AC 2009-459: DESIGN OF A BRIDGE STRUCTURAL INTEGRITY WIRELESS MONITORING SYSTEM FOR COMPUTER ENGINEERING EDUCATION

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Design of a Bridge Structural Integrity Wireless Monitoring System for Computer Engineering Education

Abstract

A wireless sensors based system is designed for computer engineering students to remotely monitor the structural integrity of a truss metal bridge model. Triple axes accelerometers are attached to the trusses of the bridge such that the vibrations due to the bridge movements can be transmitted wirelessly using 2.4 GHz signals. The system then collects and analyzes the signals with a receiver attached to a computer. Data logging of the bridge vibrations is implemented using a multi-sensor data link to routinely collect the normal waveform patterns when an impulse impact is applied to the bridge. Using the Fast Fourier transform MATLAB program, analysis of the waveforms yields a definite shift in the characteristic signature, when one or more of the bridge truss joints are intentionally compromised. Consequently, this simple but effective technique can be employed to monitor the structural integrity of bridges routinely using this system. When a characteristic frequency shift is detected, the wireless monitoring may be supplemented with visual inspections, to warn the bridge safety personnel and users of imminent bridge deficiency. The designed system provides a good opportunity for our Computer Engineering students to culminate their technical education in a Senior Design Project using their knowledge of Signals and Systems as well as Communications and Electronics. By participating in this project, the students successfully implement the knowledge learned in courses on frequency domain analysis, impulse response, signal amplification, and physical vibrations to electrical signal conversion.

Introduction

Bridge integrity is an issue of national priority following the Minnesota bridge collapse[1], shown in Figure 1 and the subsequent publicity that a significant percentage of the nation's bridges are in need of repair[2].

Figure 1: Collapse of the Minneapolis, MN Bridge [1]

The frequency of bridge inspection and subsequent repair is hindered by the lack of funds, personnel and suitable technology to routinely monitor the bridge's structural integrity. Computer engineering can help solve this problem; it is a discipline that combines both computer science and electrical engineering and prepares students for careers that deal with software and hardware components of modern computer systems[3]. To educate computer engineering students at our university effectively and practically, we have instituted a Senior Design Project to provide hands-on activity in class. This is beneficial since students are exposed to real-world engineering problems, that involve both software and hardware components of computer systems. Utilizing a computer platform to build a wireless system provides hands-on and practical examples for students[4]. In this paper, we employ a wireless system to monitor the structural integrity of a model bridge, and to design a data acquisition system as the platform and develop signal analysis computer programs to determine indications for possible compromise of bridge safety.

To simulate an actual bridge, a metal truss model bridge was employed in the configuration shown in Figure 2. MircroStrain wireless triple axes accelerometers were attached to several gusset plates to monitor the vibrations as indicators of bridge structural integrity[5]. Accelerometers are electromechanical devices that measure dynamic acceleration forces caused by impact. An analysis of dynamic forces allows for accelerometers to detect displacement of an object such as a pin joint on a bridge[6]. On each end of the bridge are steel plates with shock absorbent pads, which are responsible for isolating the bridge and bounding on each of its ends.

