

## 4.4 RESULTS AND DISCUSSIONS

In the Results & Discussions section of the thesis, the first set of data presented comprises the acceleration time history graphs for the x, y, and z axes specifically for span 1. These graphs illustrate the recorded acceleration values over time, and they were plotted using the data obtained from the wearing surface of the span. Upon analyzing the acceleration time history graphs, a consistent trend was observed across most spans, indicating similar behavior in terms of acceleration patterns.

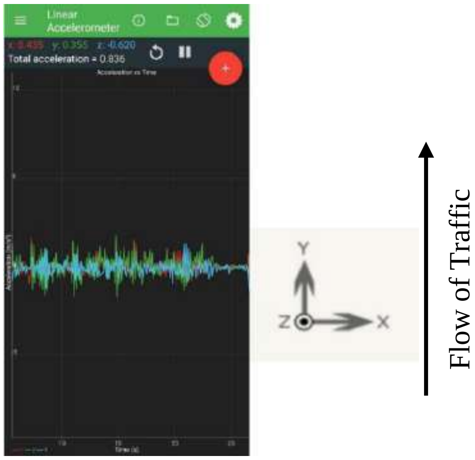
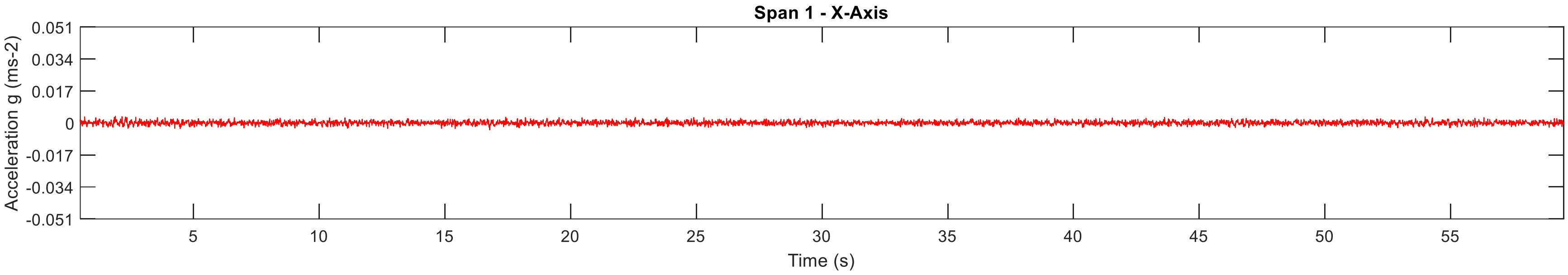
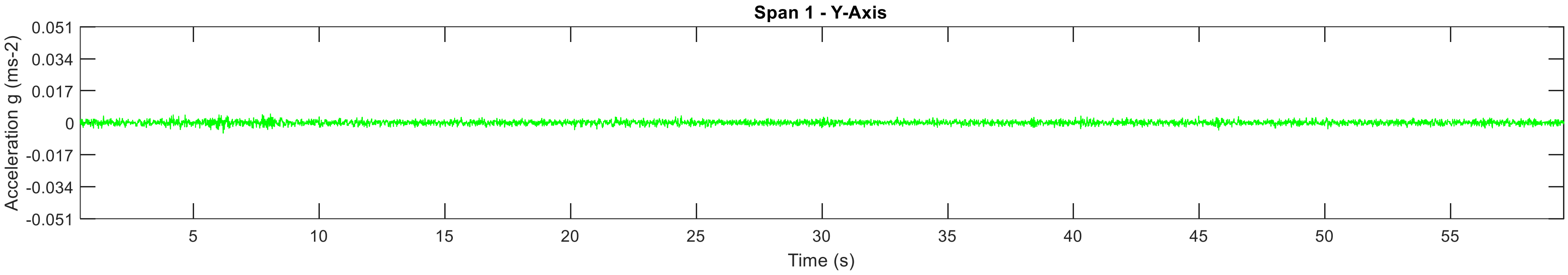


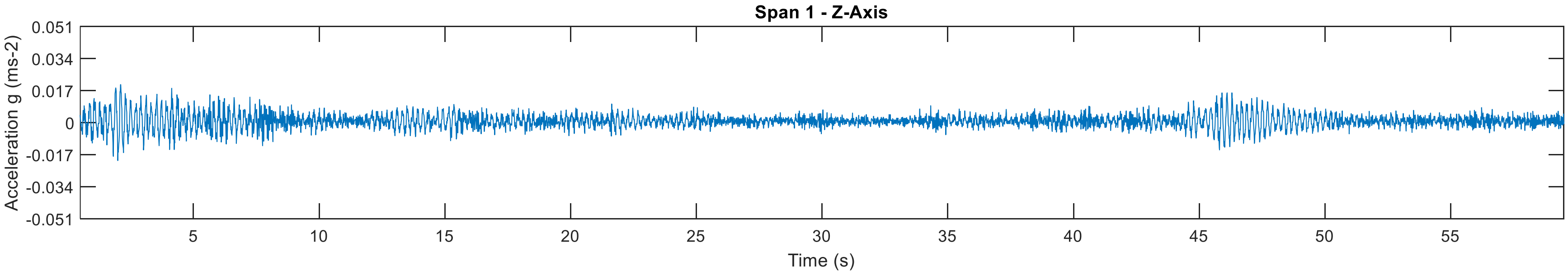
Figure 4.7: Axis of Linear Accelerometer



Graph 4.1: Span 1 – X axis Acceleration Time History



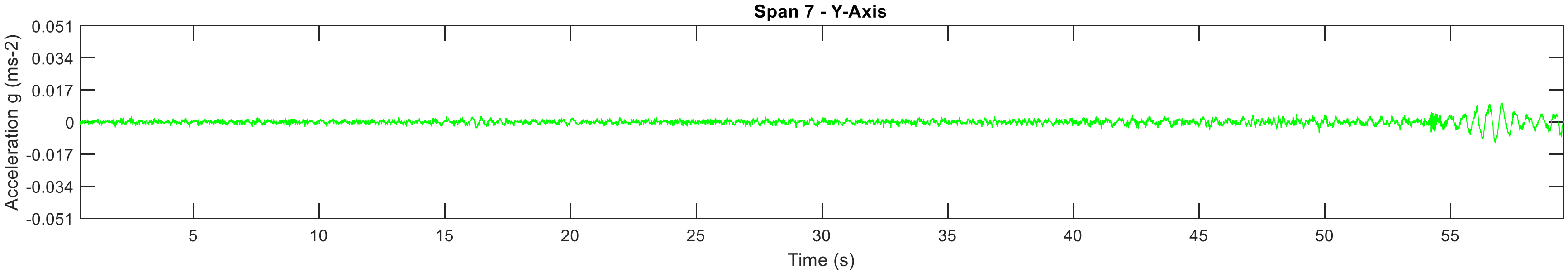
Graph 4.2: Span 1 – Y axis Acceleration Time History



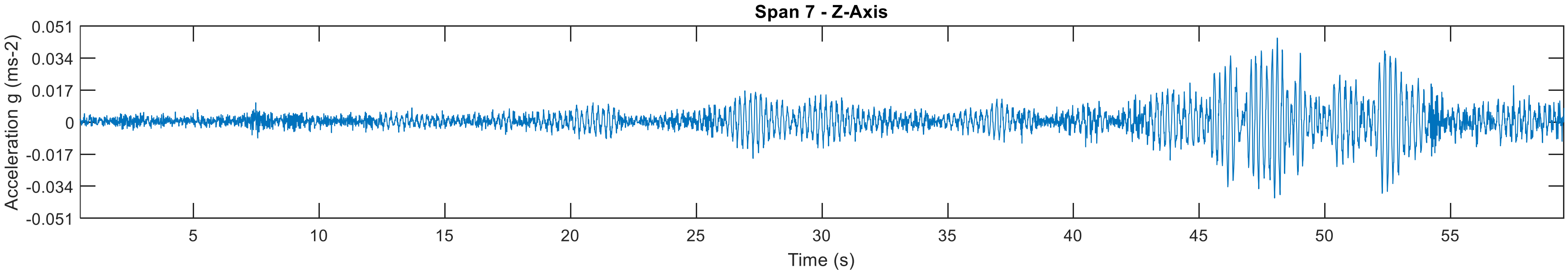
Graph 4.3: Span 1 – Z axis Acceleration Time History

### 4.4.1 Distinct Behavior in Span 7

Upon analysis of the recorded data, it was observed that span 7 exhibited slightly higher values of acceleration compared to the other spans. This deviation in acceleration levels suggests the presence of unique factors influencing the structural response in this particular span. Furthermore, a closer examination reveals that the slightly higher values of acceleration in span 7 were primarily observed in the z-axis measurements. Additionally, a slight elevation in acceleration values was also noticed in the y-axis measurements of span 7, albeit to a lesser extent. These observations indicate localized variations in the dynamic behavior of the bridge within span 7, specifically in the vertical (z-axis) and longitudinal (y-axis) directions. Further investigation and analysis will be necessary to identify the underlying causes and assess the implications of these slightly elevated acceleration levels on the overall structural integrity of the bridge.



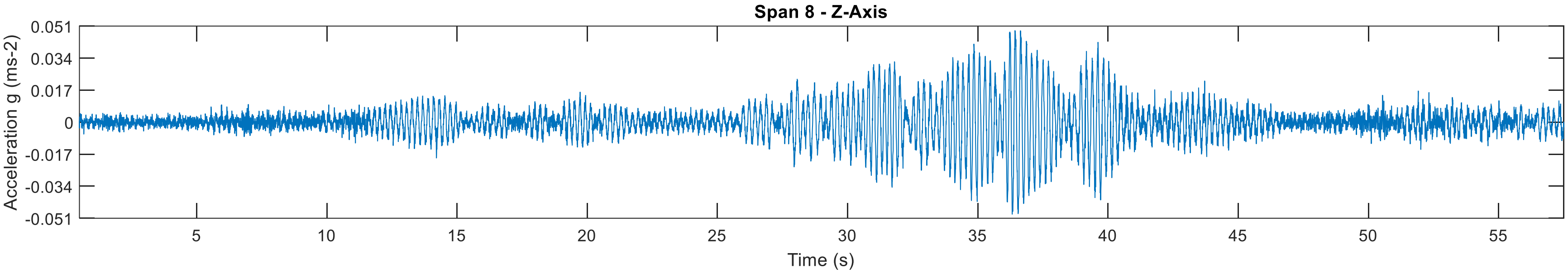
Graph 4.4: Span 7 – Y axis Acceleration Time History



Graph 4.5: Span 7 – Z axis Acceleration Time History

### 4.4.2 Distinct Behavior in Span 8

Upon analyzing the collected data, it was evident that the maximum value of acceleration was observed in span 8. This maximum acceleration value was predominantly observed in the z-axis direction, with a magnitude of approximately 0.051 times the acceleration due to gravity.

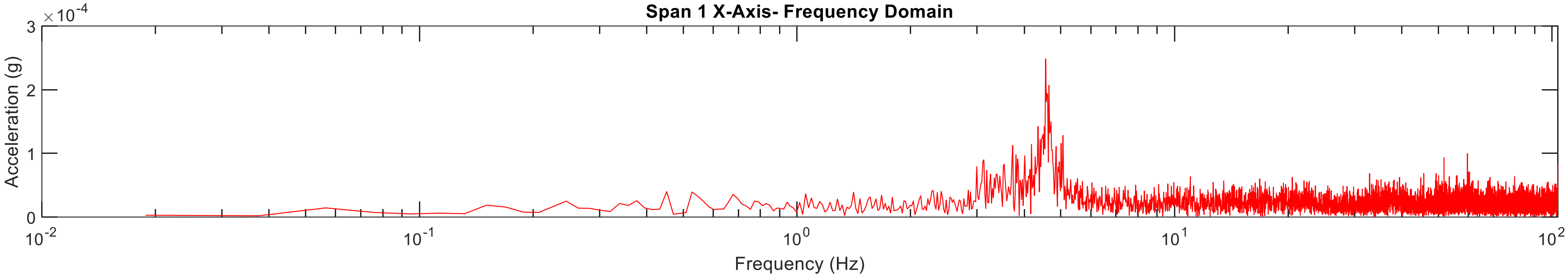


Graph 4.6: Span 8 – Z axis Acceleration Time History

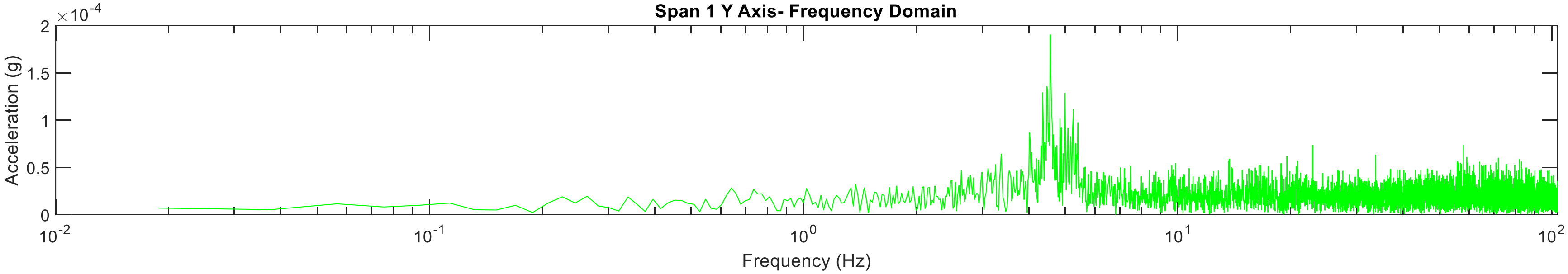
In ***Appendix A***, the acceleration time history graphs for all 15 spans of the Old Ravi Bridge are provided. These graphs depict the recorded acceleration values in the x, y, and z axes for each respective span. By examining the acceleration time history graphs, valuable insights can be gained into the dynamic behavior and response of the bridge structure. These graphs serve as a comprehensive visual representation of the collected data, enabling a detailed analysis and comparison of acceleration patterns across different spans. The inclusion of these graphs in the appendix enhances the transparency and thoroughness of the research, allowing readers to refer to the specific acceleration trends observed in each span.

### 4.4.3 Frequency Domain Graphs

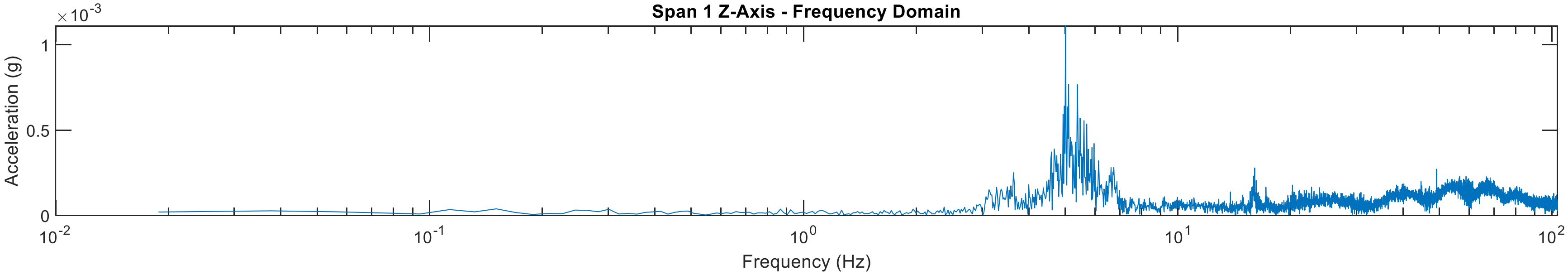
The frequency domain analysis of the Old Ravi Bridge revealed a consistent natural frequency across all three axes, indicating a uniform structural behavior. The most prominent frequency observed in each axis was approximately 5 Hz, highlighting the resonance characteristics of the bridge. This finding suggests that the bridge's dynamic response is governed by this dominant frequency.



Graph 4.7: Span 1 – X axis Frequency Domain

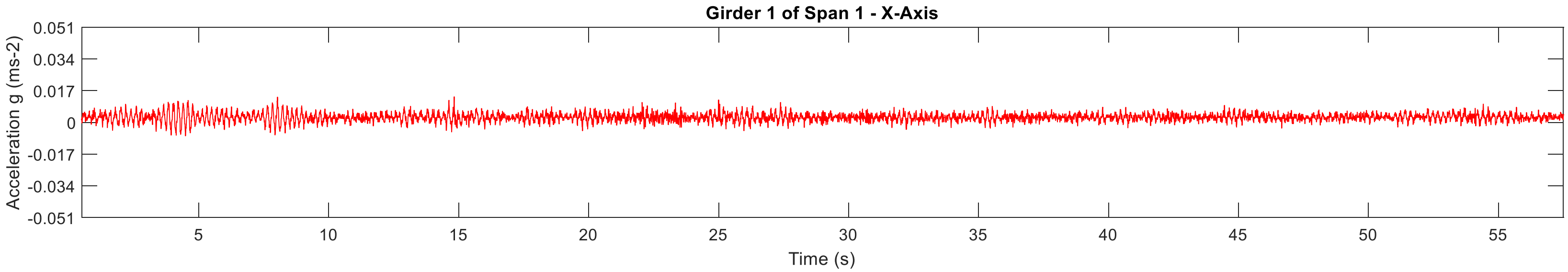


Graph 4.8: Span 1 – Y axis Frequency Domain

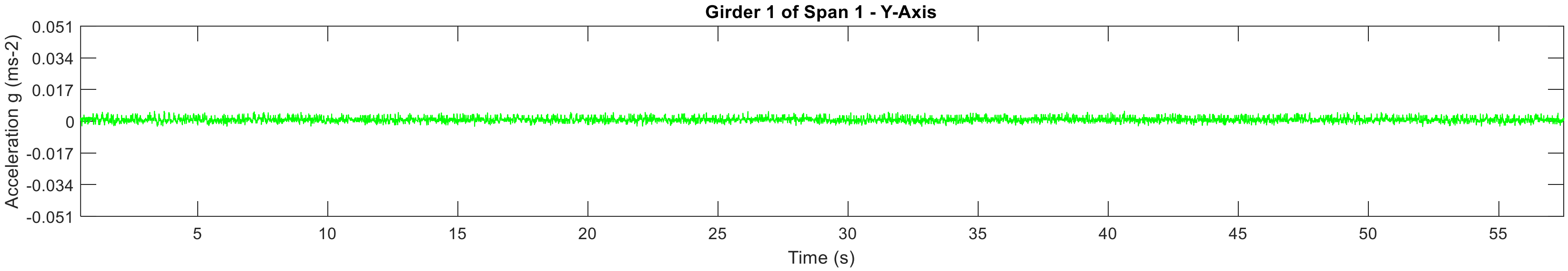


Graph 4.9: Span 1 – Z axis Frequency Domain

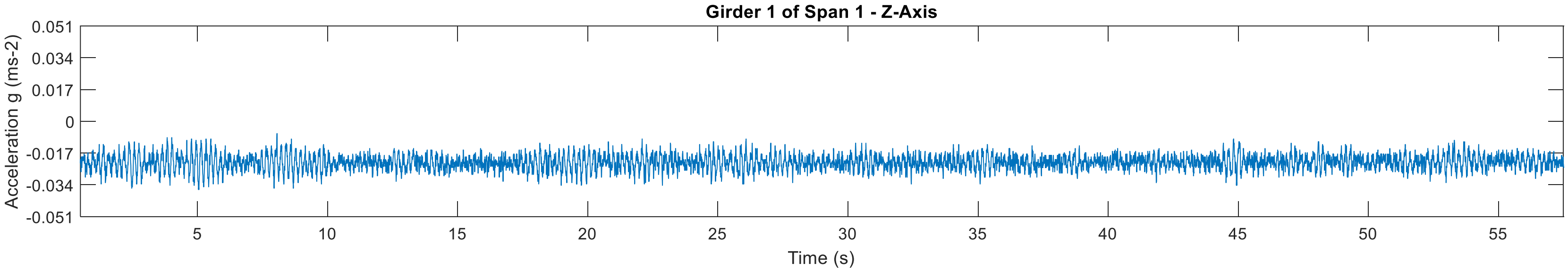
### 4.4.4 Acceleration Time History for Girders



Graph 4.10: Girder 1 Span 1 – X axis Acceleration Time History



Graph 4.11: Girder 1 Span 1 – Y axis Acceleration Time History



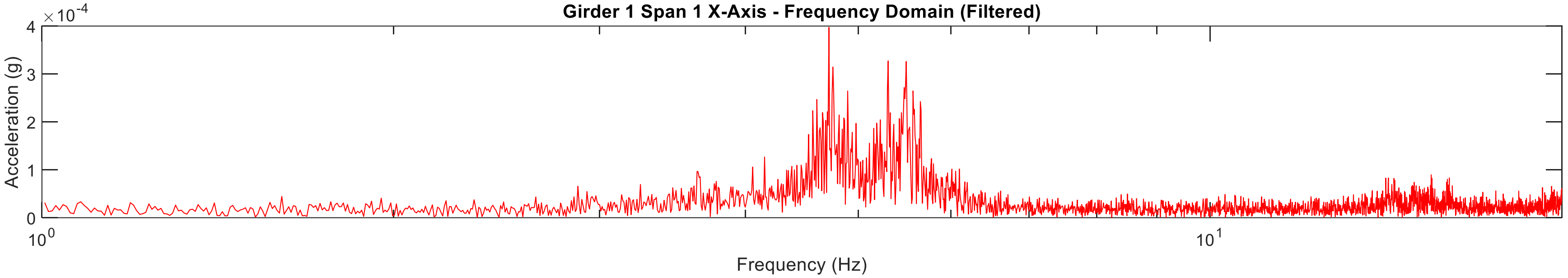
Graph 4.12: Girder 1 Span 1 – Z axis Acceleration Time History

Upon analyzing the acceleration time history for the girder of the Old Ravi Bridge, it was observed that the values of acceleration remained within acceptable limits. The maximum acceleration value recorded during the analysis was approximately 0.034 g. This finding indicates that the structural response of the girder, in terms of acceleration, remained well within the prescribed safety thresholds. The adherence of the acceleration values to the specified limits is a positive indication of the structural performance and integrity of the girder. It suggests that the girder can withstand the applied loads and environmental forces without experiencing excessive acceleration levels that could potentially compromise its stability and safety. These results provide valuable insights into the behavior of the girder under operational conditions and contribute to the overall understanding of its structural health.

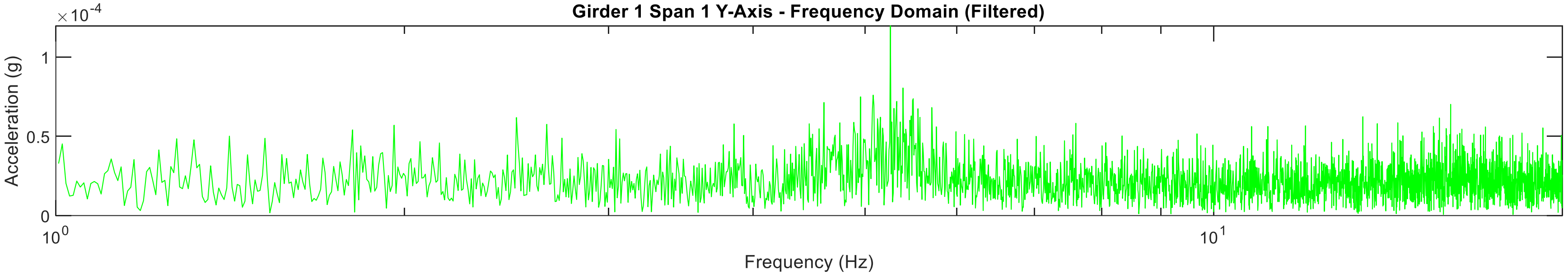
### 4.4.5 Frequency Domain of the Girder

Upon examining the frequency domain graphs for the girder of span 1, it is noteworthy that the most prominent frequency observed is approximately 5 Hz. Interestingly, this frequency bears a striking resemblance to the dominant frequency obtained from the wearing surface. This intriguing similarity suggests a potential correlation between the structural response of the girder and the dynamic characteristics of the road's wearing surface. It implies that the girder's behavior, particularly in terms of acceleration, is significantly influenced by the dynamics of the wearing surface at this specific frequency range. This finding sheds light on the intricate interaction between the girder and the road surface, unveiling a potential connection that warrants further investigation.

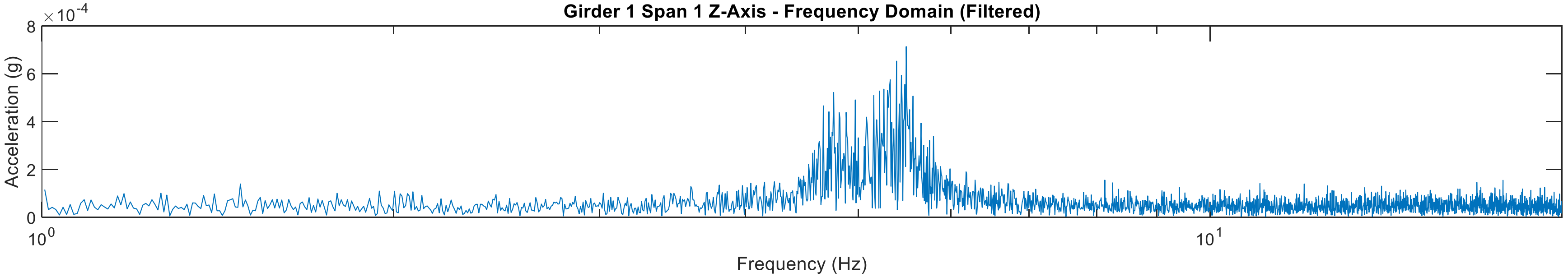
The close alignment in frequencies between the girder and the wearing surface holds implications for understanding the structural dynamics and performance of the bridge system. By identifying the resonant frequency shared between the girder and the wearing surface, we can gain valuable insights into their coupled behavior. This knowledge is instrumental in assessing the structural integrity, identifying potential vulnerabilities, and implementing appropriate mitigation measures. Furthermore, it offers valuable information for designing and engineering future bridge systems, as it underscores the importance of considering the interaction between the bridge structure and the road surface to enhance overall performance and longevity. Understanding the resonant behavior and frequency characteristics facilitates a comprehensive understanding of the bridge system's response to dynamic loads, contributing to the development of more resilient and efficient infrastructure.



Graph 4.13: Girder 1 Span 1 – X axis Frequency Domain



Graph 4.14: Girder 1 Span 1 – Y axis Frequency Domain



Graph 4.15: Girder 1 Span 1 – Z axis Frequency Domain

### 4.4.6 Comparison of e-Quake Arm Triaxial Seismic Accelerometer and Mobile Linear Accelerometer

To overcome the limitation of the e-quake arm triaxial seismic accelerometer's inability to record time history data, the researcher focused on comparing the maximum acceleration values obtained from both the mobile accelerometer and the e-quake arm triaxial seismic accelerometer. By examining the maximum acceleration due to gravity values, the study aimed to draw a meaningful comparison between the two measurement devices.

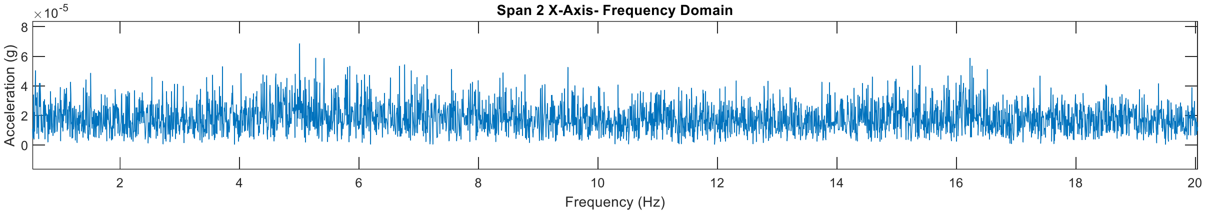
**Table 4.1: Comparison of maximum g values between mobile and e-Quake arm tri-axial seismic Accelerometer**

| Maximum Acceleration (g) | Mobile Accelerometer | E-Quake Arm Triaxial Seismic Accelerometer |
|---|---|---|
| X- Axis | 0.014287 | 0.033945 |
| Y- Axis | 0.006435 | 0.005893 |
| Z- Axis | 0.030746 | 0.021216 |

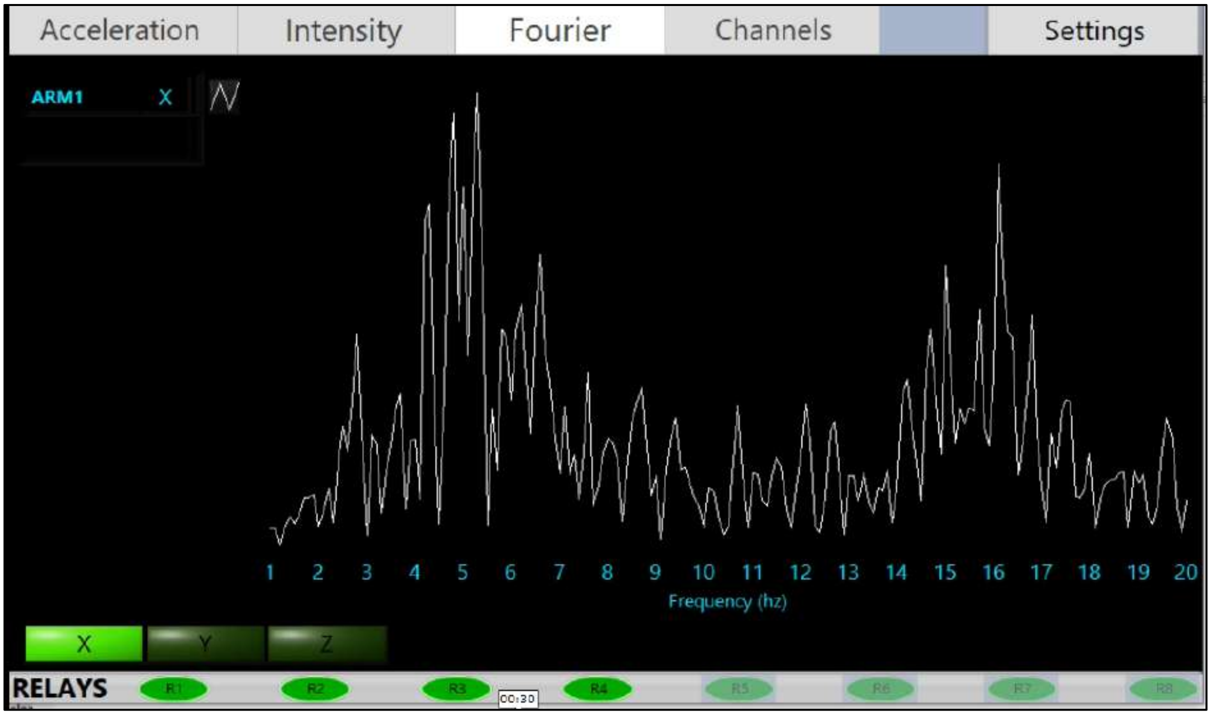
Upon comparing the maximum values obtained from the e-quake arm triaxial seismic accelerometer and the mobile accelerometer, slight differences were observed. While both devices provided valuable data on the maximum acceleration experienced by the bridge structure, the recorded values exhibited some variation. These disparities can be attributed to the inherent differences in the measurement techniques and characteristics of the two instruments. Factors such as sensor sensitivity, data acquisition algorithms, and the positioning of the devices may contribute to the variations in the recorded maximum values. Despite these differences, the comparative analysis of the maximum values offers valuable insights into the dynamic behavior of the bridge and aids in understanding the variations in acceleration response between the e-quake arm triaxial seismic accelerometer and the mobile accelerometer.

#### 4.4.4.1 Comparison of Frequency Domain

The comparison of frequency domain values for span 2 obtained from both the e-quake arm triaxial seismic accelerometer and the mobile accelerometer revealed a striking similarity. This implies a strong concurrence in the frequency content captured by both sensors, indicating their efficacy in accurately measuring the structural response of the bridge. The consistent frequency domain values provide assurance regarding the accuracy and reliability of the data collected, enabling reliable analysis and assessment of the bridge's dynamic behavior. The agreement in frequency domain values between the two sensors signifies their compatibility and suitability for capturing the bridge's vibrations. This coherence allows for seamless integration and comparison of data from multiple sensors, facilitating a comprehensive understanding of the bridge's behavior and supporting informed decisions regarding its structural health and performance. Overall, the consistent frequency domain values obtained from the e-quake arm triaxial seismic accelerometer and the mobile accelerometer reinforce their reliability and validate their usage in assessing the dynamic characteristics of the bridge's span 2.



Graph 4.16: Span 2 – X axis Frequency Domain



Graph 4.17: Span 2 – X axis Frequency Domain using E-Quake Smart Software

## 4.5 SUMMARY

In conclusion, this chapter focused on the analysis and comparison of the acceleration data obtained from the mobile accelerometer and the e-quake arm triaxial seismic accelerometer for structural health monitoring of the bridge spans. The time-domain and frequency-domain analysis provided valuable insights into the dynamic behavior of the bridge under various loading conditions. The acceleration time history graphs highlighted the trends and variations in the acceleration values along different axes for each span, while the frequency domain analysis revealed the dominant frequencies associated with the structural response.

One significant finding was the remarkable similarity in the results obtained from both the mobile accelerometer and the e-quake arm triaxial seismic accelerometer. The comparable values in both the time domain and the frequency domain signify the consistency and accuracy of the data collected by the mobile accelerometer. This observation highlights the potential of mobile accelerometers as a cost-effective solution for structural health monitoring applications. The affordability and accessibility of mobile accelerometers make them a promising alternative to traditional monitoring systems, enabling wider implementation and extensive data collection in a cost-efficient manner.

The congruence in the results obtained from the mobile and e-quake sensors demonstrates the feasibility and reliability of mobile accelerometers for structural health monitoring. Their low cost and ease of deployment make them an attractive option for continuous monitoring of structures, enabling real-time assessment and timely intervention in case of any deviations or anomalies in the structural response. The consistent results obtained from both sensors validate the use of mobile accelerometers as an efficient and economical solution for monitoring the structural health of bridges and other infrastructure systems.

## CHAPTER NO. 5

# CONCLUSIONS & RECOMMENDATIONS

## 5.1 CONCLUSIONS

In conclusion, this thesis has provided valuable insights into the condition assessment and structural health monitoring of the Old Ravi Bridge. Through a comprehensive analysis of the bridge's components and the application of different sensors, several key findings have been identified.

Firstly, the investigation revealed that Spans 7 and 8 of the bridge are critical spans exhibiting higher vibration levels compared to other spans. This suggests the need for focused attention and potential remedial measures to address the structural behavior and integrity of these sections. The identification of these critical spans serves as a crucial step toward targeted maintenance and monitoring strategies.

Furthermore, the study highlighted the significant impact of improper functioning of expansion joints and drainage systems on the deterioration of the bridge. These findings emphasize the importance of regular inspections and proactive maintenance practices to ensure the efficient performance and longevity of the bridge structure. Attention should be directed towards addressing the issues related to these components, such as proper maintenance of expansion joints and the implementation of effective drainage systems.

Another critical aspect that emerged from the research is the condition of the bearing pads. The evaluation of these components revealed their critical situation, suggesting the urgent need for maintenance or potential replacement. Neglecting the proper functioning of bearing pads can lead to structural instability and compromise the overall safety and performance of the bridge.

The outcomes of this study have significant implications for the bridge engineering community and infrastructure management authorities. The identified critical spans, along with the issues related to expansion joints, drainage systems, and bearing pads, highlight the areas that require immediate attention and remedial actions. These findings can guide decision-making processes, prioritize resource allocation, and enable the development of targeted maintenance and monitoring plans for the OLD Ravi Bridge.

## 5.2 RECOMMENDATIONS

Based on the insights gained from this research, several future recommendations can be proposed to enhance the field of Structural Health Monitoring (SHM) in Pakistan and improve the condition assessment of bridges:

1. Establish a schedule of inspection for bridges, with particular emphasis on monitoring the drainage system prior to the rainy season. This proactive measure will help prevent water accumulation and potential damage, safeguarding the structural integrity of bridges and prolonging their service life.
2. Recognize the critical importance of proper maintenance and regular monitoring of expansion joints in bridge structures, especially in the context of Pakistan. Develop comprehensive maintenance protocols and conduct routine inspections to ensure that expansion joints function effectively, accommodating thermal movements and minimizing the risk of structural deterioration.
3. Implement a comprehensive and periodic traffic count program specifically tailored for bridges, with a recommended frequency of assessment every five years. This practice will enable the evaluation of traffic loading patterns, identification of potential overloading issues, and informed decision-making regarding necessary retrofitting or rehabilitation measures to extend the service life of bridges.
4. Prioritize the procurement and deployment of cutting-edge inspection technologies within highway authorities and agencies. Establish dedicated Bridge Rating and Monitoring Units (**BRMUs**) equipped with state-of-the-art tools and expertise to ensure accurate and comprehensive bridge evaluation, early detection of anomalies, and timely implementation of remedial actions.
5. Foster the development and implementation of an integrated Bridge Management System (MBS) at the national level in Pakistan. This system should encompass data collection, analysis, and decision-making processes, enabling efficient asset management, optimized maintenance strategies, and resource allocation based on sound engineering principles and lifecycle cost considerations.
6. Emphasize a proactive approach to bridge maintenance and repair, focusing on preventive measures rather than reactive interventions. Establish a robust preventive maintenance program that includes regular inspections, structural health monitoring, and targeted maintenance activities to identify and address potential issues early on, mitigating risks, and minimizing long-term costs.
7. In situations where financial constraints limit monitoring approaches, leverage the cost-effectiveness and accessibility of mobile linear accelerometers for structural health monitoring of bridges. Leveraging the ubiquitous nature of mobile phones and their built-in accelerometers can provide a practical and affordable solution to gather valuable data, facilitating wider implementation of monitoring systems, particularly in resource-constrained environments.

8. Embrace the advancements in sensor technology and explore the adoption of modern sensors, such as fiber-optic sensors and wireless sensor networks, to enhance the accuracy, sensitivity, and real-time monitoring capabilities for bridge condition assessment. Harness the power of advanced data analytics and machine learning techniques to process and interpret sensor data, enabling more informed decision-making and proactive maintenance strategies.

By incorporating these future recommendations into bridge management practices, we can foster a culture of proactive maintenance, informed decision-making, and optimized resource allocation, ultimately ensuring the longevity, safety, and sustainability of bridge infrastructure.

# REFERENCES

*AASHTO LRFD Bridge Design Specifications*. (2017) (8th ed.). Washington, DC: American Association of State Highway and Transportation Officials.

Agdas, D., Rice, J. A., Martinez, J. R., & Lasa, I. R. (2016). Comparison of visual inspection and structural-health monitoring as bridge condition assessment methods. *Journal of Performance of Constructed Facilities*.

Bakht, B., & Mufti, A. (2015). Structural Health Monitoring. *Bridges*.

*BRIDGE SAFETY INSPECTION*. (2012) (5th ed.). National Institute for Certification in Engineering Technologies (NICET).

Mufti, A., Raeisi, F., Khalid, H., Horosko, A., & Bakht, B. (2021). A case for adding an inspection level related to Structural Health Monitoring (SHM) for Bridge Evaluation. *Canadian Journal of Civil Engineering*.

*National Bridge Inspection Standards*. (2004). Federal Highway Administration (FHWA).

Rabia, N., Danish, M., Sehresh, A., & Ali, U. (2021). *A study of Structural Health Monitoring Practices in Pakistan* (thesis).

Rafique, S. B. (2014). *Rating of Highway Bridges in Lahore* (thesis).

*The Manual for Bridge Evaluation.* (3rd ed.). Washington, DC: American Association of State Highway and Transportation Officials.