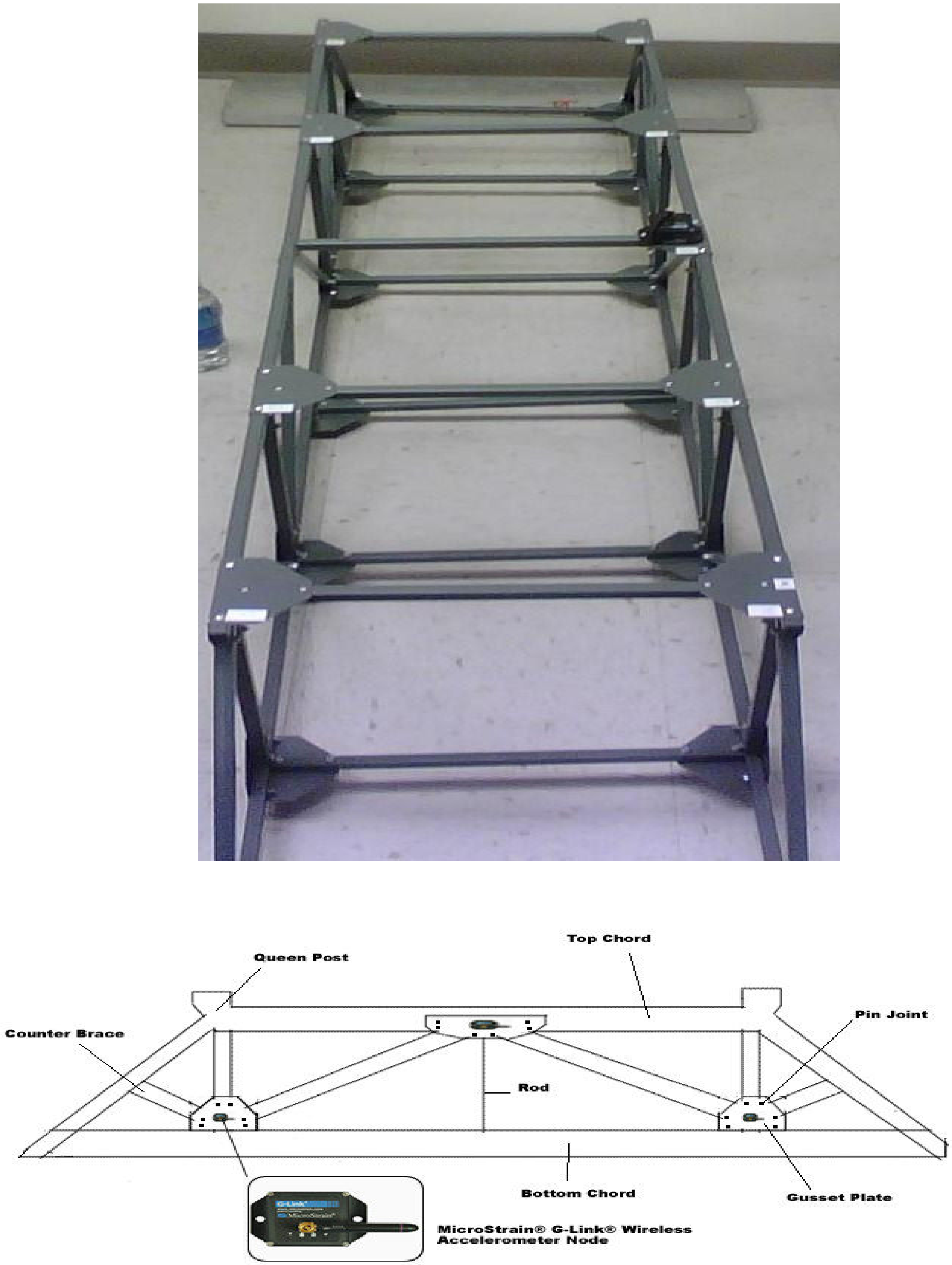

Figure 2: Model of bridge structural integrity monitoring system using wireless accelerometers

In a high-level overview, the model bridge is assumed to be a linear system that exhibits superposition properties. Figure 3 is a block diagram that illustrates the linear system.