## *APPENDIX - A*

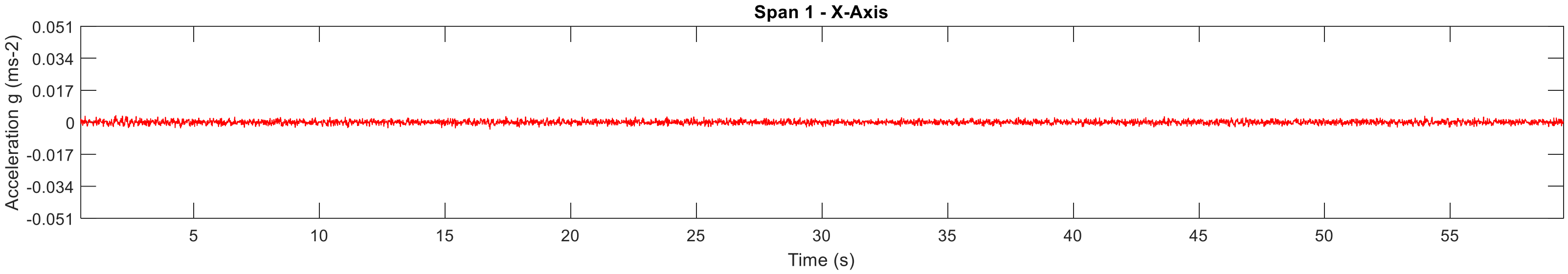


Figure 1: Span 1 – X axis Acceleration Time History

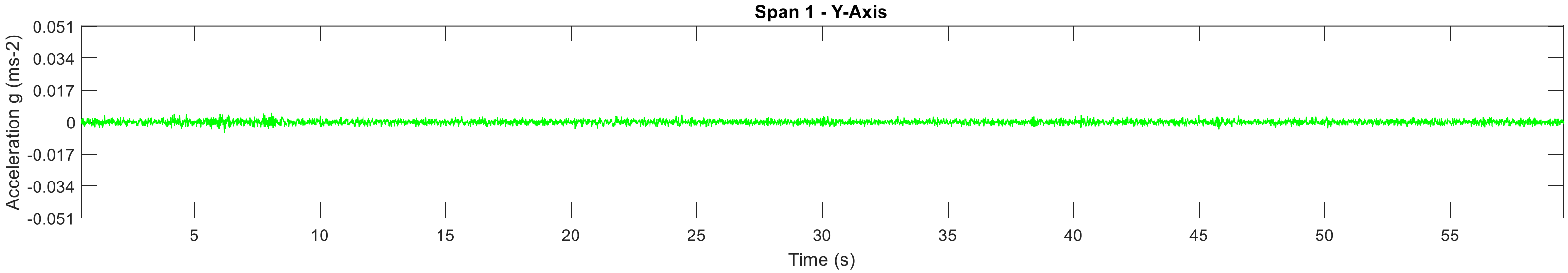


Figure 2: Span 1 – Y axis Acceleration Time History

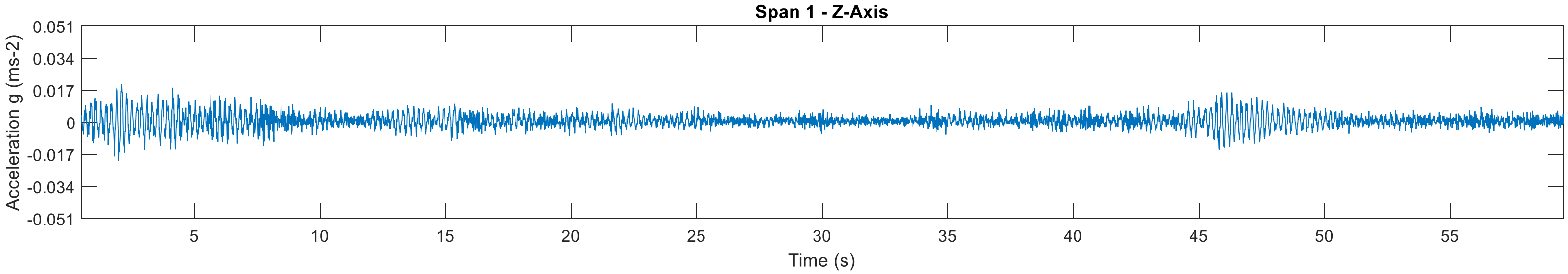


Figure 3: Span 1 – Z axis Acceleration Time History

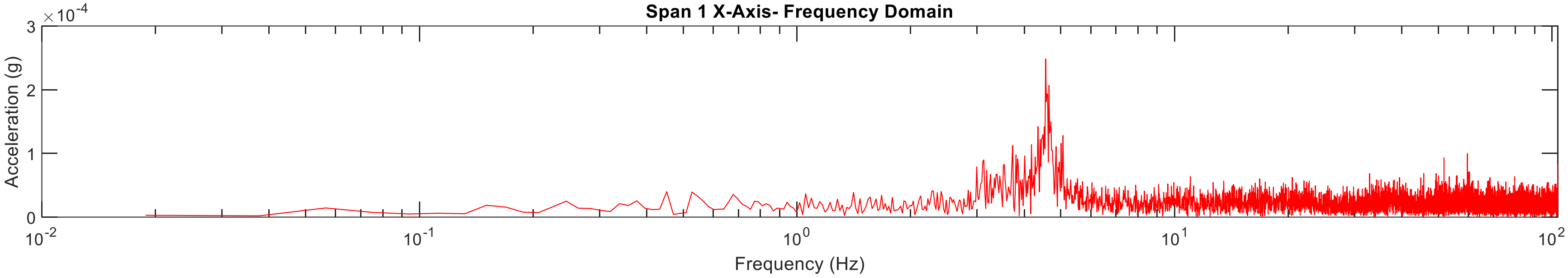


Figure 4: Span 1 – X axis Frequency Domain

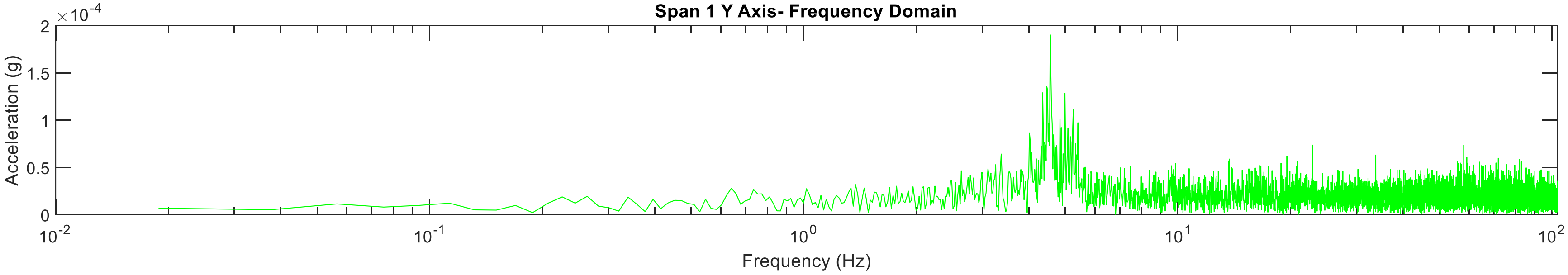


Figure 5: Span 1 – Y axis Frequency Domain

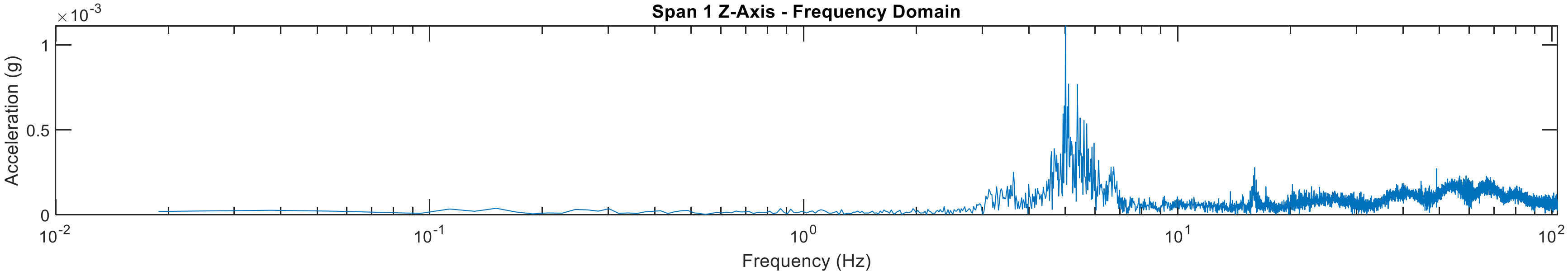


Figure 6: Span 1 – Z axis Frequency Domain

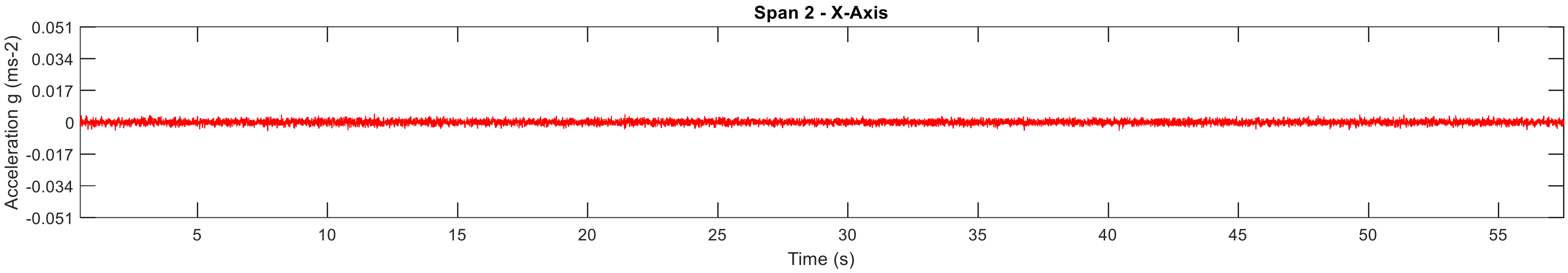


Figure 7: Span 2 – X axis Acceleration Time History

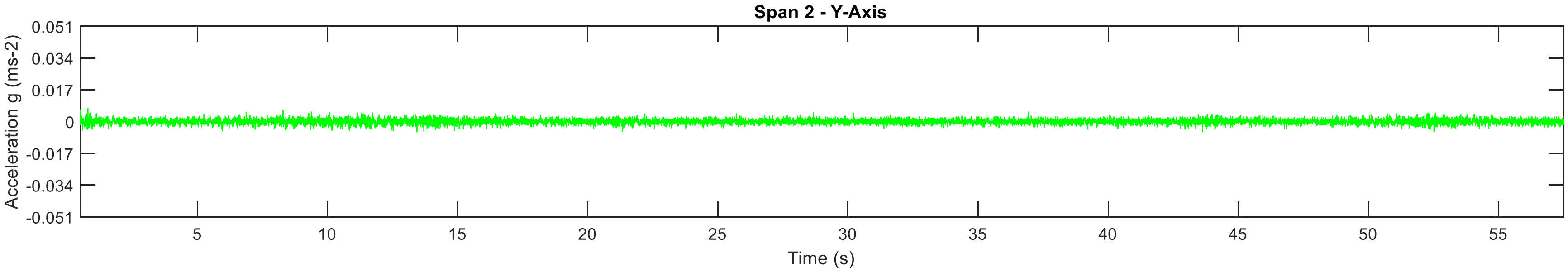


Figure 8: Span 2 – Y axis Acceleration Time History

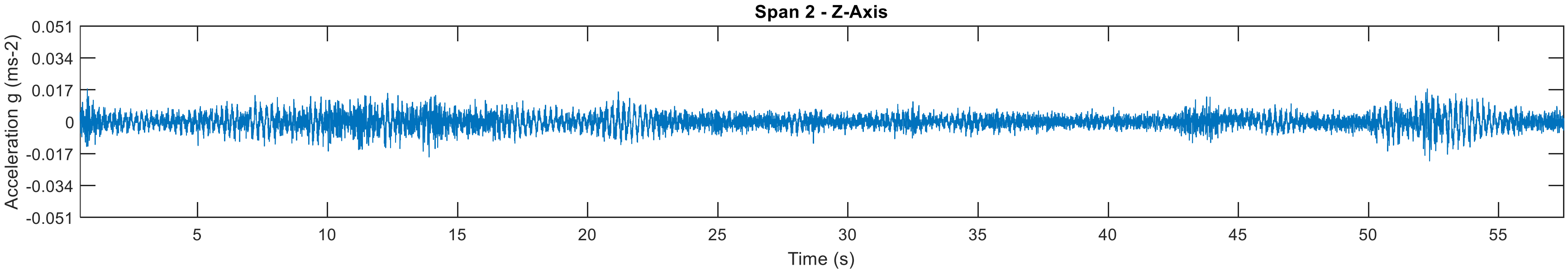


Figure 9: Span 2 – Z axis Acceleration Time History

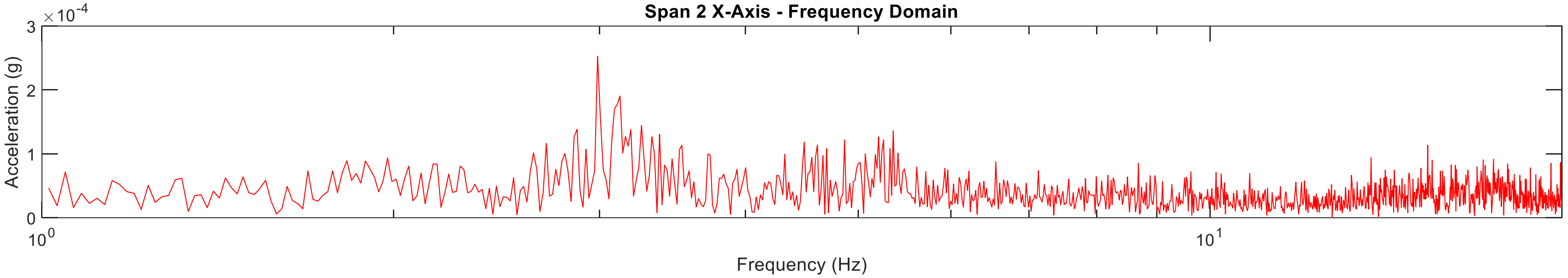


Figure 10: Span 2 – X axis Frequency Domain

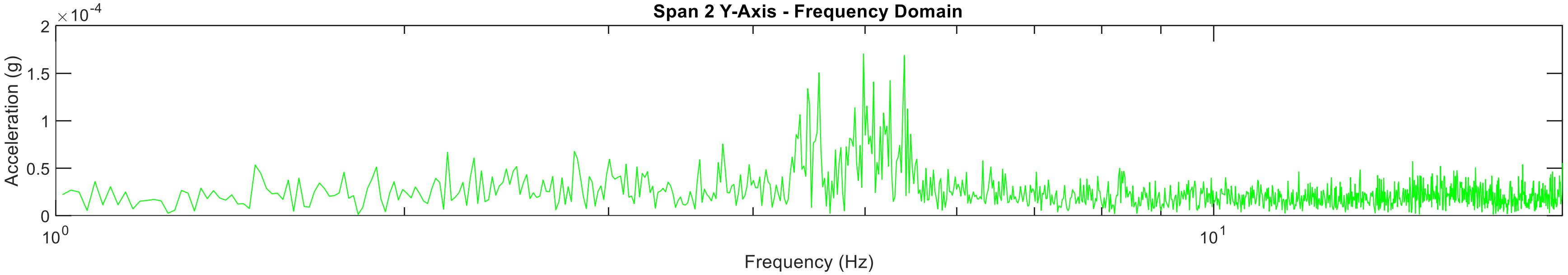


Figure 11: Span 2 – Y axis Frequency Domain

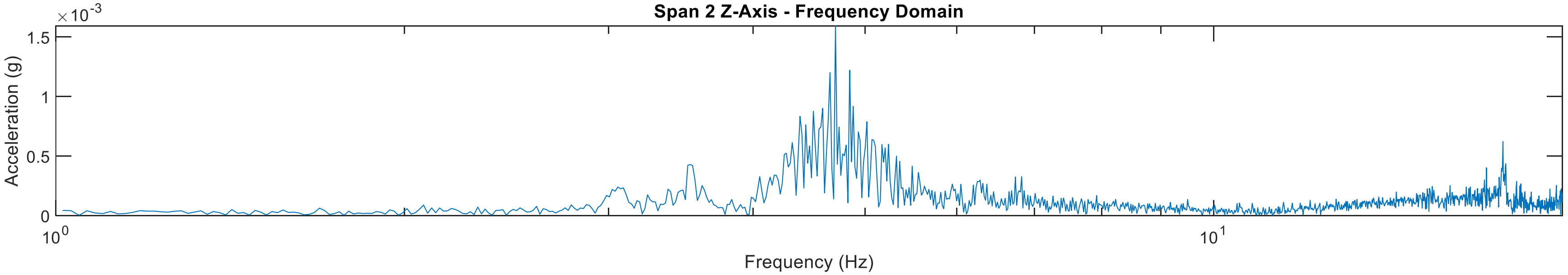


Figure 12: Span 2 – Z axis Frequency Domain

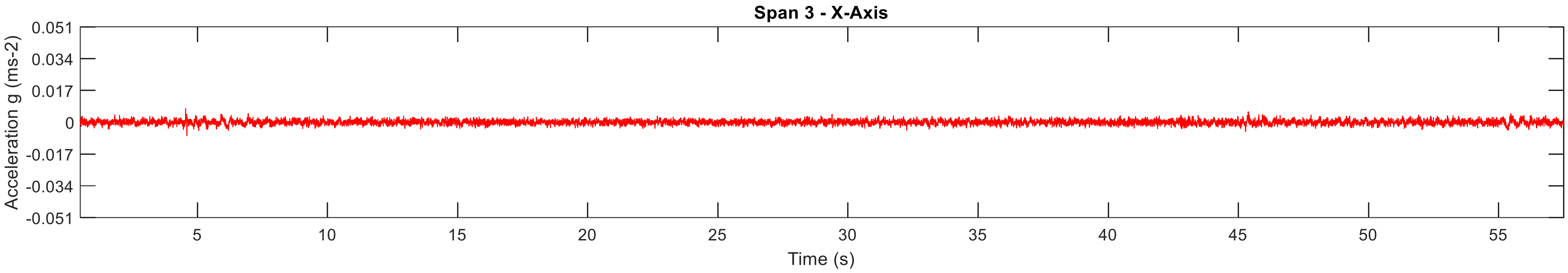


Figure 13: Span 3 – X axis Acceleration Time History

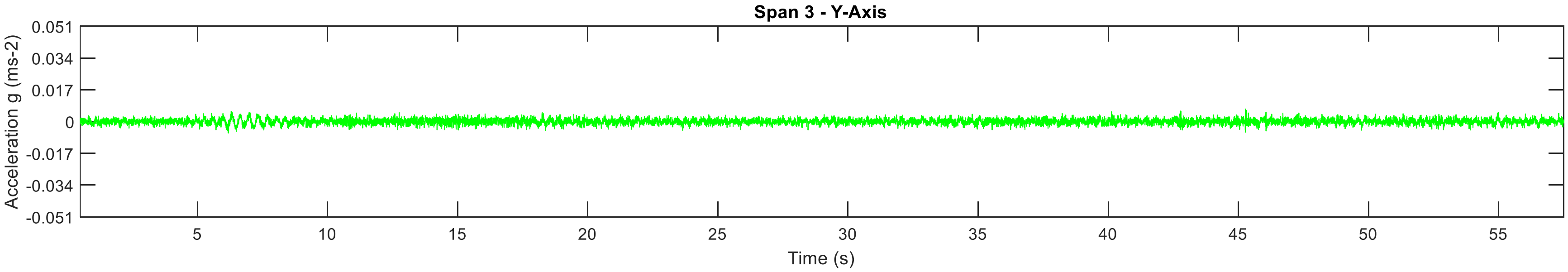


Figure 14: Span 3 – Y axis Acceleration Time History

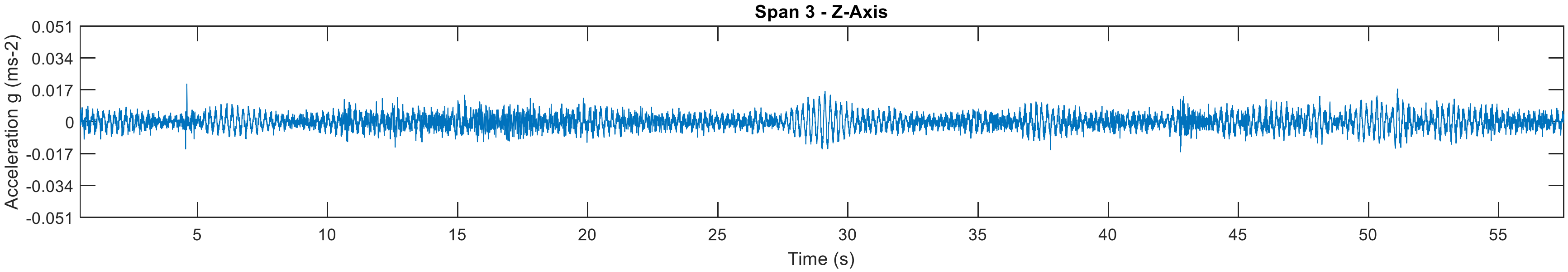


Figure 15: Span 3 – Z axis Acceleration Time History

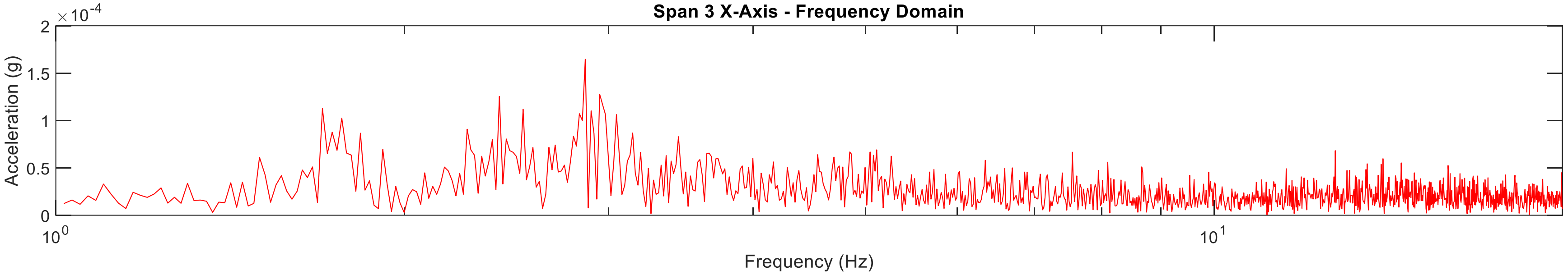


Figure 16: Span 3 – X axis Frequency Domain

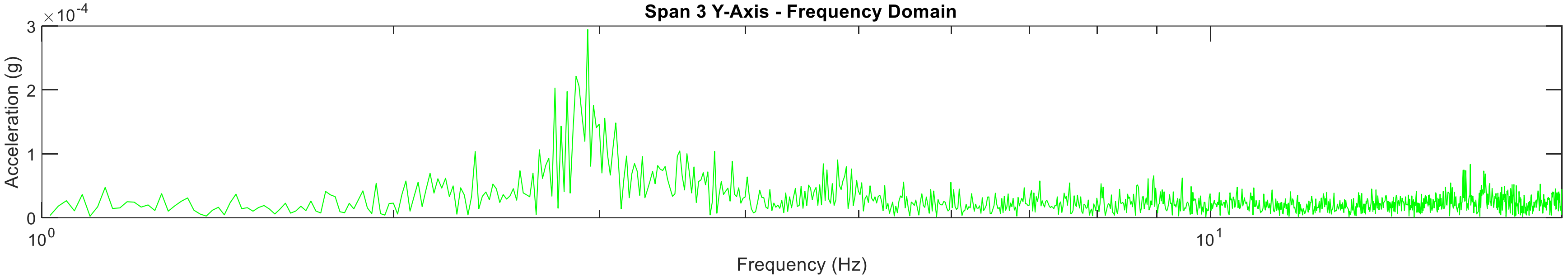


Figure 17: Span 3 – Y axis Frequency Domain

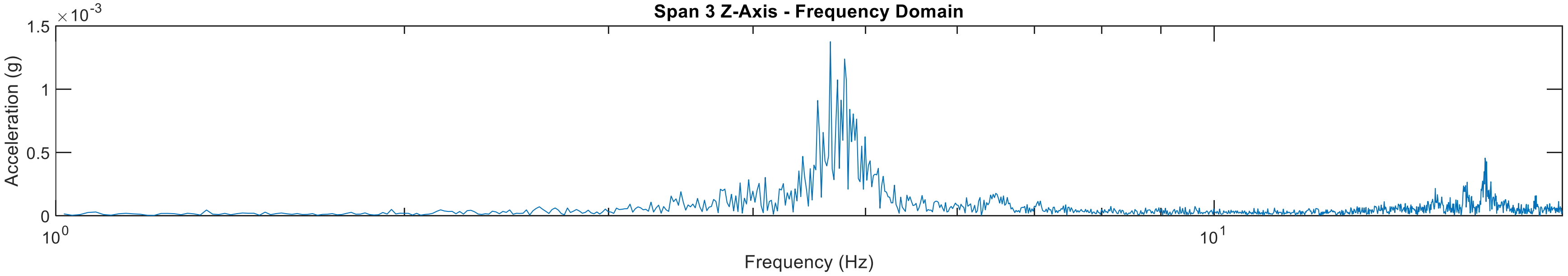


Figure 18: Span 3 – Z axis Frequency Domain

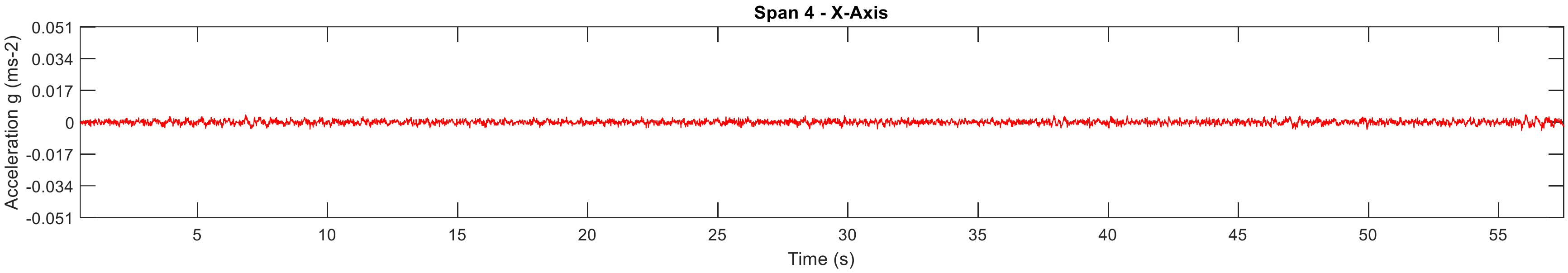


Figure 19: Span 4 – X axis Acceleration Time History

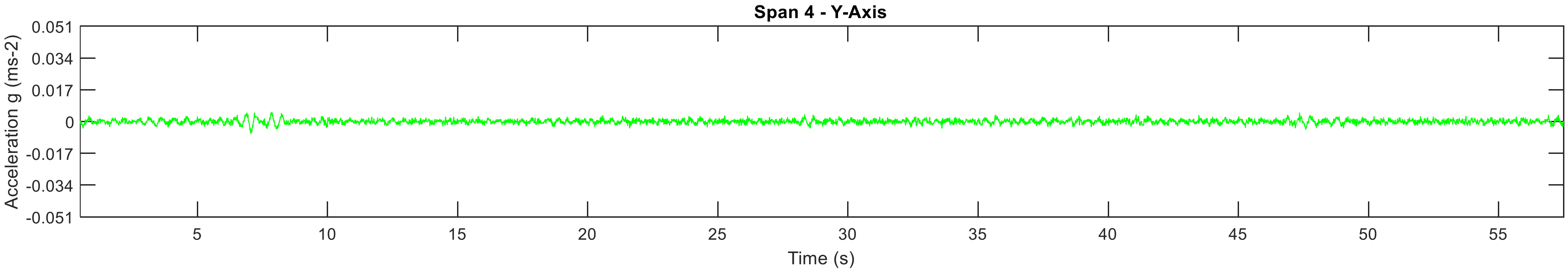


Figure 20: Span 4 – Y axis Acceleration Time History

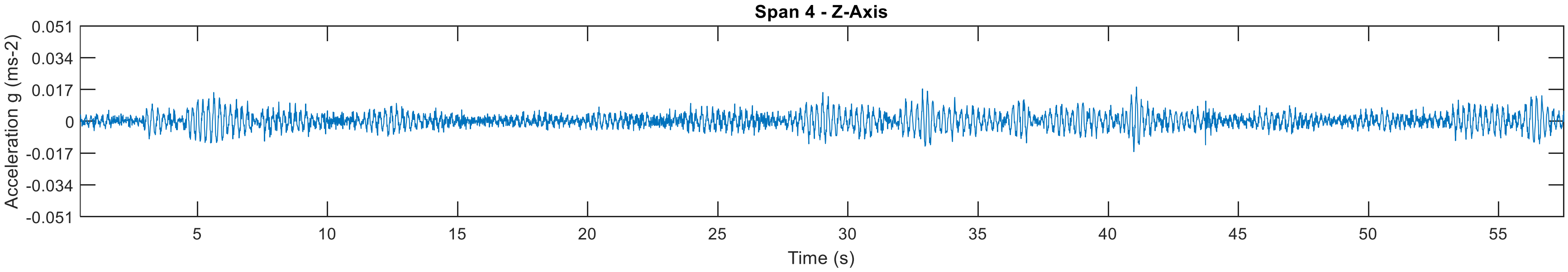


Figure 21: Span 4 – Z axis Acceleration Time History

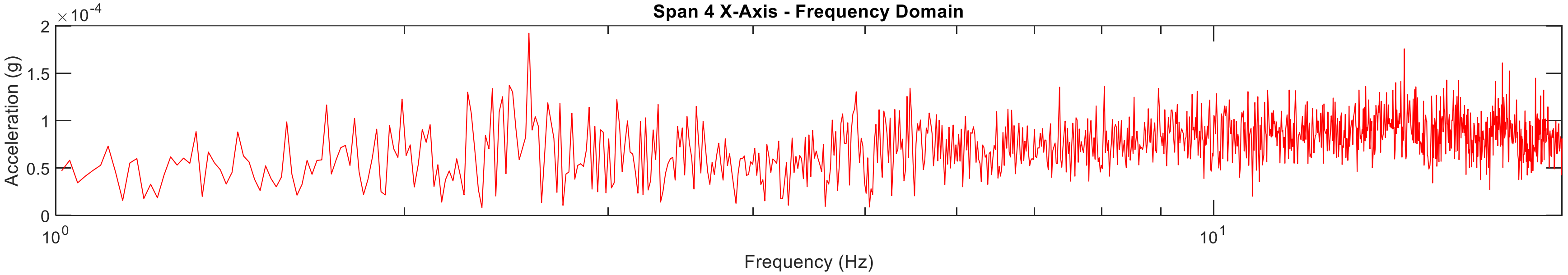


Figure 22: Span 4 – X axis Frequency Domain

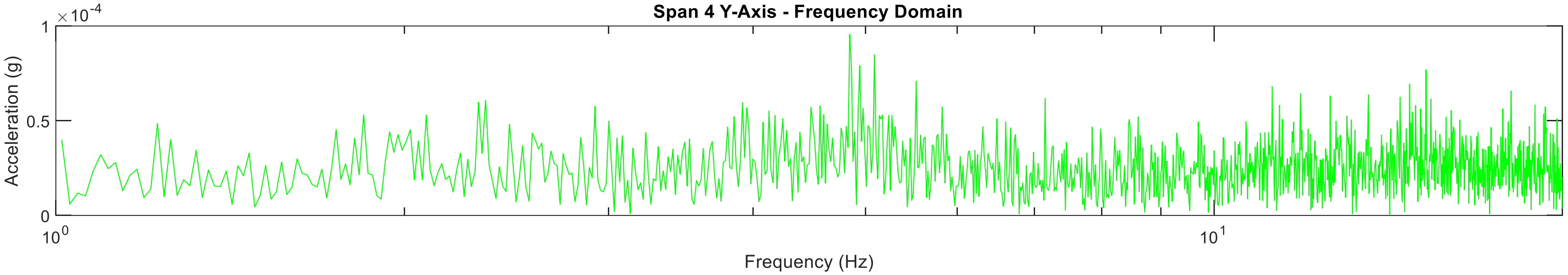


Figure 23: Span 4 – Y axis Frequency Domain

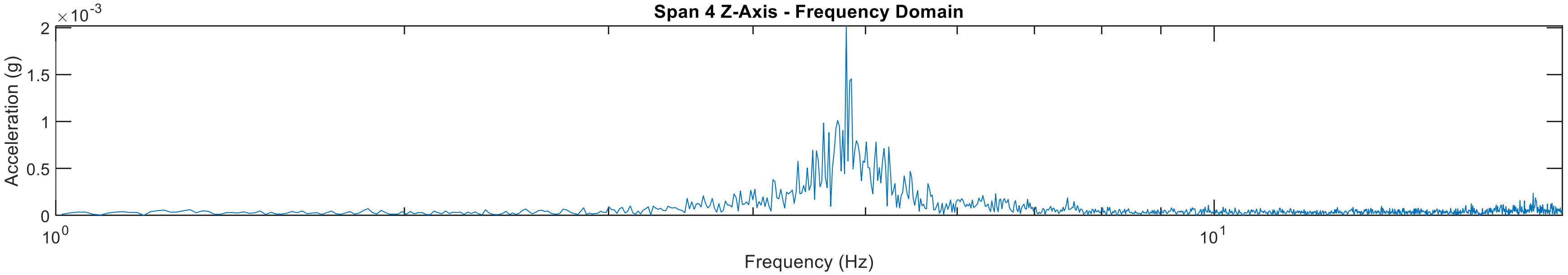


Figure 24: Span 4 – Z axis Frequency Domain

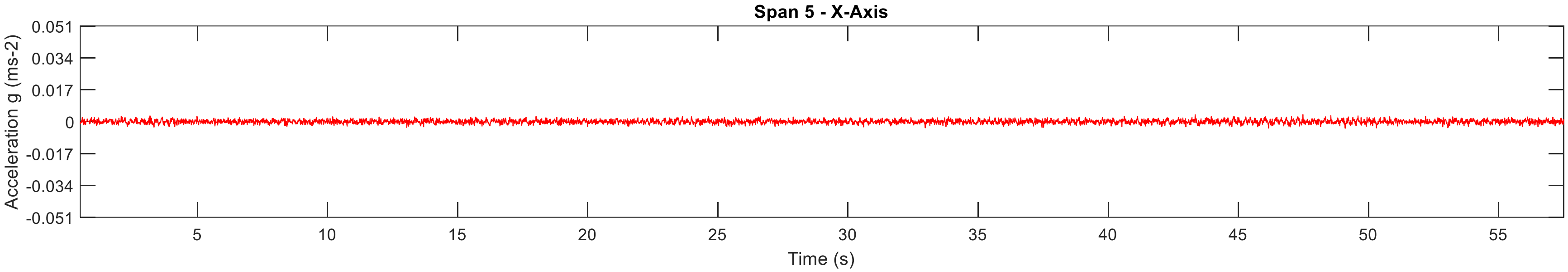


Figure 25: Span 5 – X axis Acceleration Time History

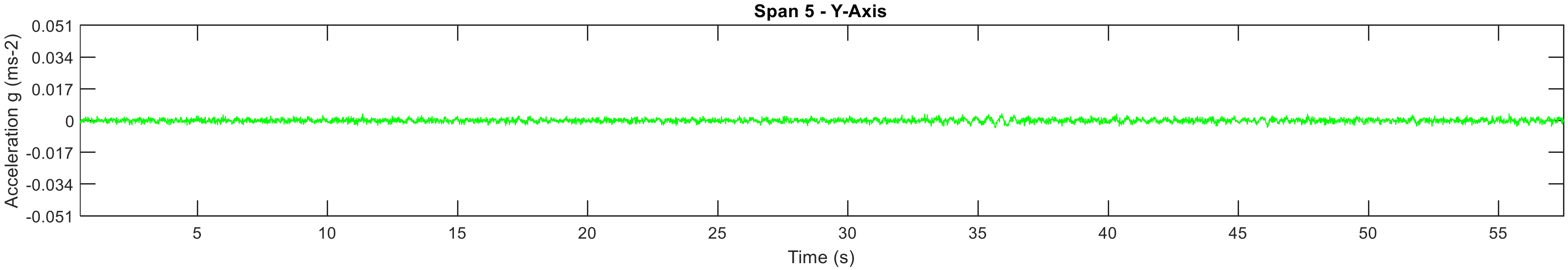


Figure 26: Span 5 – Y axis Acceleration Time History

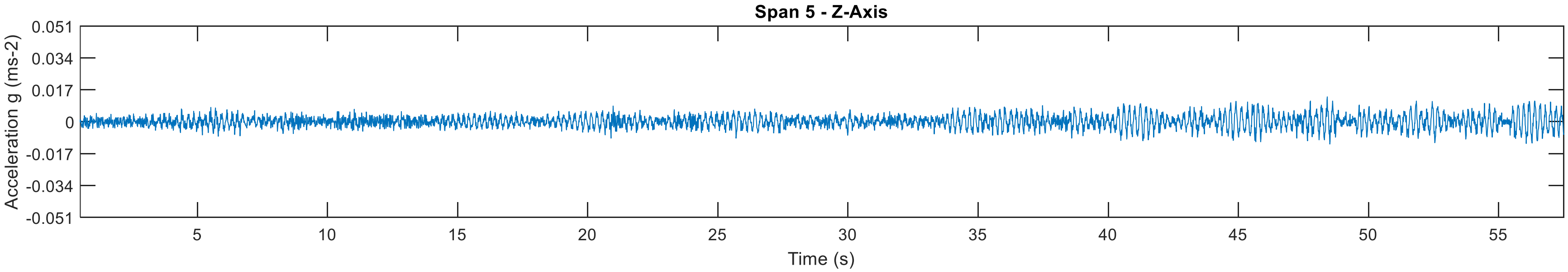


Figure 27: Span 5 – Z axis Acceleration Time History

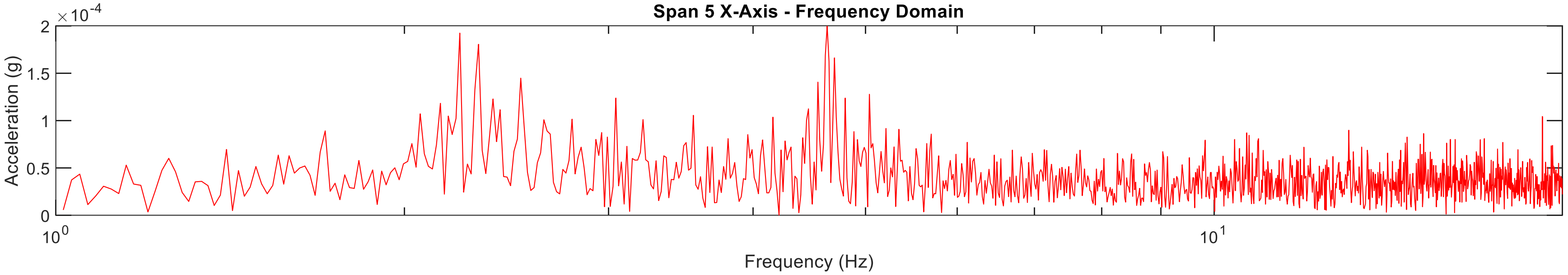


Figure 28: Span 5 – X axis Frequency Domain

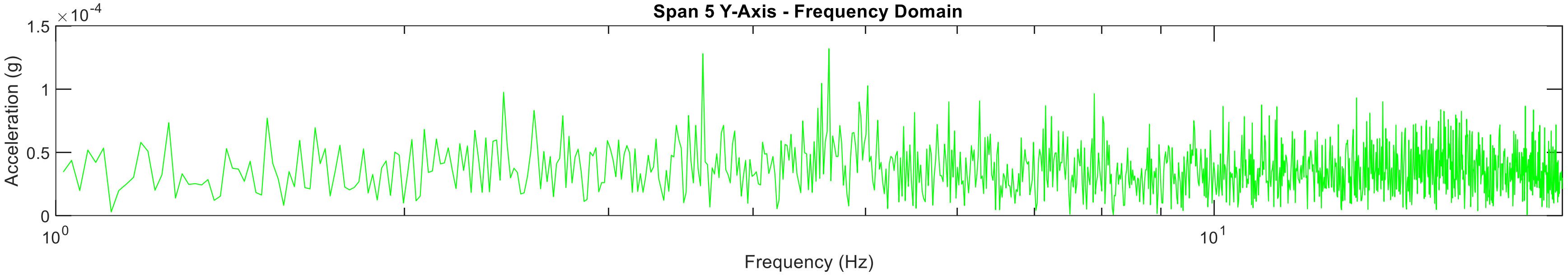


Figure 29: Span 5 – Y axis Frequency Domain

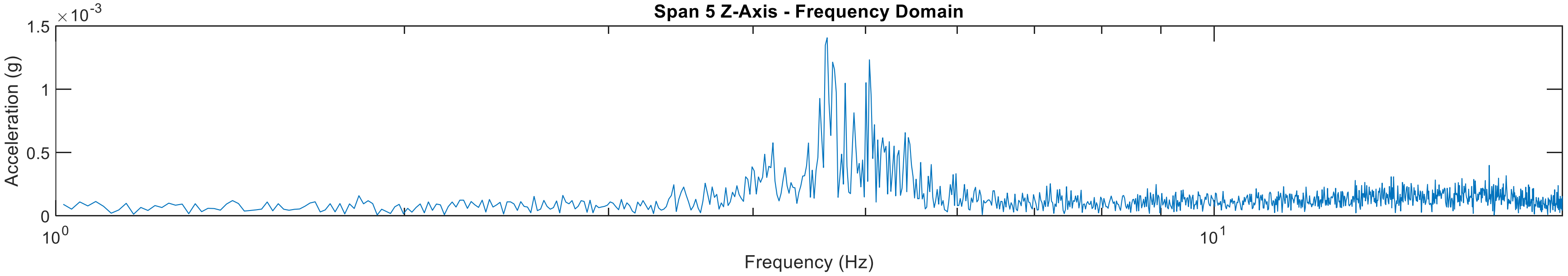


Figure 30: Span 5 – Z axis Frequency Domain

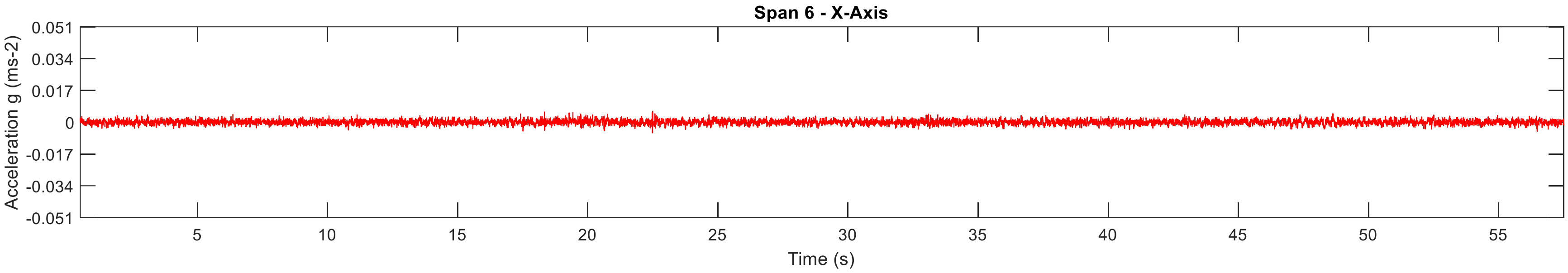


Figure 31: Span 6 – X axis Acceleration Time History

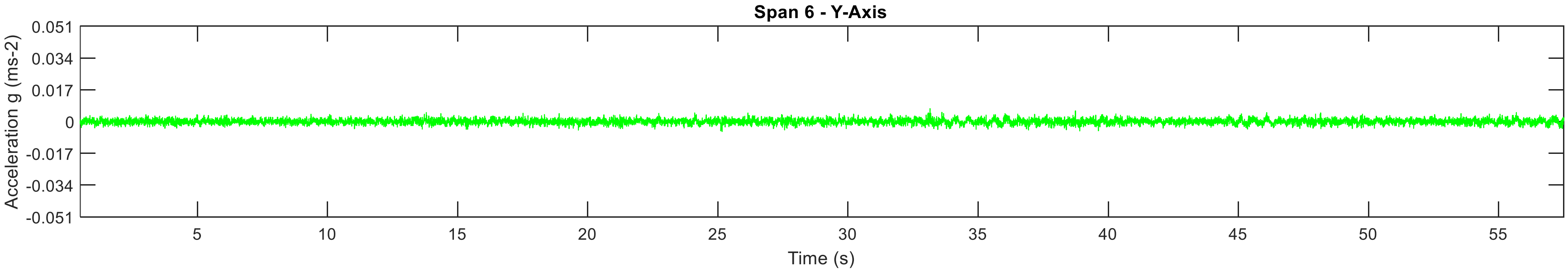


Figure 32: Span 6 – Y axis Acceleration Time History

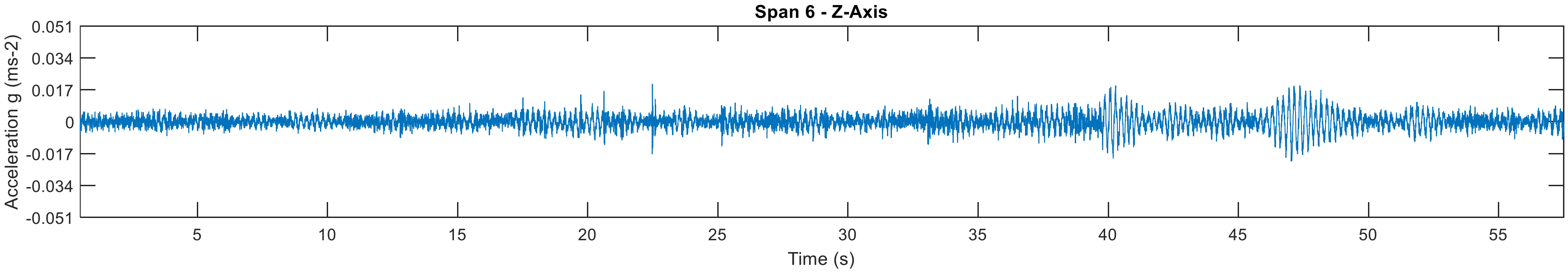


Figure 33: Span 6 – Z axis Acceleration Time History

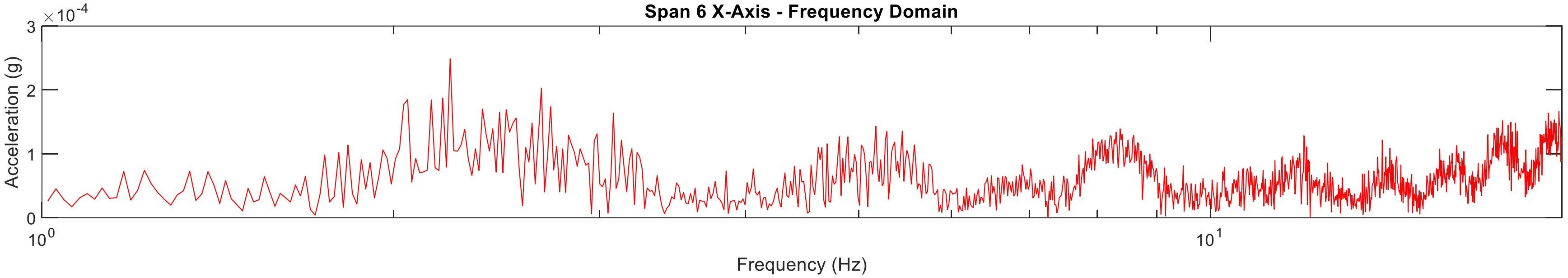


Figure 34: Span 6 – X axis Frequency Domain

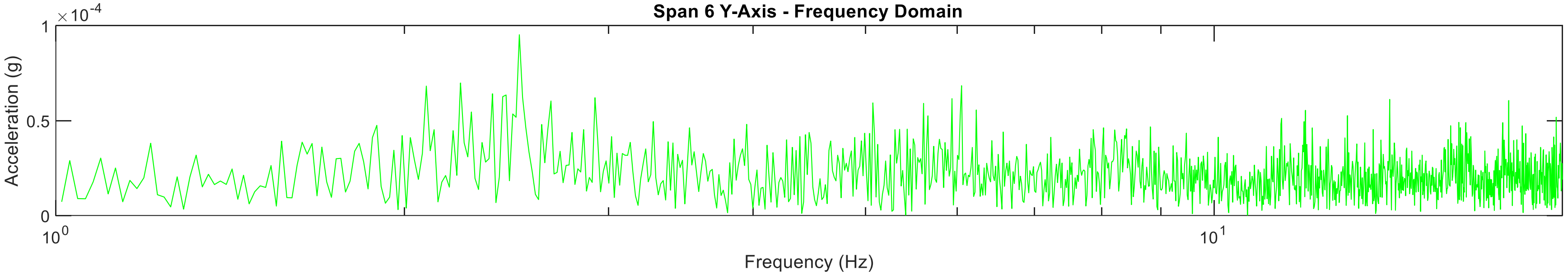


Figure 35: Span 6 – Y axis Frequency Domain

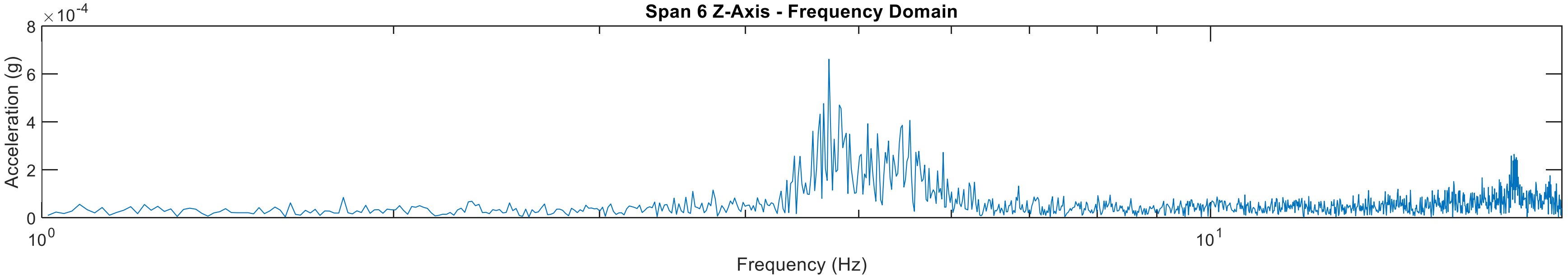


Figure 36: Span 6 – Z axis Frequency Domain

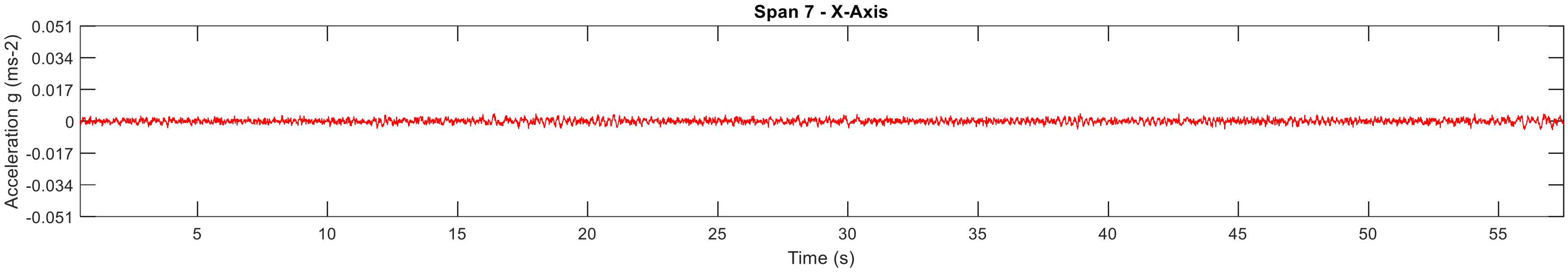


Figure 37: Span 7 – X axis Acceleration Time History

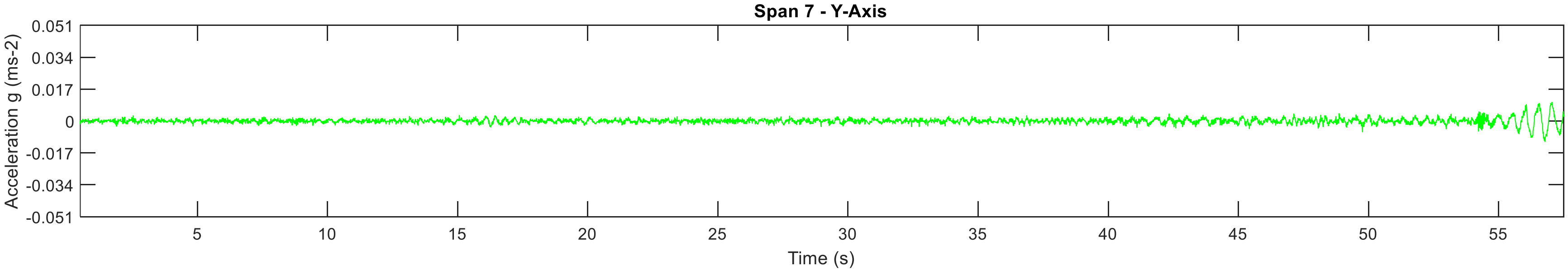


Figure 38: Span 7 – Y axis Acceleration Time History

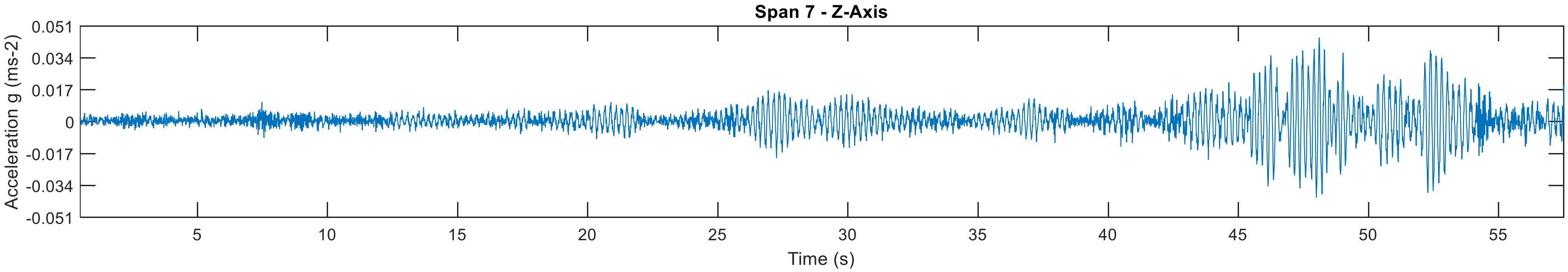


Figure 39: Span 7 – Z axis Acceleration Time History