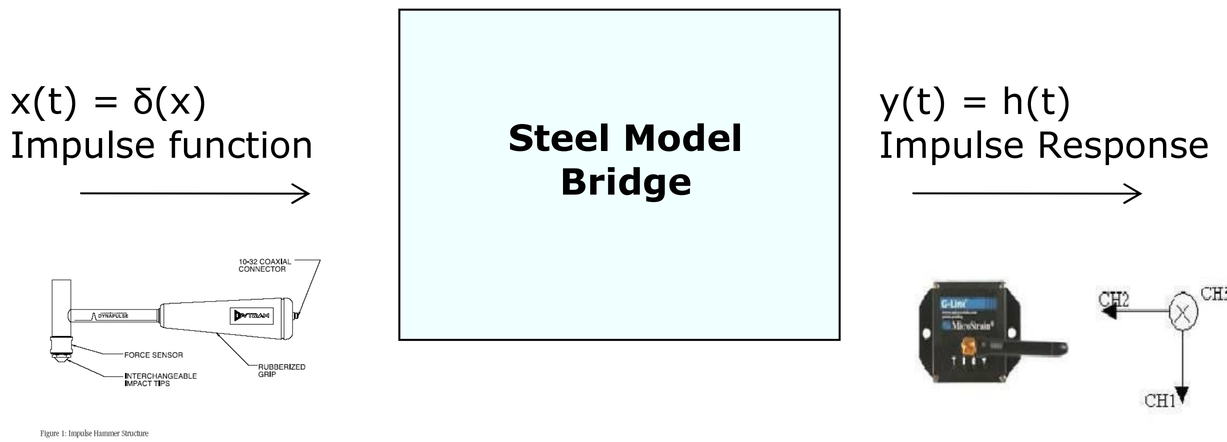

Figure 3: Linear system representation of the bridge monitor

In Figure 3, the impulse hammer (Omega's IH-101) is the input and the accelerometer signal is the output. An impulse hammer is used to excite the bridge structure while simultaneously measuring the magnitude of the excitation.

First, the bridge prototype is excited using the impulse hammer. Once the impulse hammer hits the structure in a fixed location, it generates a characteristic voltage that is sent to the input of a PC's sound card. The characteristic voltage is recorded using the Windows built-in Sound Recorder program to determine the validity of the impulse signal. In Windows Sound Recorder, the response is recorded and saved as a '.wav' file. The '.wav' file is then imported into a MATLAB program that generates a graph of the impulse. If the generated graph appears to be an approximated delta function with a single pulse, then the excitation is considered to be appropriate. Figure 4 shows an idealized impulse signal and an impulse signal generated by the hammer.