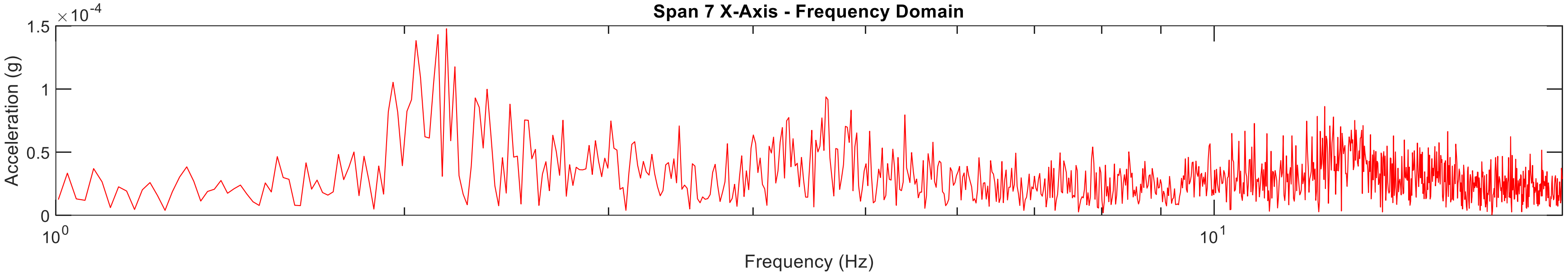


Figure 40: Span 7 – X axis Frequency Domain

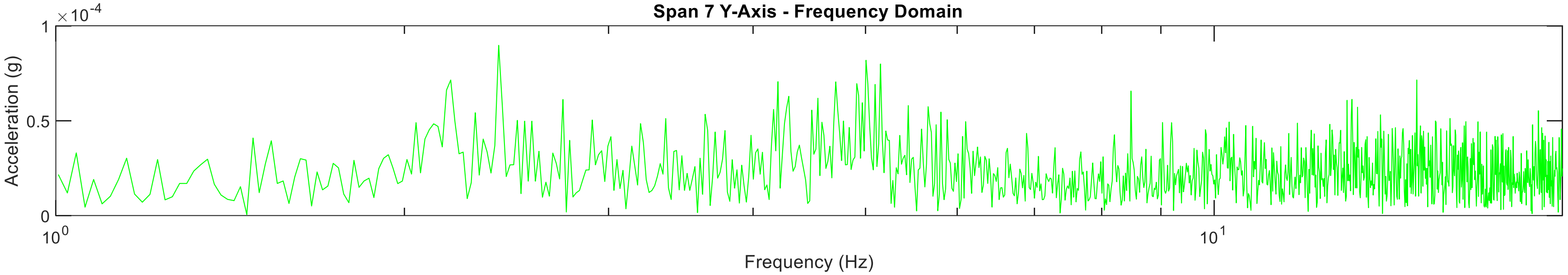


Figure 41: Span 7 – Y axis Frequency Domain

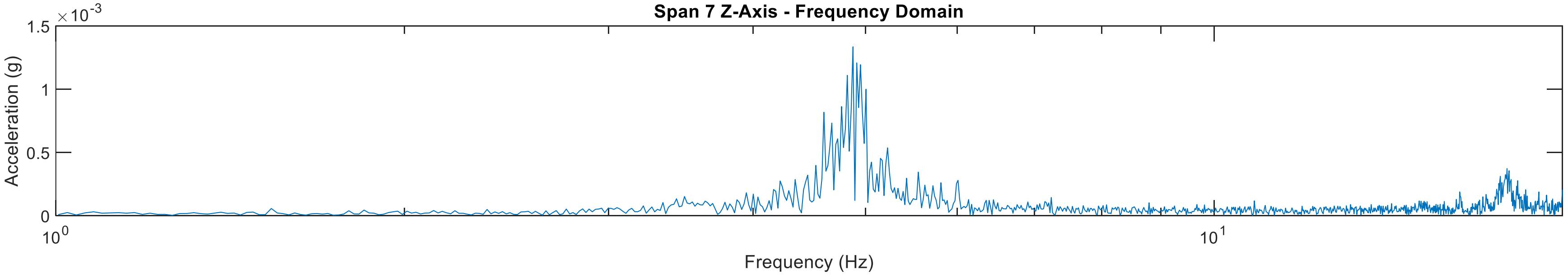


Figure 42: Span 7 – Z axis Frequency Domain

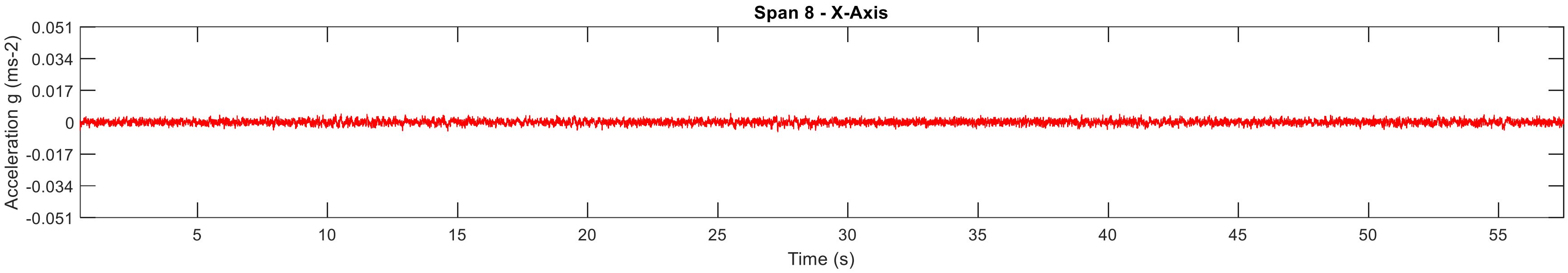


Figure 43: Span 8 – X axis Acceleration Time History

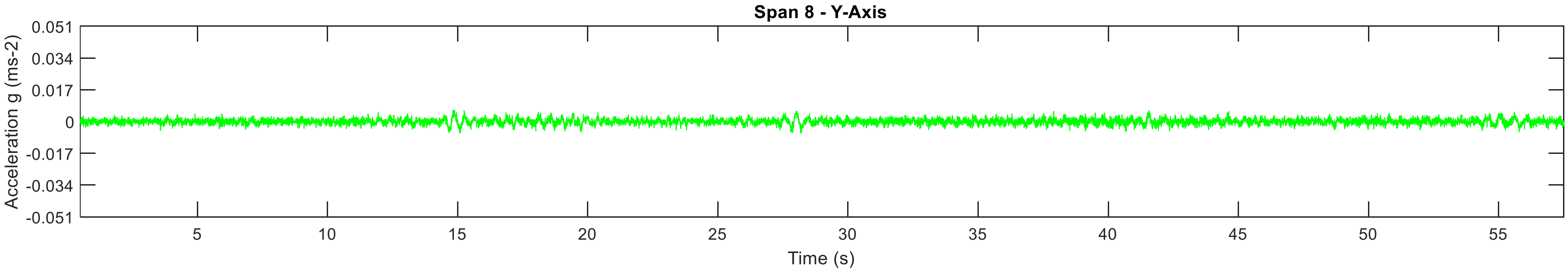


Figure 44: Span 8 – Y axis Acceleration Time History

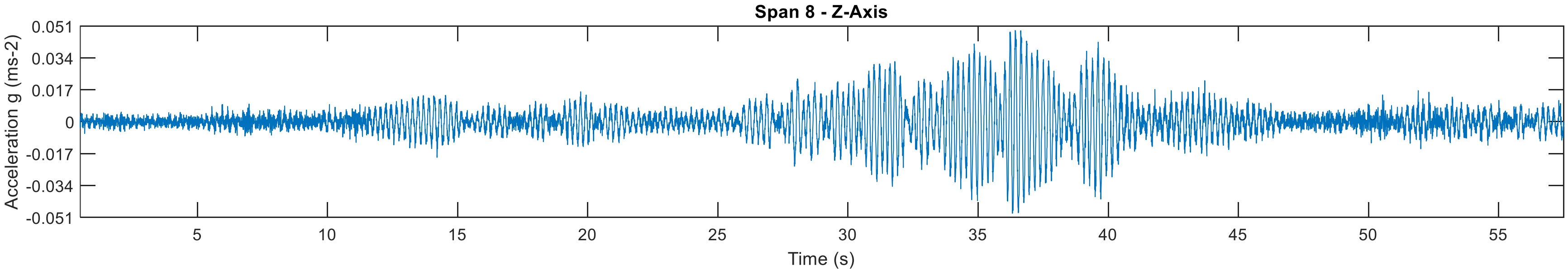


Figure 45: Span 8 – Z axis Acceleration Time History

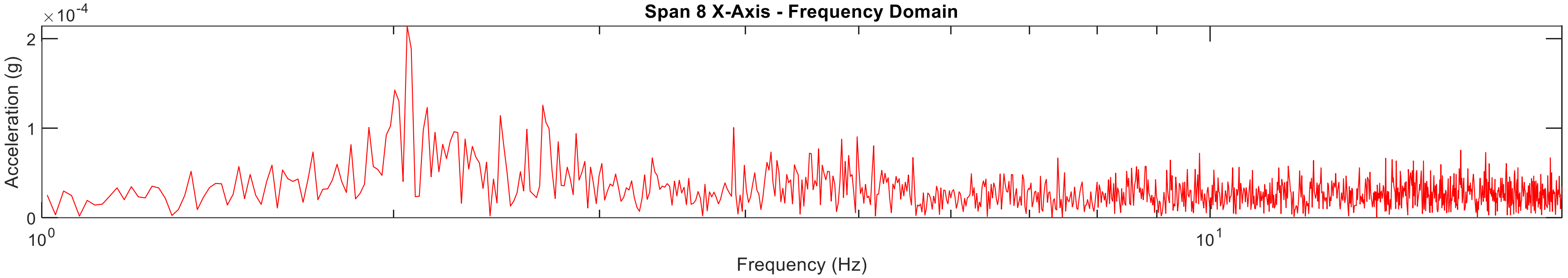


Figure 46: Span 8 – X axis Frequency Domain

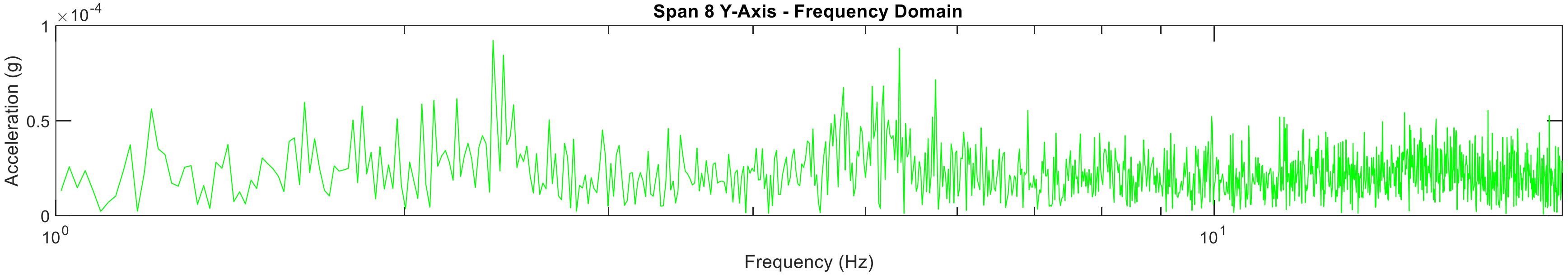


Figure 47: Span 8 – Y axis Frequency Domain

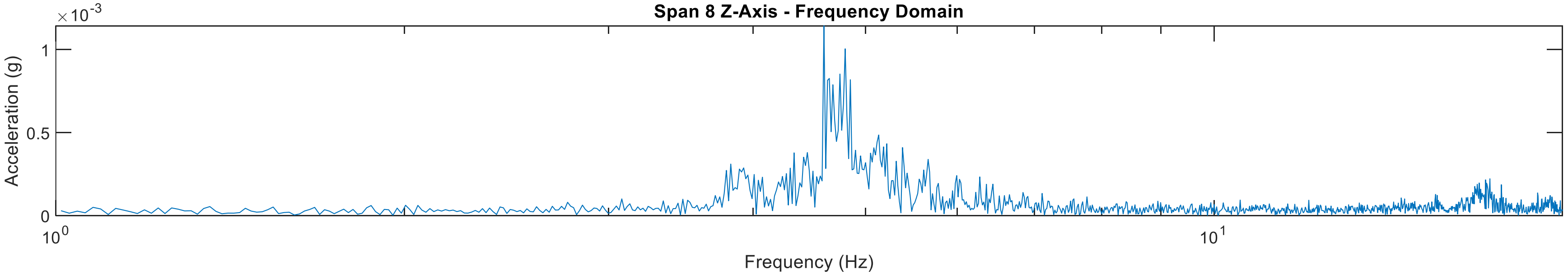


Figure 48: Span 8 – Z axis Frequency Domain

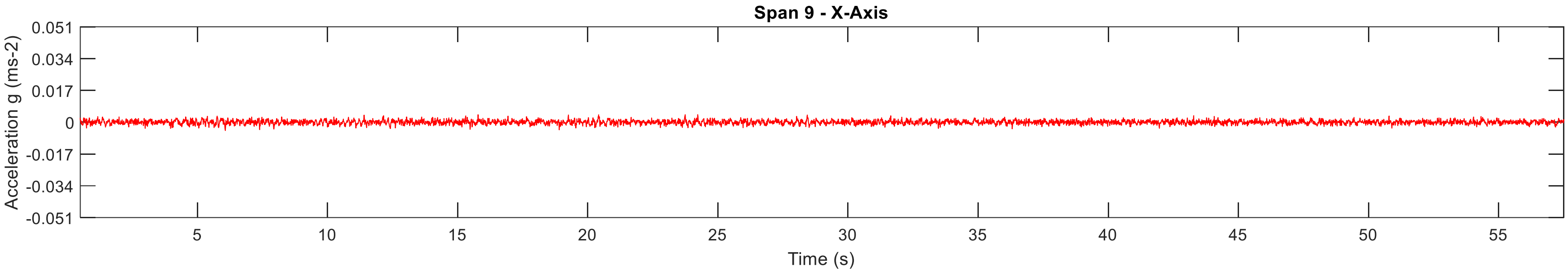


Figure 49: Span 9 – X axis Acceleration Time History

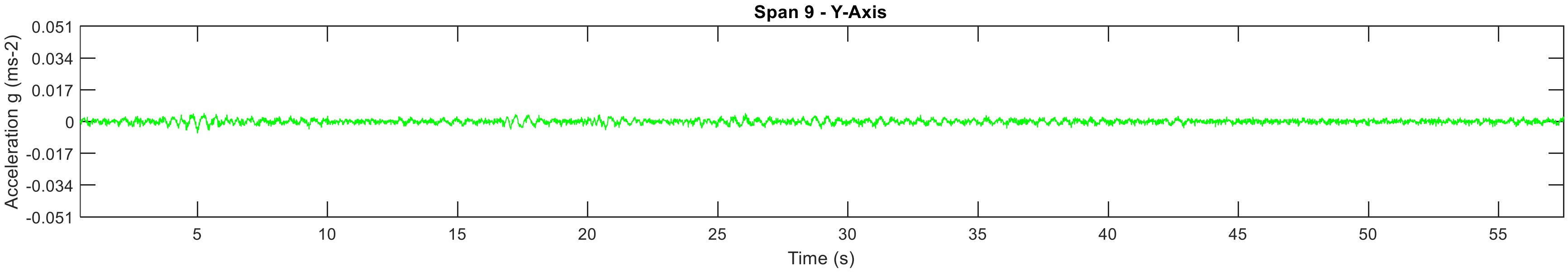


Figure 50: Span 9 – Y axis Acceleration Time History

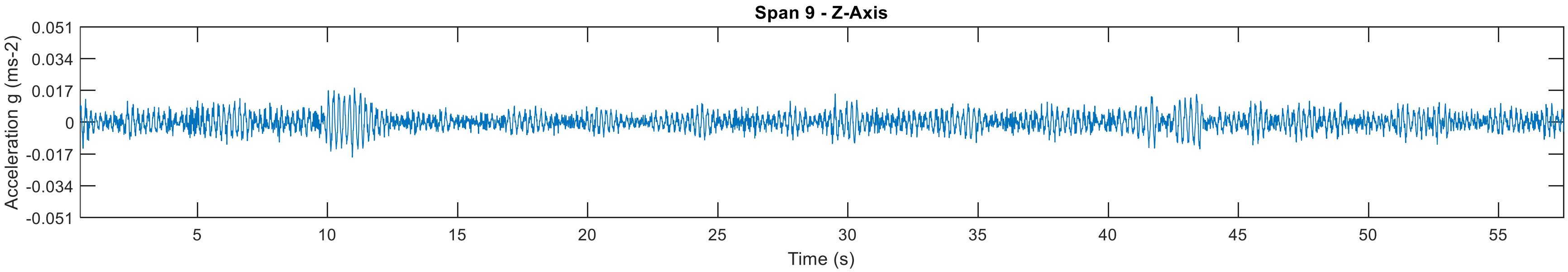


Figure 51: Span 9 – Z axis Acceleration Time History

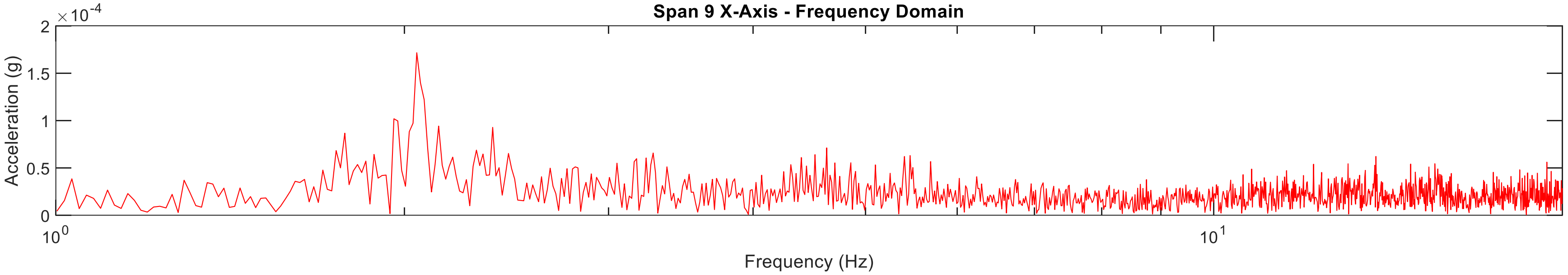


Figure 52: Span 9 – X axis Frequency Domain

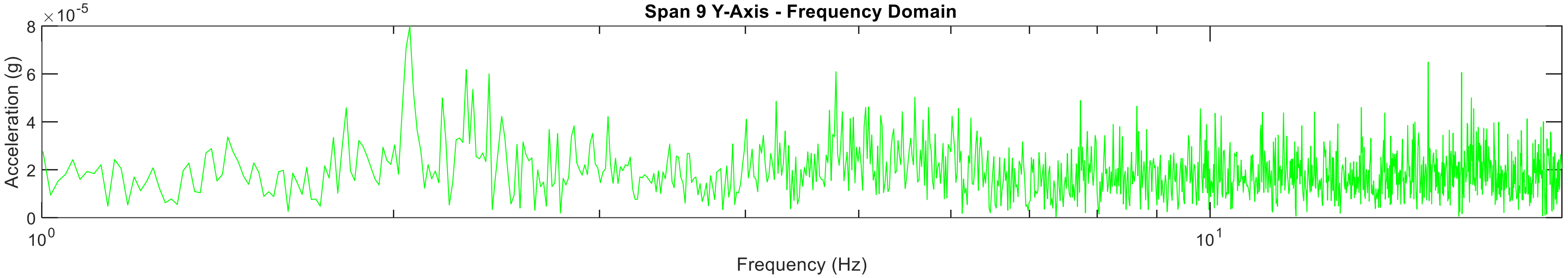


Figure 53: Span 9 – Y axis Frequency Domain

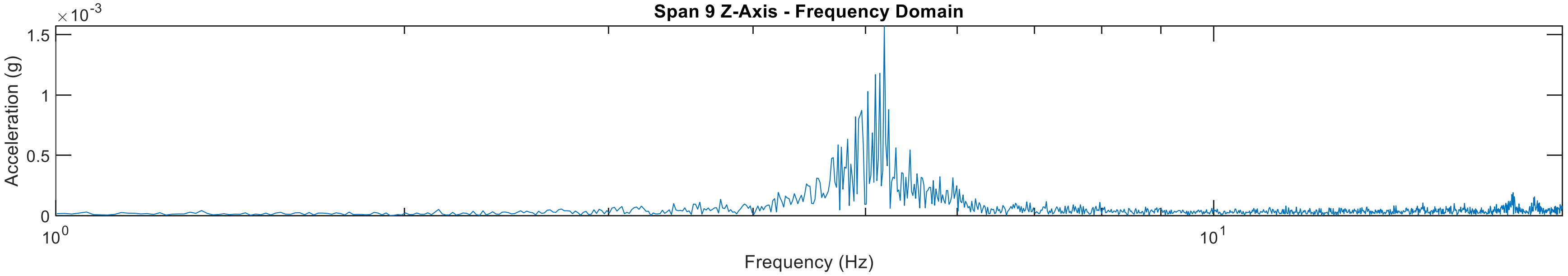


Figure 54: Span 9 – Z axis Frequency Domain

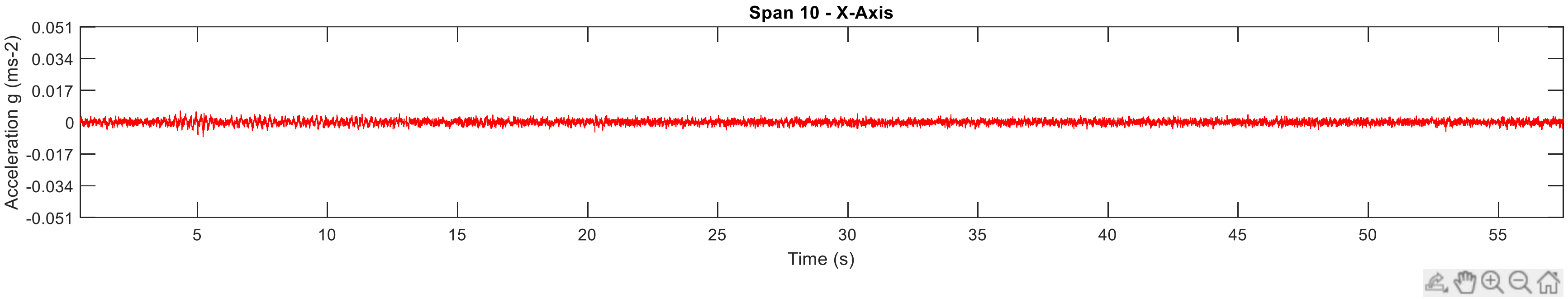


Figure 55: Span 10 – X axis Acceleration Time History

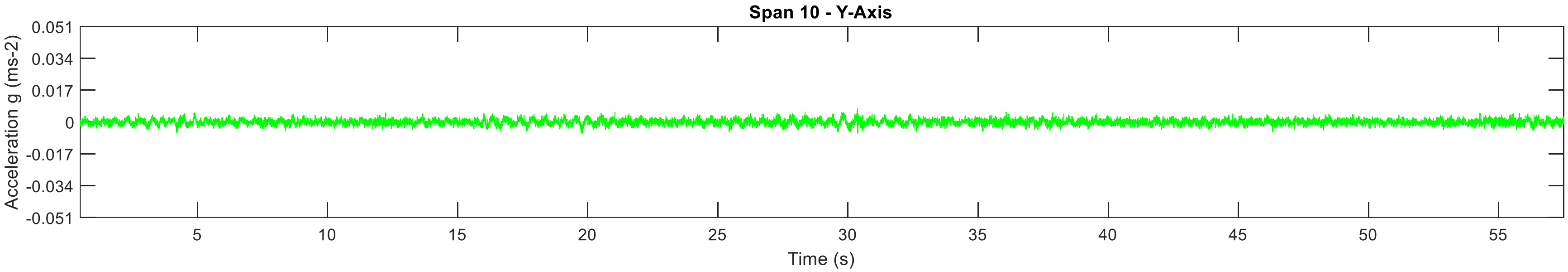


Figure 56: Span 10 – Y axis Acceleration Time History

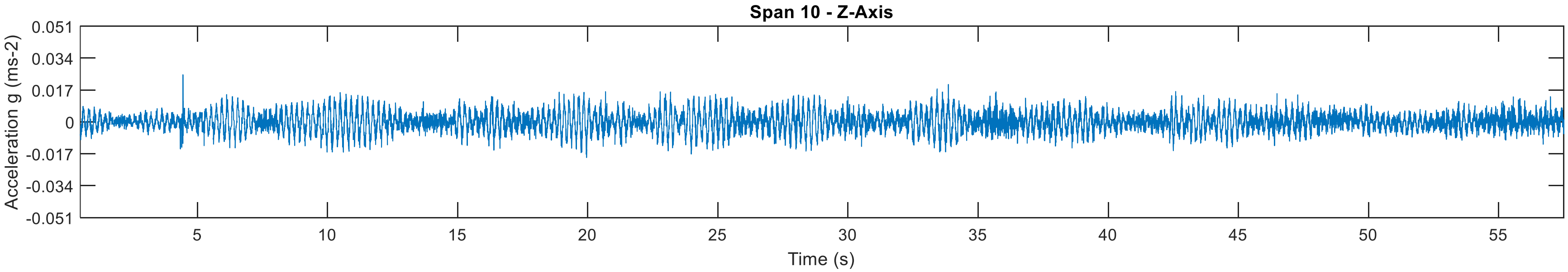


Figure 57: Span 10 – Z axis Acceleration Time History

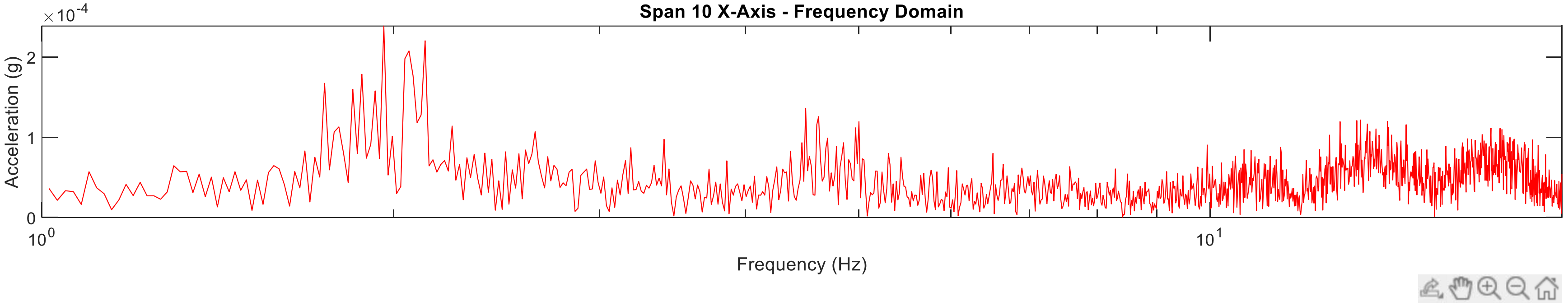


Figure 58: Span 10 – X axis Frequency Domain

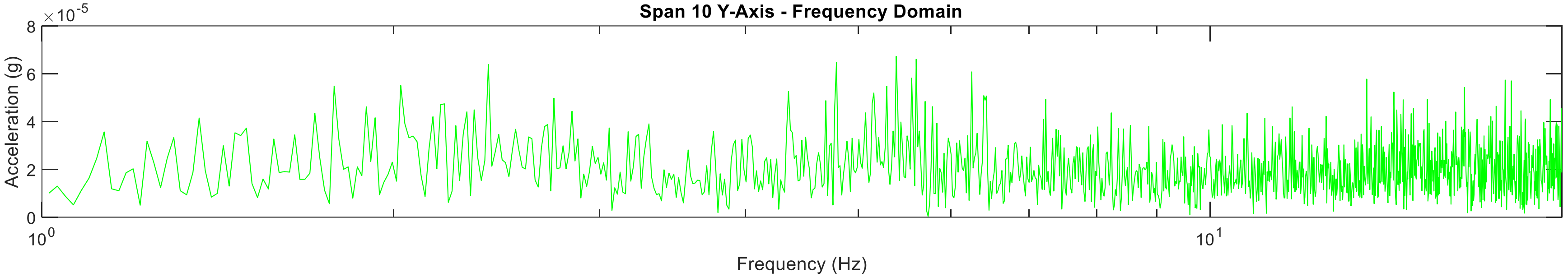


Figure 59: Span 10 – Y axis Frequency Domain

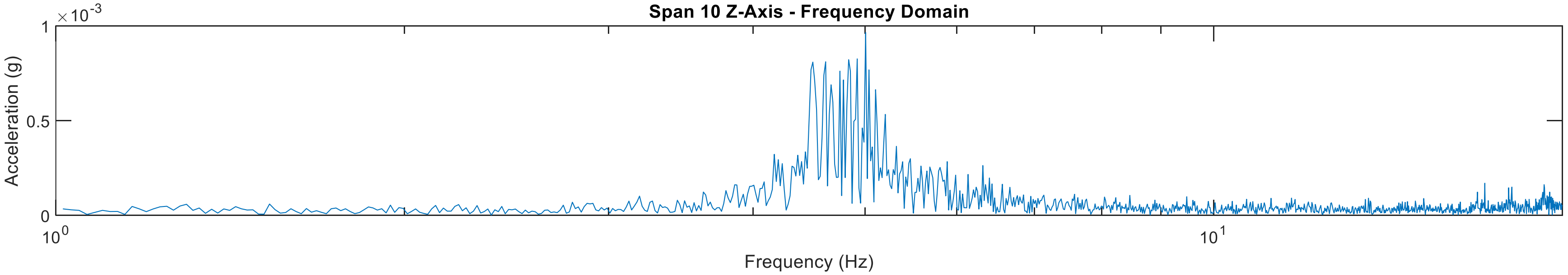


Figure 60: Span 10 – Z axis Frequency Domain

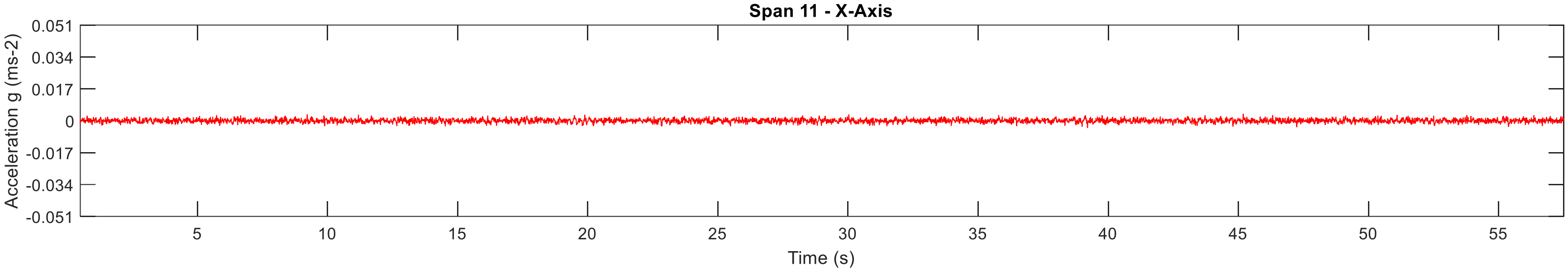


Figure 61: Span 11 – X axis Acceleration Time History

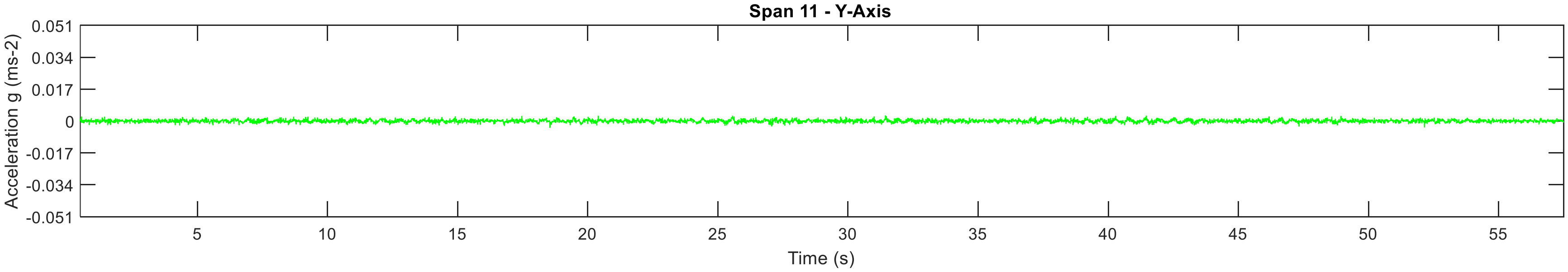


Figure 62: Span 11 – Y axis Acceleration Time History

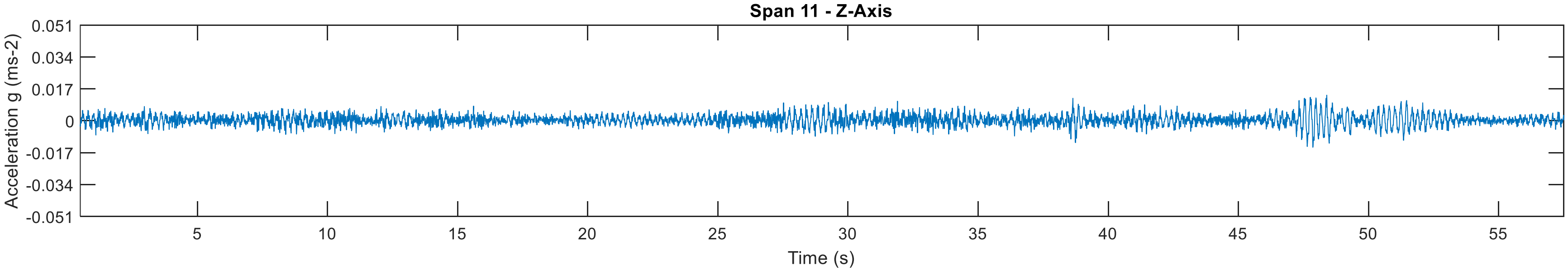


Figure 63: Span 11 – Z axis Acceleration Time History

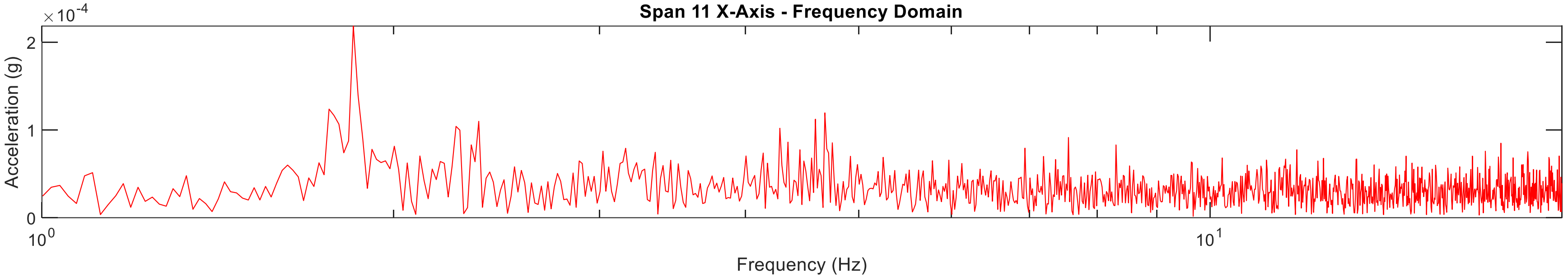


Figure 64: Span 11 – X axis Frequency Domain

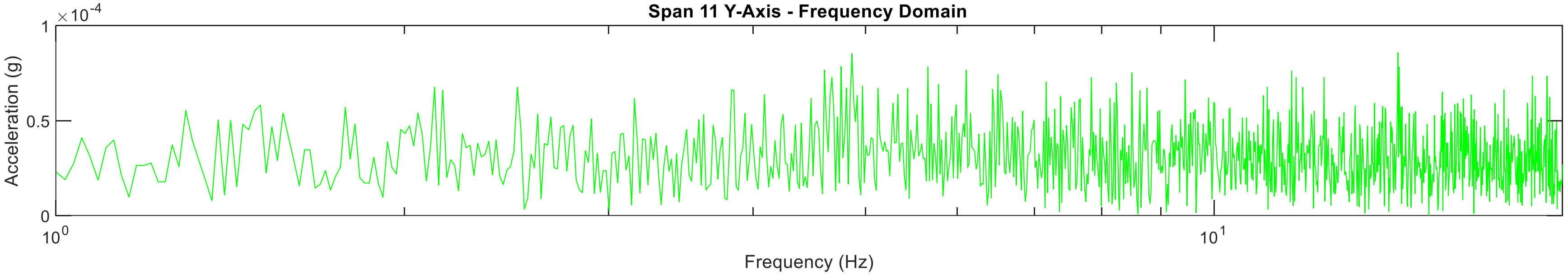


Figure 65: Span 11 – Y axis Frequency Domain

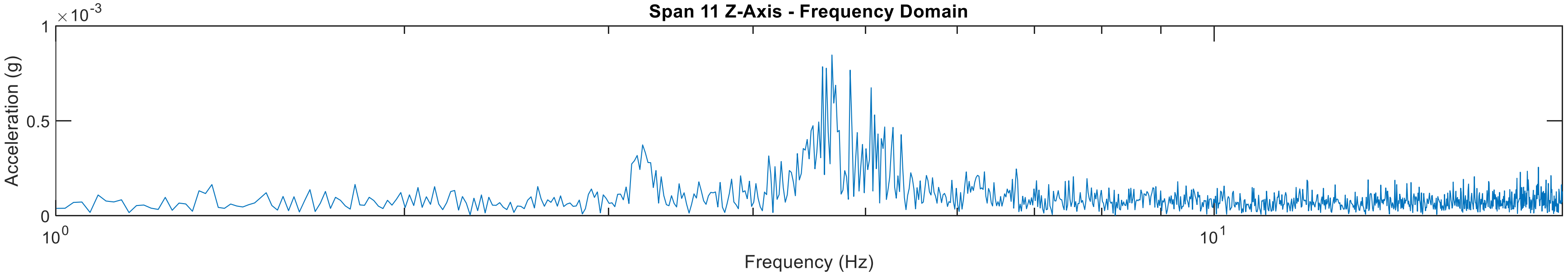


Figure 66: Span 11 – Z axis Frequency Domain

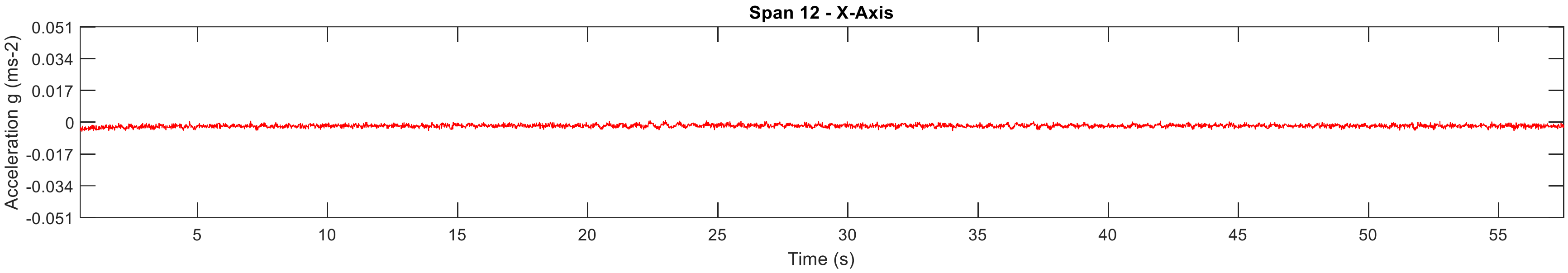


Figure 67: Span 12 – X axis Acceleration Time History

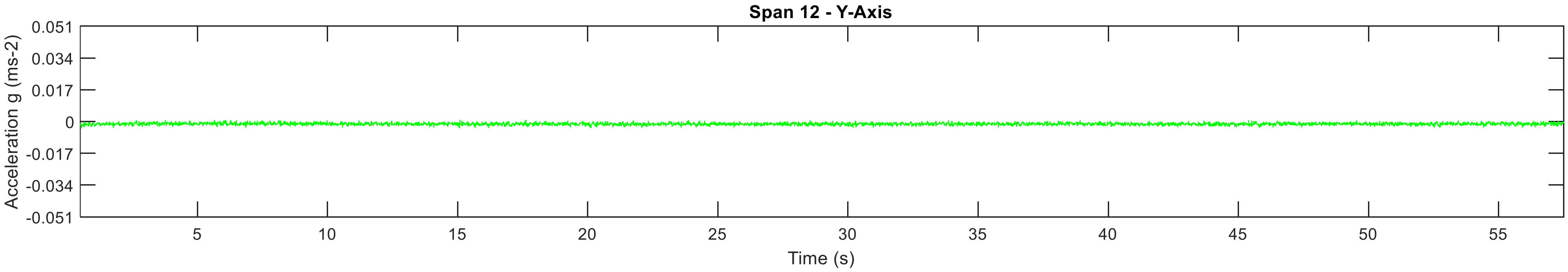


Figure 68: Span 12 – Y axis Acceleration Time History

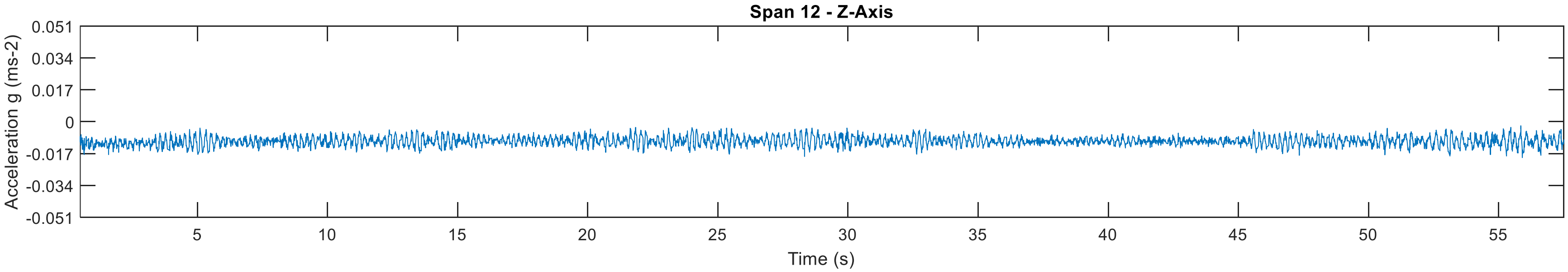


Figure 69: Span 12 – Z axis Acceleration Time History

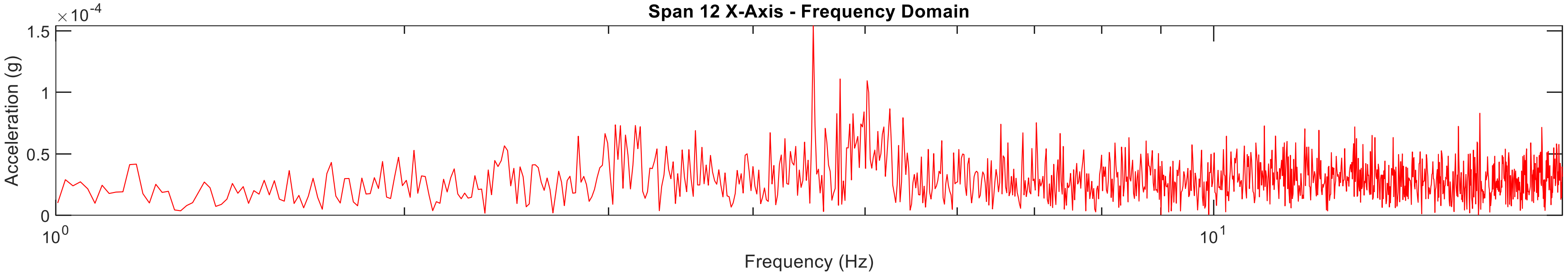


Figure 70: Span 12 – X axis Frequency Domain

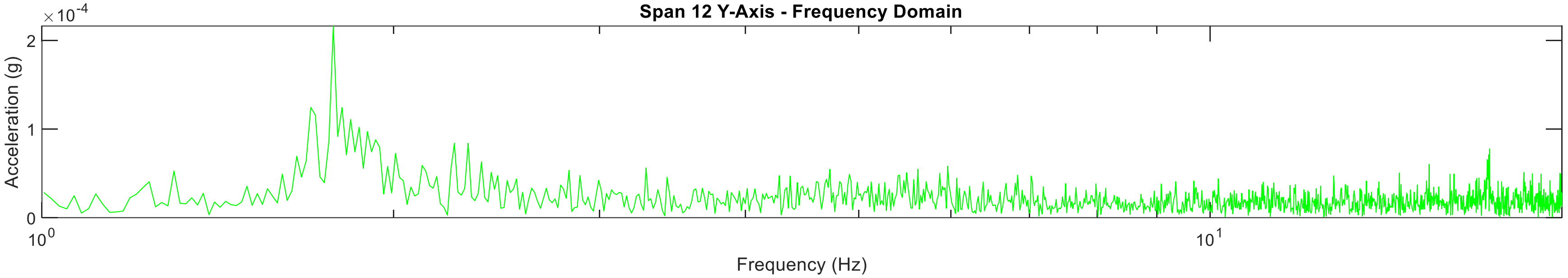


Figure 71: Span 12 – Y axis Frequency Domain

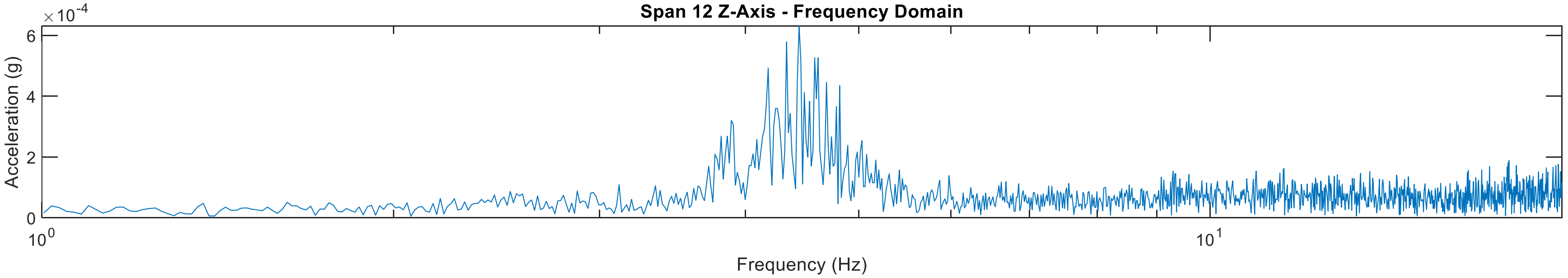


Figure 72: Span 12 – Z axis Frequency Domain

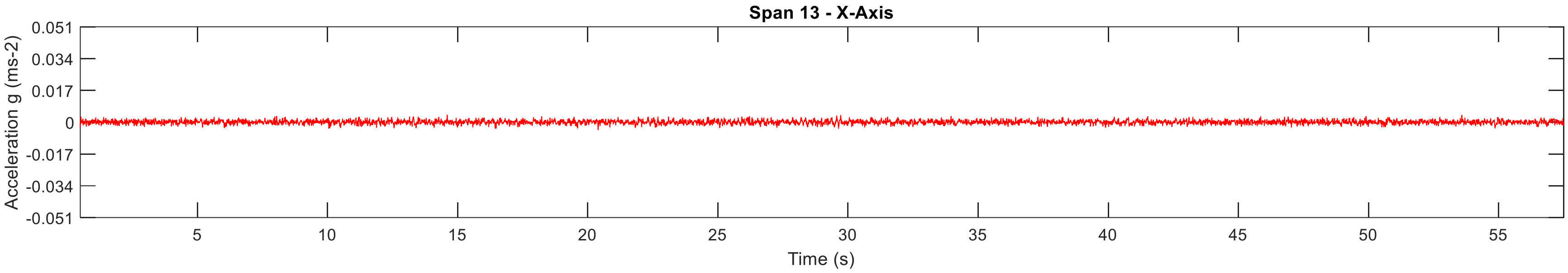


Figure 73: Span 13 – X axis Acceleration Time History

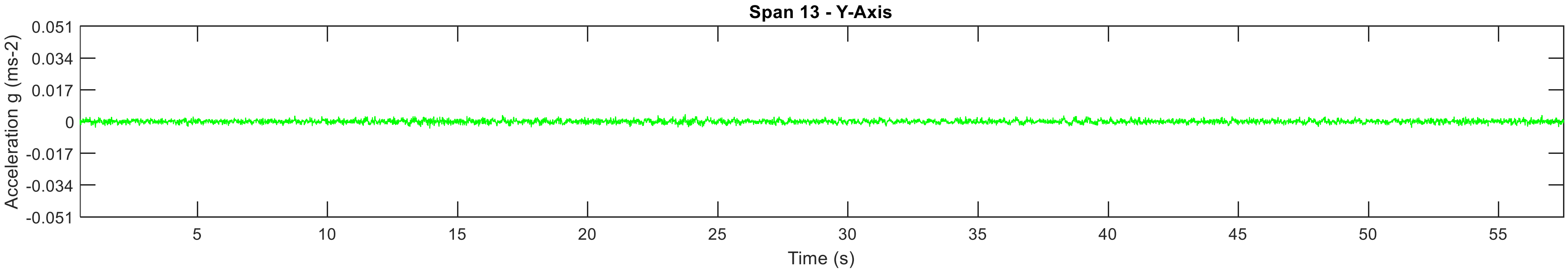


Figure 74: Span 13 – Y axis Acceleration Time History

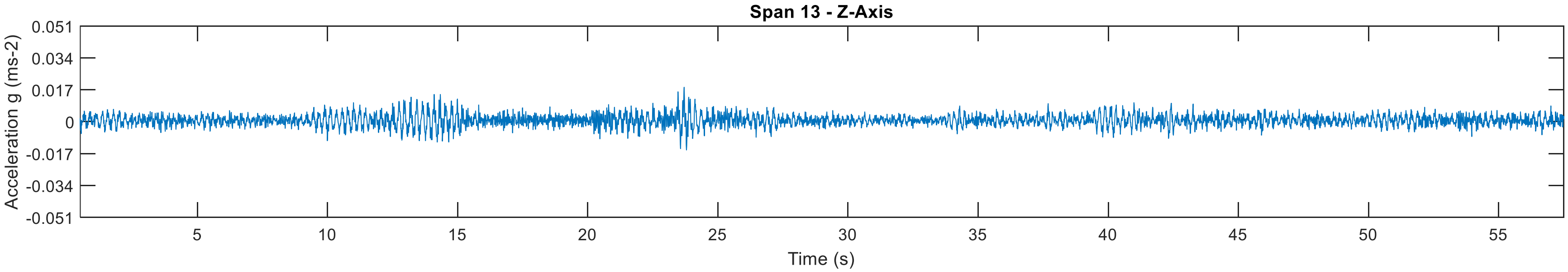


Figure 75: Span 13 – Z axis Acceleration Time History

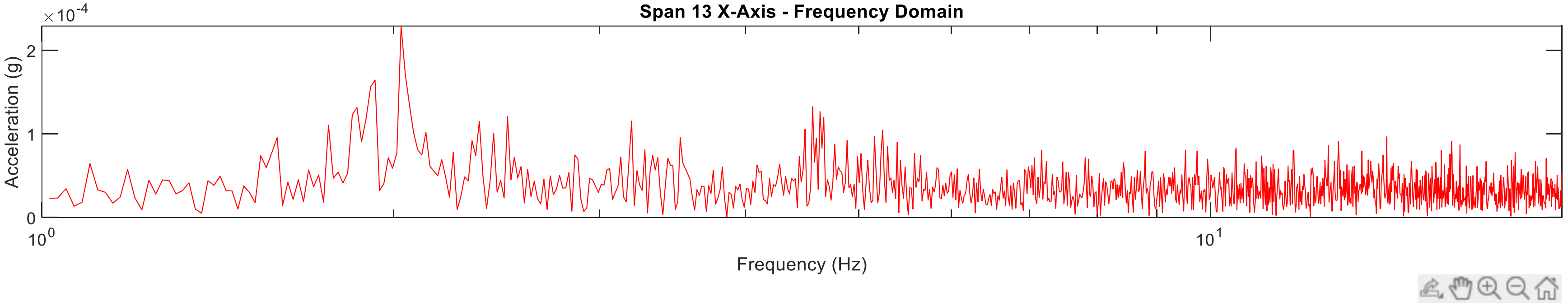


Figure 76: Span 13 – X axis Frequency Domain

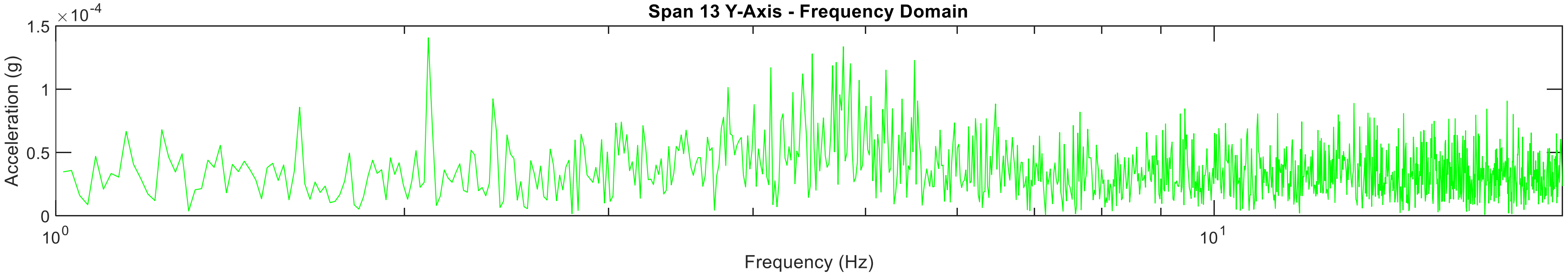


Figure 77: Span 13 – Y axis Frequency Domain

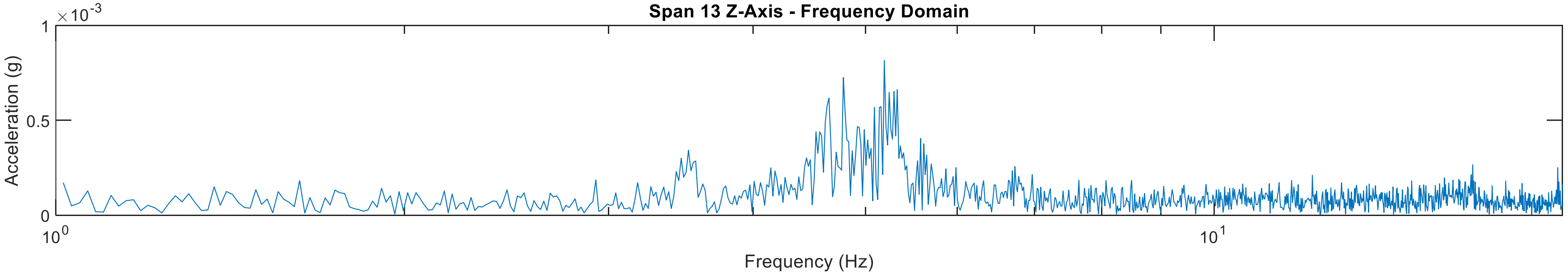


Figure 78: Span 13 – Z axis Frequency Domain

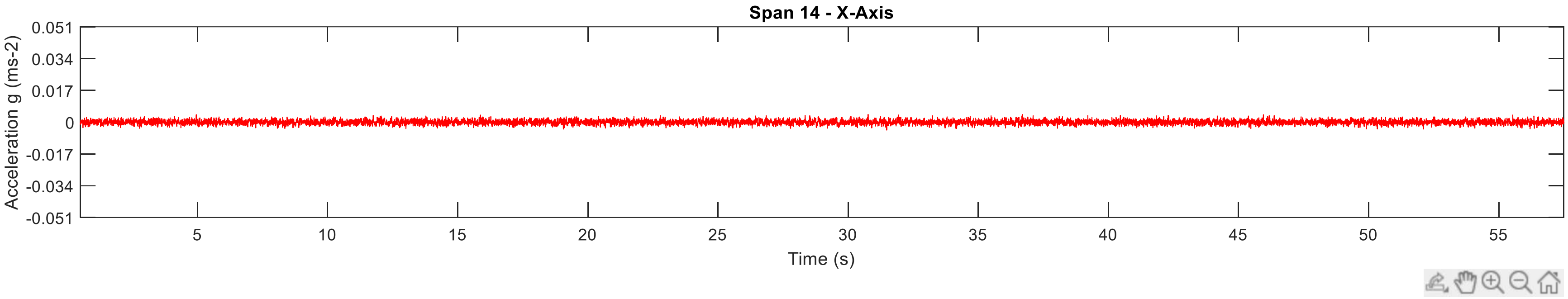