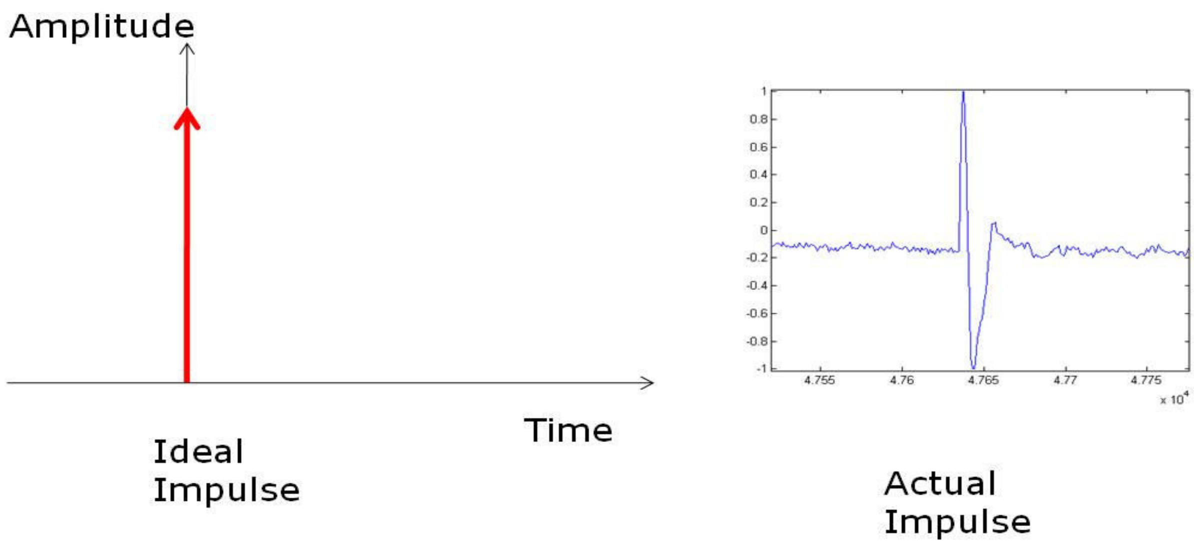

Figure 4: Impulse signal generated for signal analysis

After an impulse signal is generated and tested, the vibrations of the excitation oscillate throughout the bridge structure. Once the accelerometers "sense" the vibrations in the X, Y, and Z directions, the data collected by the wireless transmitter is transferred to a base node (receiver) attached to a PC USB port.

Agile-Link, software provided by MicroStrain, shows the data in time domain, as depicted in Figure 5. Subsequently, the Agile-Link data is exported to MS Excel, as shown in Figure 6.

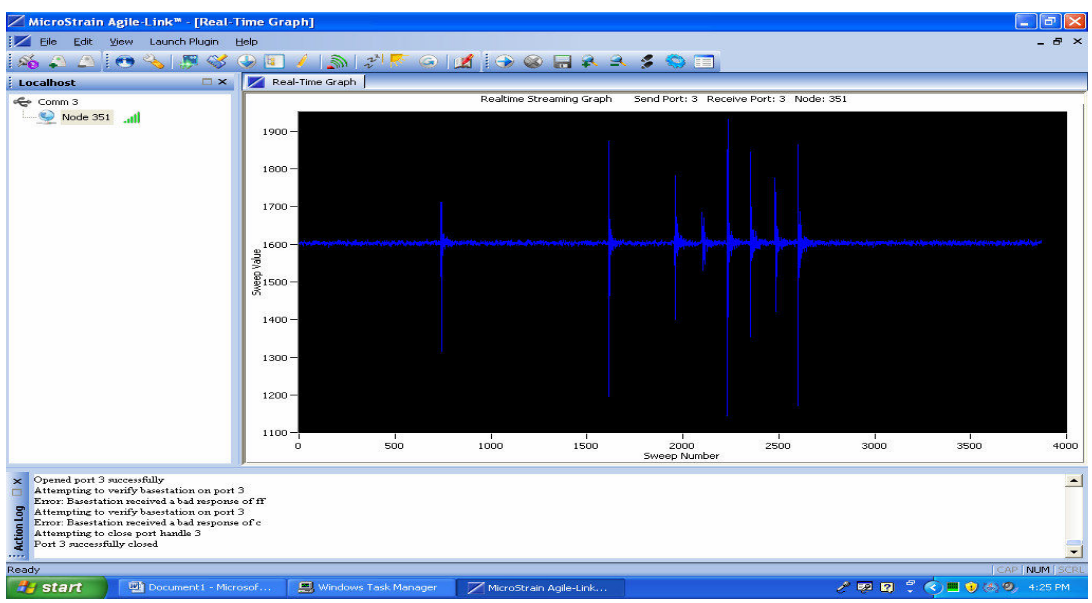

Figure 5: Time domain signal received from a base node

A MATLAB program was developed to transform the time-domain signal to the frequency-domain signal, performing the FFT algorithm.