Figure 79: Span 14 – X axis Acceleration Time History

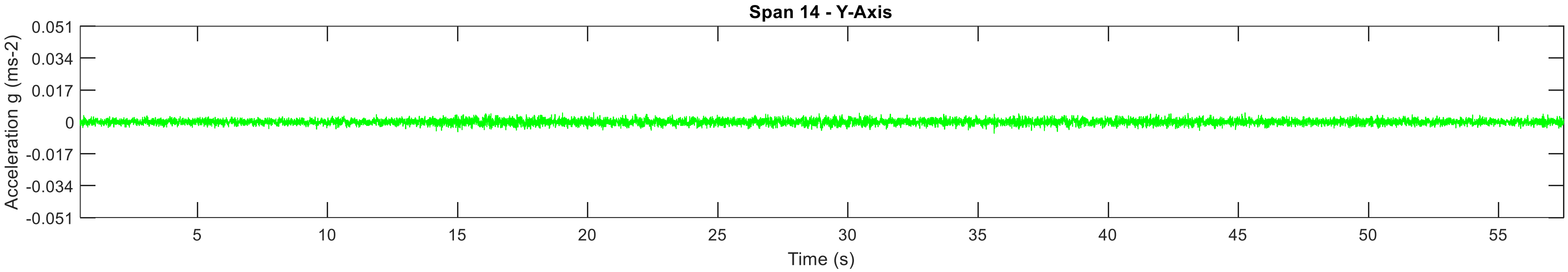


Figure 80: Span 14 – Y axis Acceleration Time History

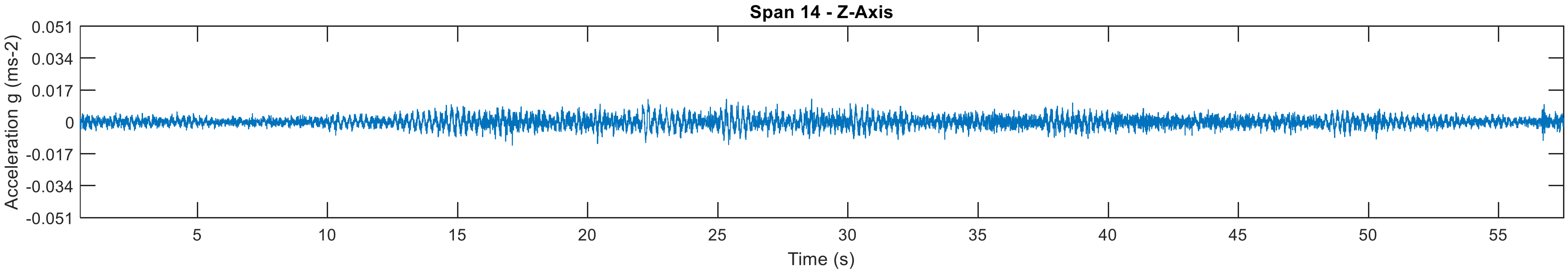


Figure 81: Span 14 – Z axis Acceleration Time History

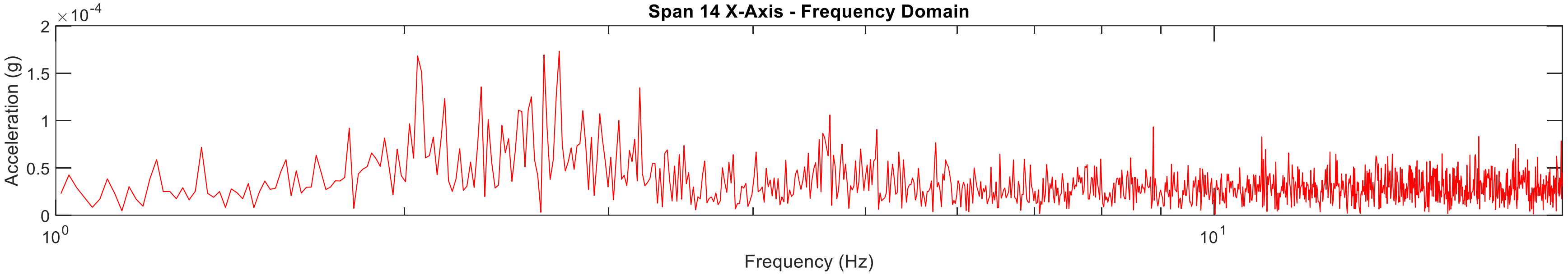


Figure 82: Span 14 – X axis Frequency Domain

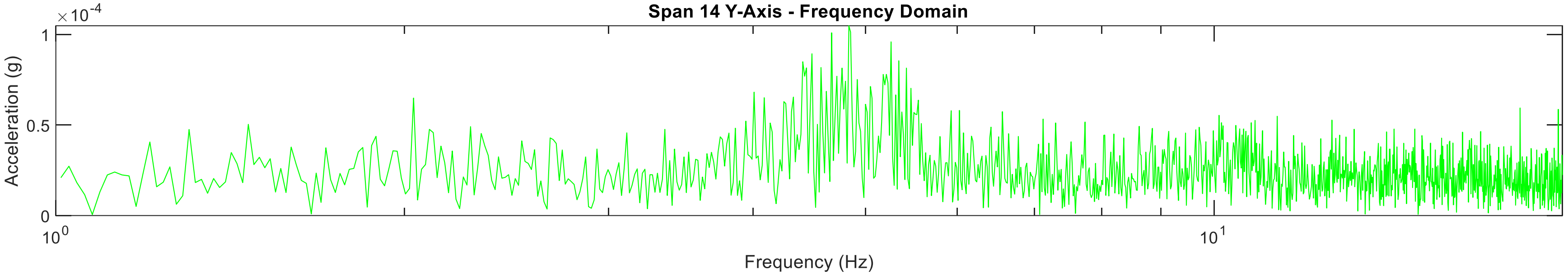


Figure 83: Span 14 – Y axis Frequency Domain

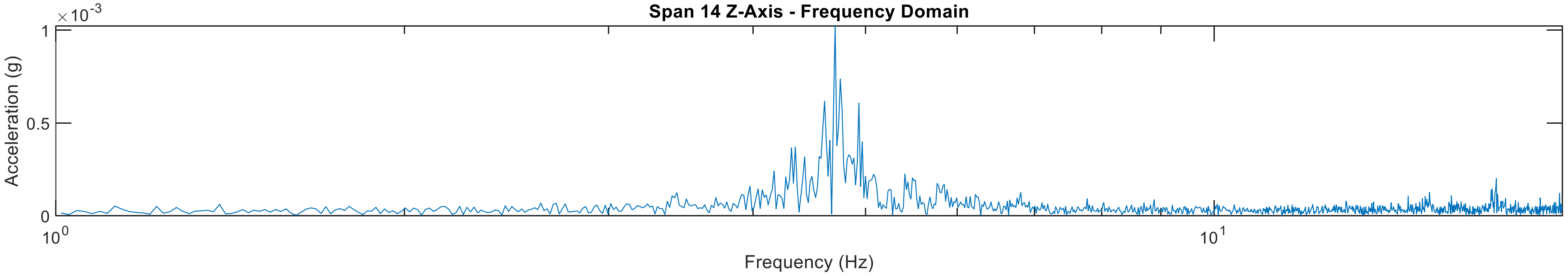


Figure 84: Span 14 – Z axis Frequency Domain

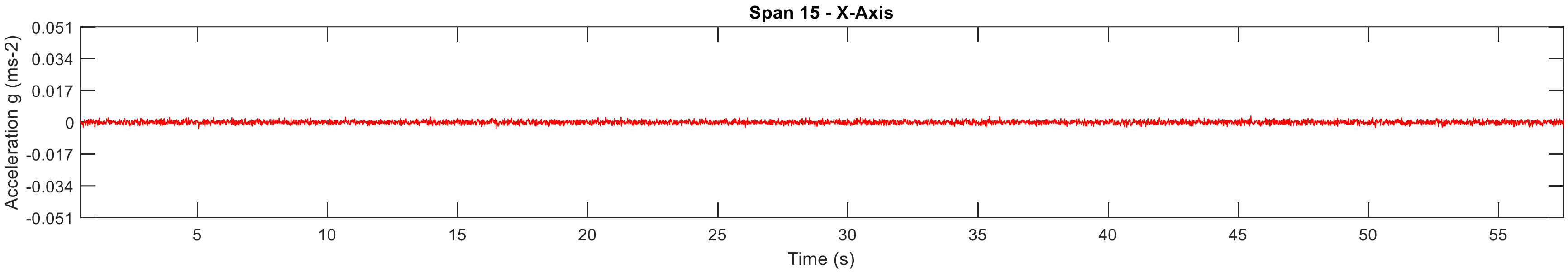


Figure 85: Span 15 – X axis Acceleration Time History

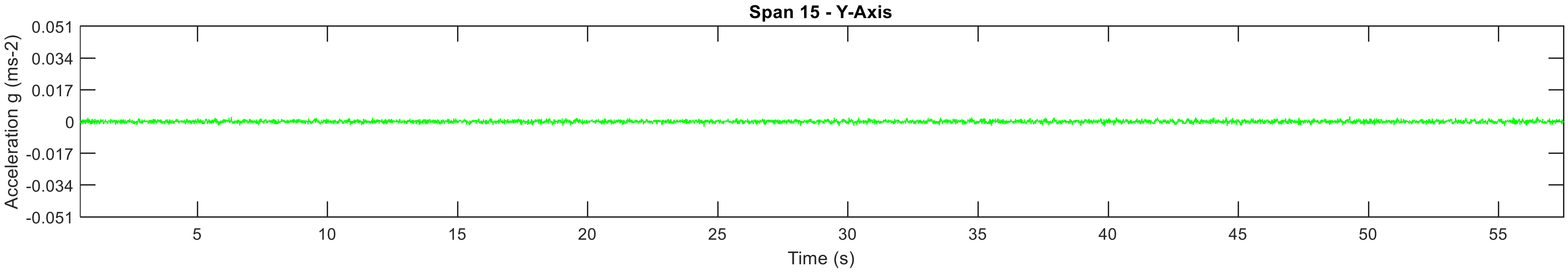


Figure 86: Span 15 – Y axis Acceleration Time History

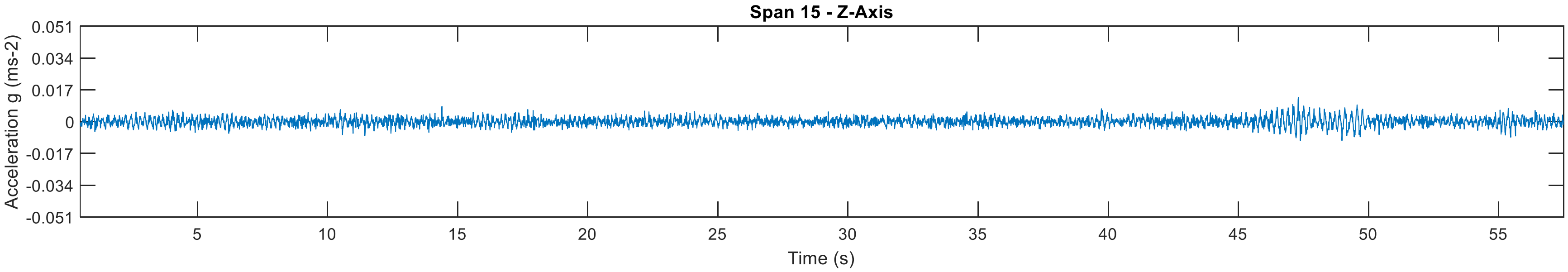


Figure 87: Span 15 – Z axis Acceleration Time History

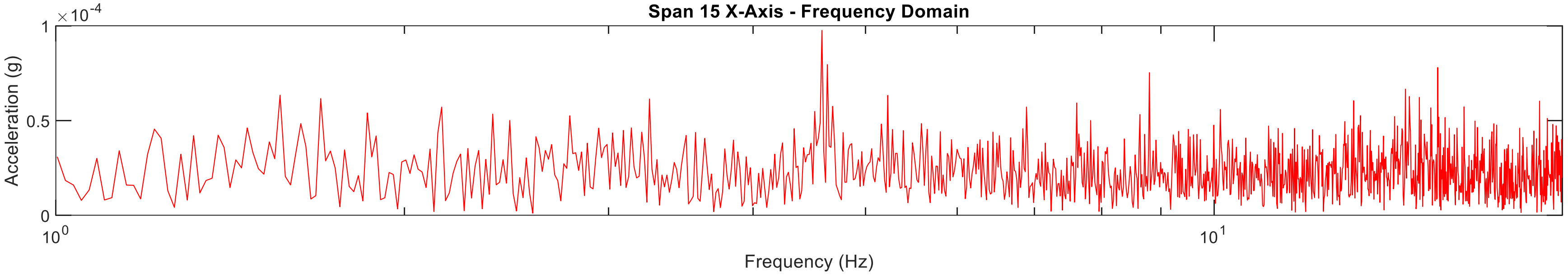


Figure 88: Span 15 – X axis Frequency Domain

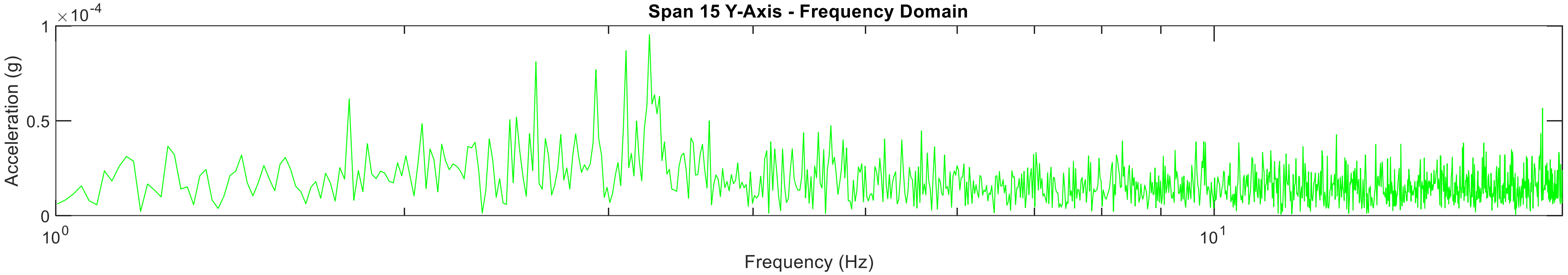


Figure 89: Span 15 – Y axis Frequency Domain

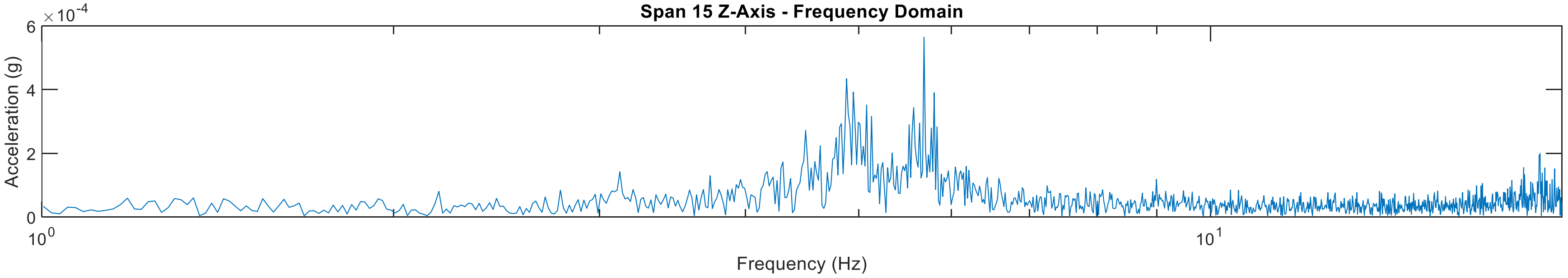


Figure 90: Span 15 – Z axis Frequency Domain

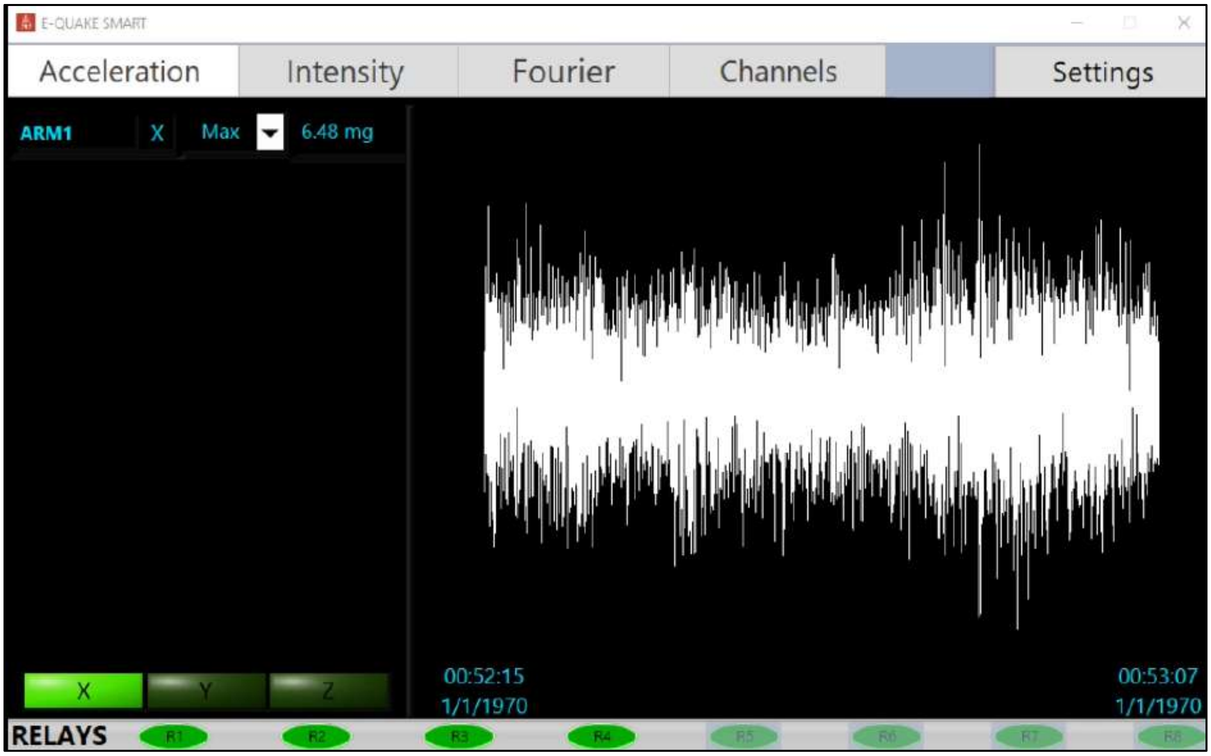


Figure 91: E-Quake Arm Accelerometer plotting real-time acceleration values of Span 2

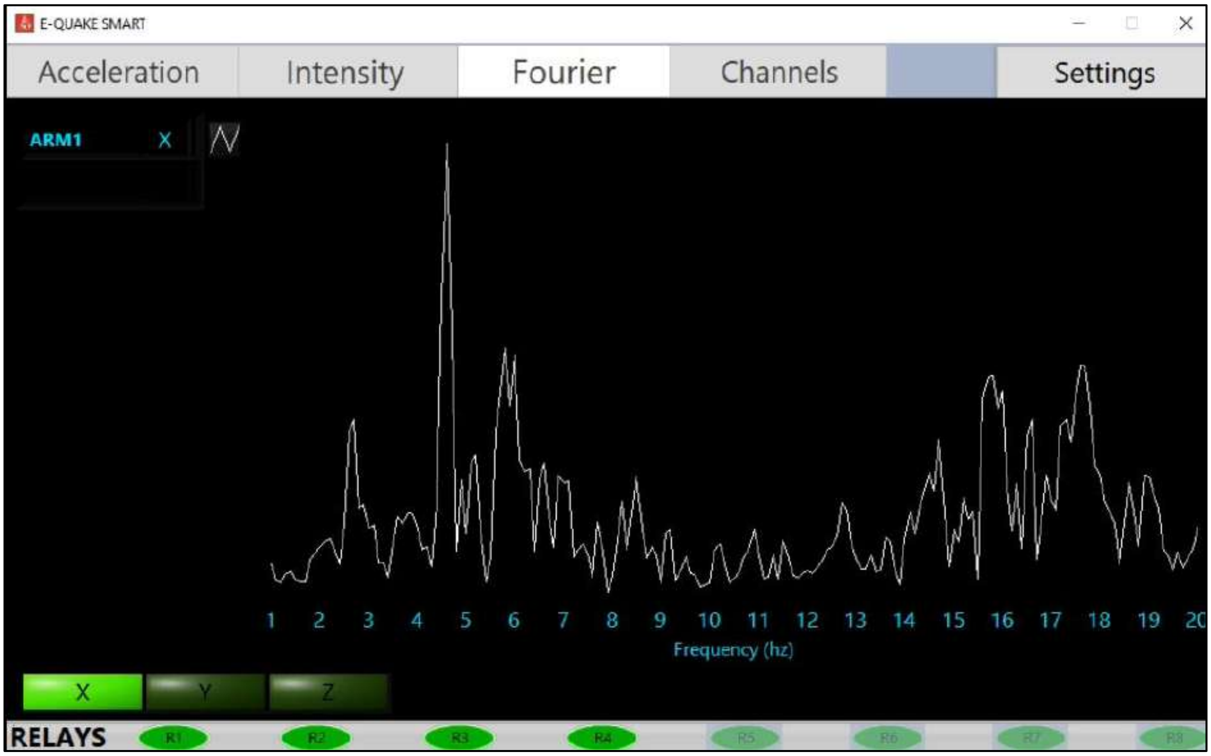


Figure 92: E-Quake Arm Accelerometer plotting real-time frequency domain of Span 2

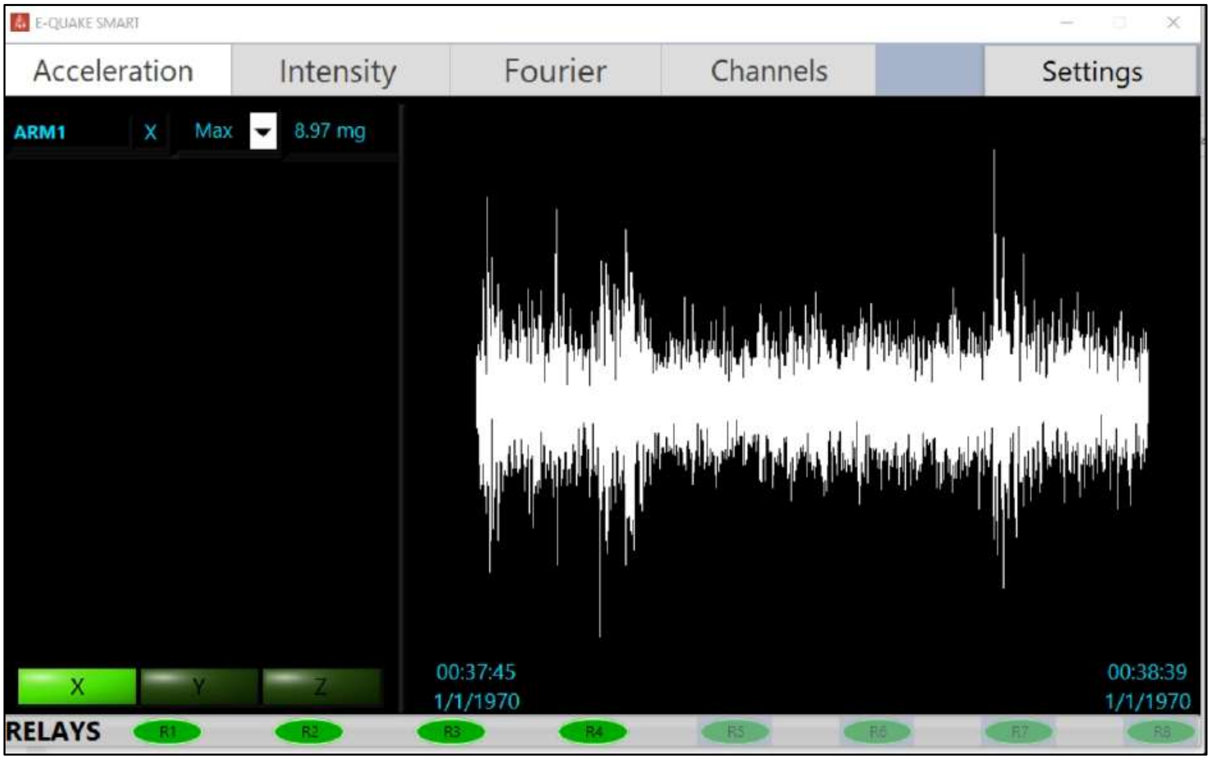


Figure 93: E-Quake Arm Accelerometer plotting real-time acceleration values of Span 7

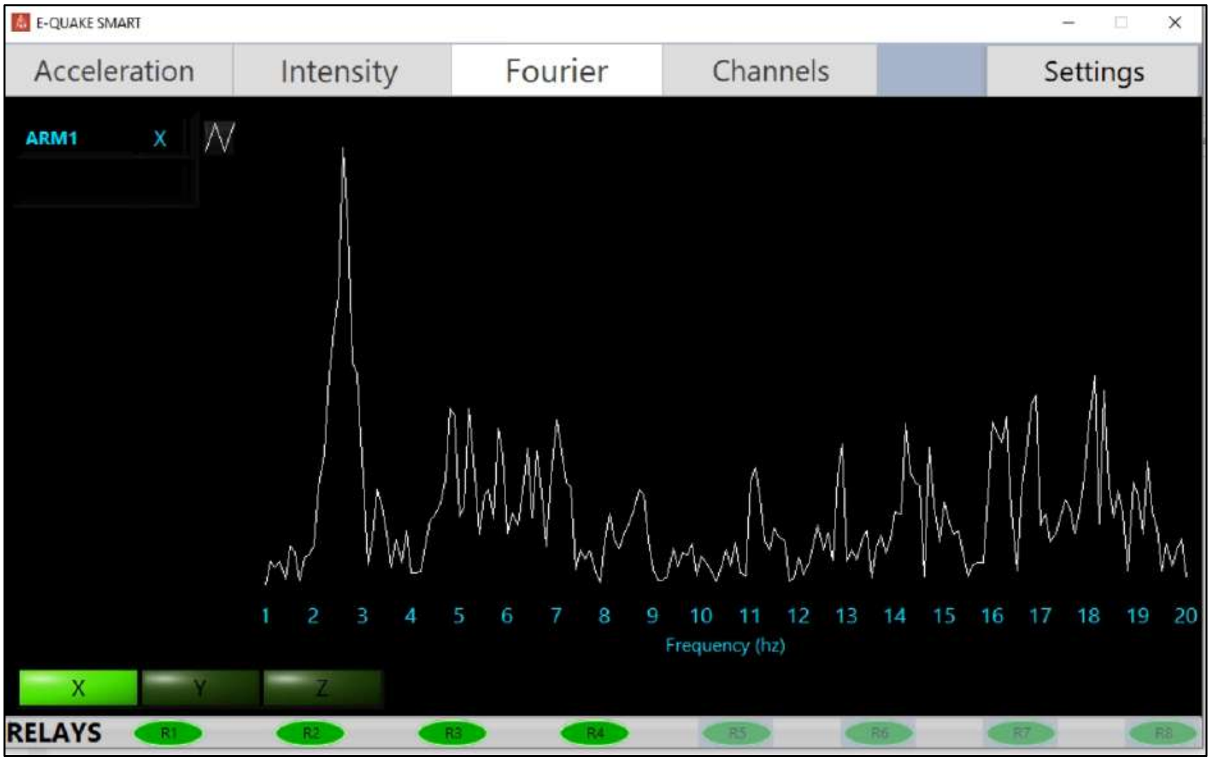


Figure 94: E-Quake Arm Accelerometer plotting real-time frequency domain of Span

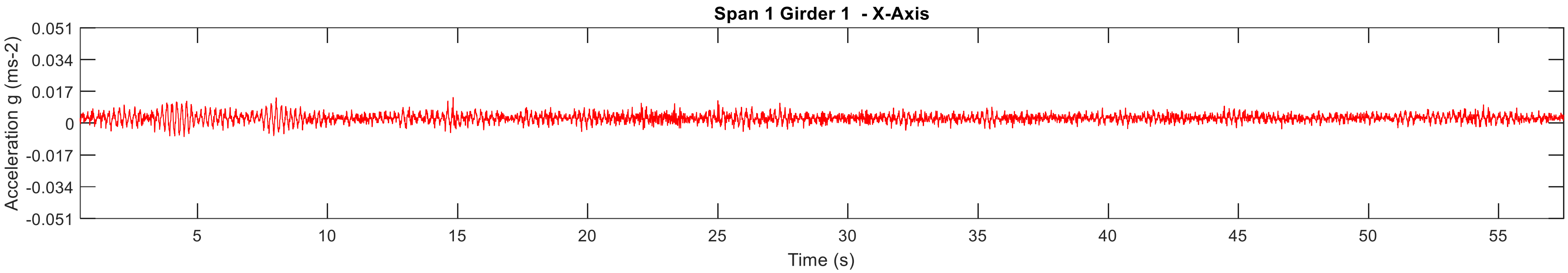


Figure 95: Span 1 Girder 1 – X axis Acceleration Time History

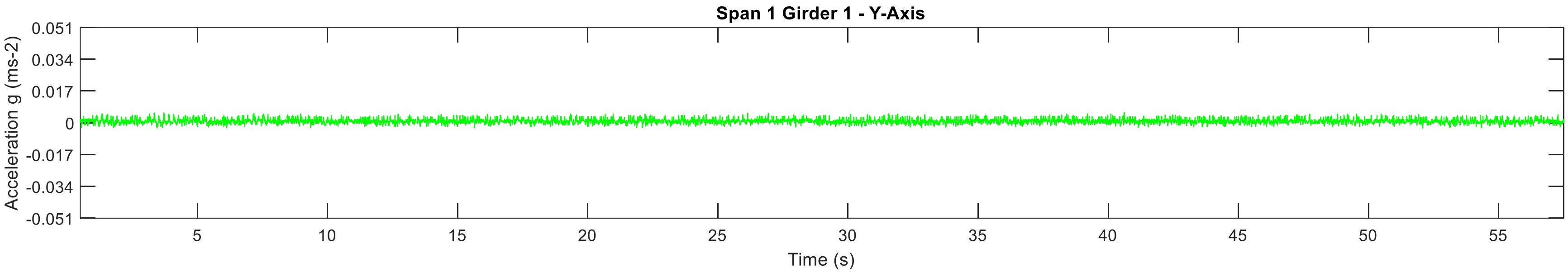


Figure 96: Span 1 Girder 1 – Y axis Acceleration Time History

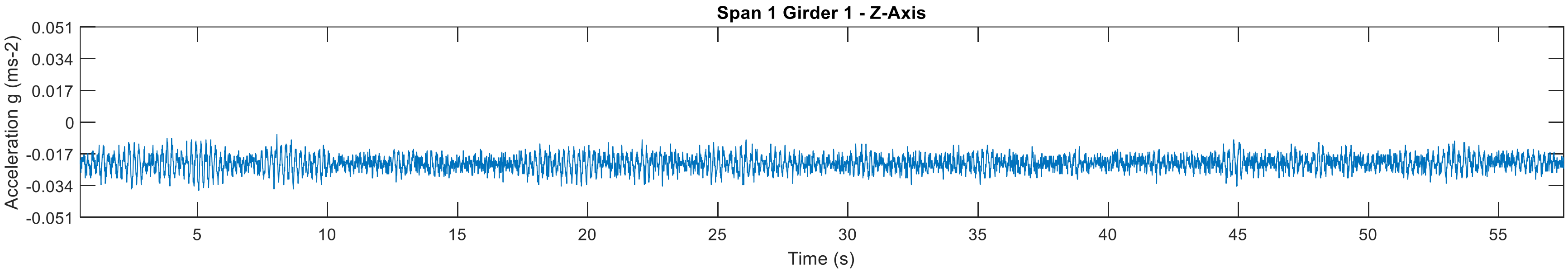