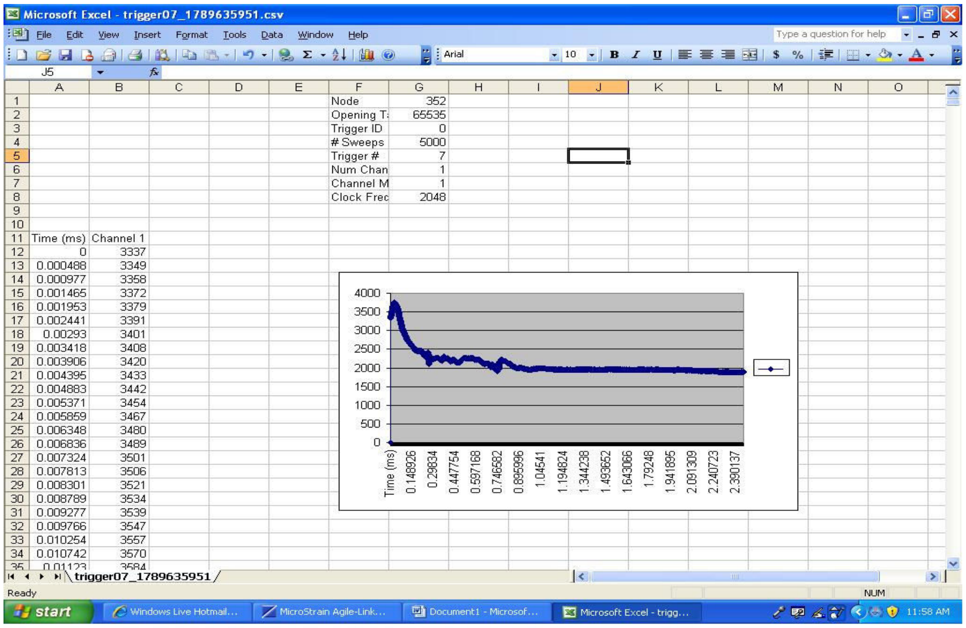

Figure 6: Exported waveform to Excel

Product Architecture

Product Architecture consists of both functional and physical elements of the bridge safety monitoring system. Individual operations and transformations that influence the overall performance of a product are known as functional elements. Parts, components, and subassemblies that in time execute the system's functions are the physical elements. The grouping of physical elements is known as a sub-system. Each sub-system usually implements one or a few functional elements. The interactions between sub-systems are usually essential for the primary functions of the monitoring system. This design has five separate sub-systems that make up the prototype[6].

The first sub-system consists of an impulse hammer and an amplifier circuit. This sub-system is a functional element because it performs an individual operation. The output from the impulse hammer is the input to the amplifier circuit. The amplifier circuit performs the necessary operation on the impulse hammer's output to allow communication between the first and second sub-systems. The second sub-system consists of the computer's sound card, and a MATLAB software program. The output of the sound card is the input to the MATLAB program. Once this sub-system receives data from the first sub-system, it checks if the data is valid. If the data is not valid, the first sub-system will need to receive a new input. If the data is valid, the data received by the third sub-system is also valid. The third sub-system consists of the bridge itself. This sub-system receives data from the first sub-system immediately upon its execution, even though the data may not be valid.

The bridge responds to the output from the impulse hammer, which becomes the bridge's input. This input is collected and sent to the fourth sub-system. The fourth sub-system consists of a sensor, and a transmitter. The output from the third sub-system is the input for the sensor. The sensor collects the data and sends it to the transmitter. The transmitter outputs the data received to the fifth sub-system. The fifth sub-system consists of a base station, storage hub, and a MATLAB software program. The input for this sub-system is the base station. Once the base station receives the data from the transmitter (sub-system 4), it sends it to the storage hub. The storage hub allows the software to communicate with the incoming data. The software outputs the results of the analyzed data. This data should be sufficient and capable of determining whether or not a bridge is structurally satisfactory. The overall signal analysis procedure is shown in Table 1.

Impulse Response Procedure for MATLAB	**Transformation Procedure for MATLAB**
❖ Use wavread function in MATLAB to load audio file ➢ y = wavread('impulse.wav') ❖ Use length function to obtain sample duration ➢ number_of_samples =length(y) ❖ Create x-axis for time ➢ x = [1:length(y)] ❖ Use plot function to output graph ➢ plot(x,y)	❖ Using load function in MATLAB to load text file ➢ SensorFile = load('r3_r2_none_3.txt') ❖ Use length function to obtain sample duration ➢ length(SensorFile) ❖ Specify sample frequency ➢ Fs = ((2.048)*1e3) ❖ Set time period of sample ➢ Time = [0:length(SensorFile)-1]/Fs ❖ Use Fast Fourier Transformation function ➢ fft(SensorFile) ❖ Use absolute function to obtain amplitude values ➢ abs(Sensor_FFT) ❖ Create x-axis for frequency values ➢ Freq_Axis = [0:N_Sensor-1]*Fs/N_Sensor ❖ Use plot function to output graph ➢ plot(Freq_Axis,Sensor_FFT_Mag)