Figure 97: Span 1 Girder 1 – Z axis Acceleration Time History

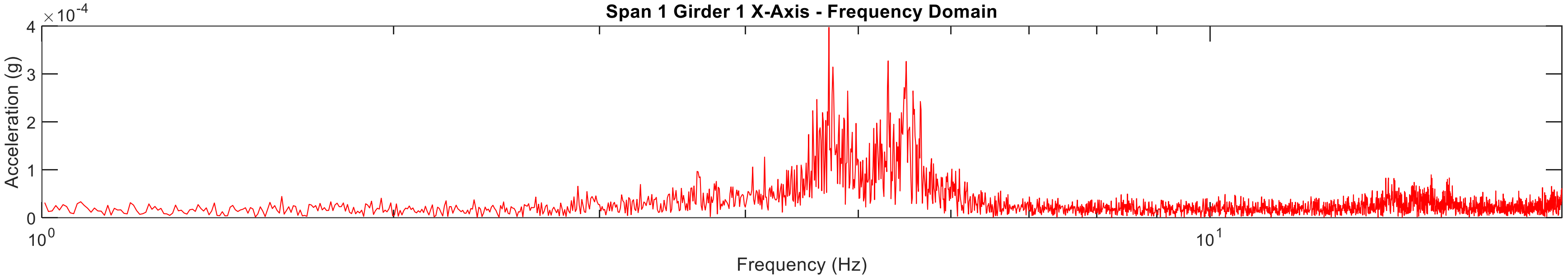


Figure 98: Span 1 Girder 1 – X axis Frequency Domain

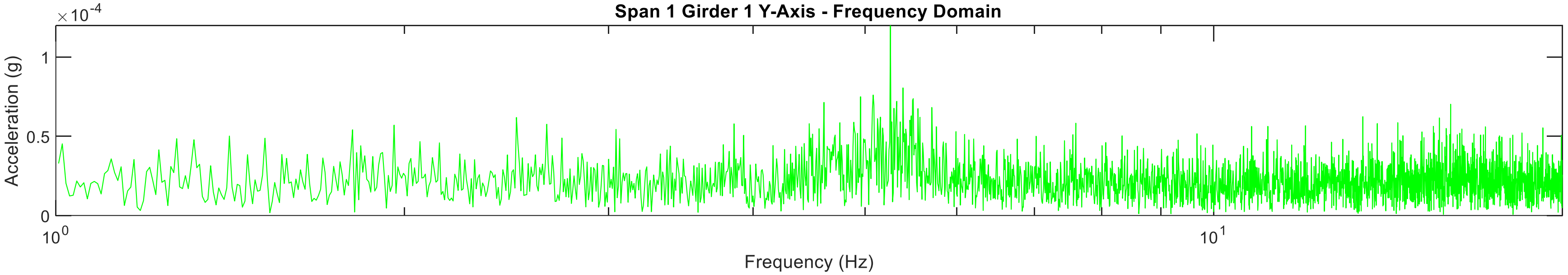


Figure 99: Span 1 Girder 1 – Y axis Frequency Domain

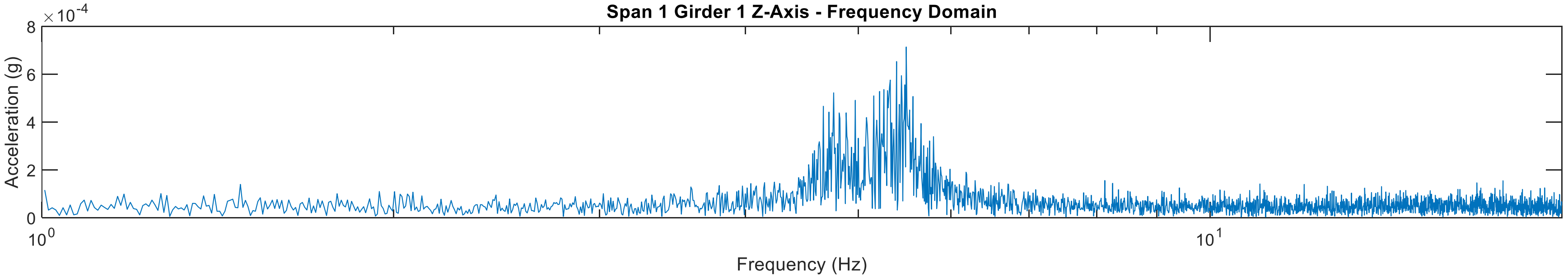


Figure 100: Span 1 Girder 1 – Z axis Frequency Domain

Figure 101: E-Quake Arm Accelerometer plotting real-time acceleration values of Girder 1 of Span 1

*Civil Engineering Department*
**UNIVERSITY OF ENGINEERING AND TECHNOLOGY, LAHORE**

---

# SOPs/SI VERIFICATION CERTIFICATE

## B.Sc. CIVIL ENGINEERING FINAL YEAR PROJECT

It is certified that **Final Year Project (FYP)** report titled **"Condition Assessment of Bridges"** submitted by Muneeb Ashraf (2019-Civ-68), Atzal ul Rehman (2019-Civ-72), Muhammad Hamza (2019-Civ-75) and Yahya Zafar (2019-Civ-81) has been checked and verified as per guidelines/SOPs given by the Department. Further, it is certified that the similarity index (SI) of the FYP report is within limit (i.e., less than or equal 19%) as per University policy.

**FYP Advisor**
**[Dr. Muhammad Mazhar Saleem]**

**Convener**
**FYP Committee**

---

***Important Notes:***

1. *All FYP advisors are requested to ask their group(s) to get the final hard copies of the FYP report after verification by the committee constituted by the Chairman for this purpose.*
2. *Title of FYP and name of students along with their registration number should be preferably computer typed in this certificate. Softcopy of this certificate will be provided to all FYP advisors.*
3. *First page of SI report indicating SI value should be signed by the FYP advisor and the same must be submitted to committee for record.*
4. *It is mandatory for all FYP groups to submit FYP poster before departmental clearance.*