Table 1: Overall signal analysis procedure

All the data and picture files associated with the bridge safety monitoring system can be stored using a data management system. The data management system was created using HTML, PHP, and SQL languages. The main objective of the database management system is to create a server-based system that is accessible by transportation workers via the internet. For instance, during or after an inspection, an inspector will be able to use a laptop computer to securely enter new bridge information, query old bridge information, or upload/download MATLAB files, and Excel files onto their firm's server for further analysis. This was accomplished by taking an open source approach.

Hardware Platform

The impulse hammer is used to excite the bridge, which is the input to the system. The signal generated when the bridge is struck needs to be captured by the computer's sound card in order to be analyze. During this phase, the signal proved to be too weak to be detected. This problem was rectified by using a simple non-inverting operational amplifier. Figure 7 shows the circuit diagram for the non-inverting amplifier used in the project whereas Figure 8 shown the actually built amplifier.

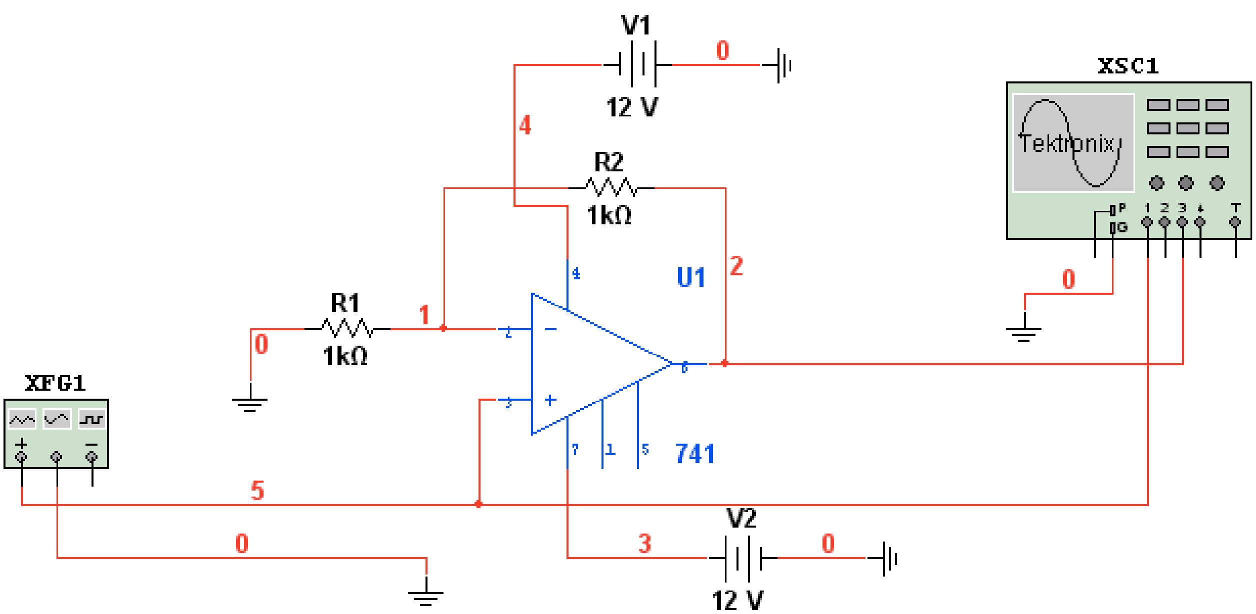

Figure 7: Non-inverting operational amplifier used to amplify the impulse hammer signal

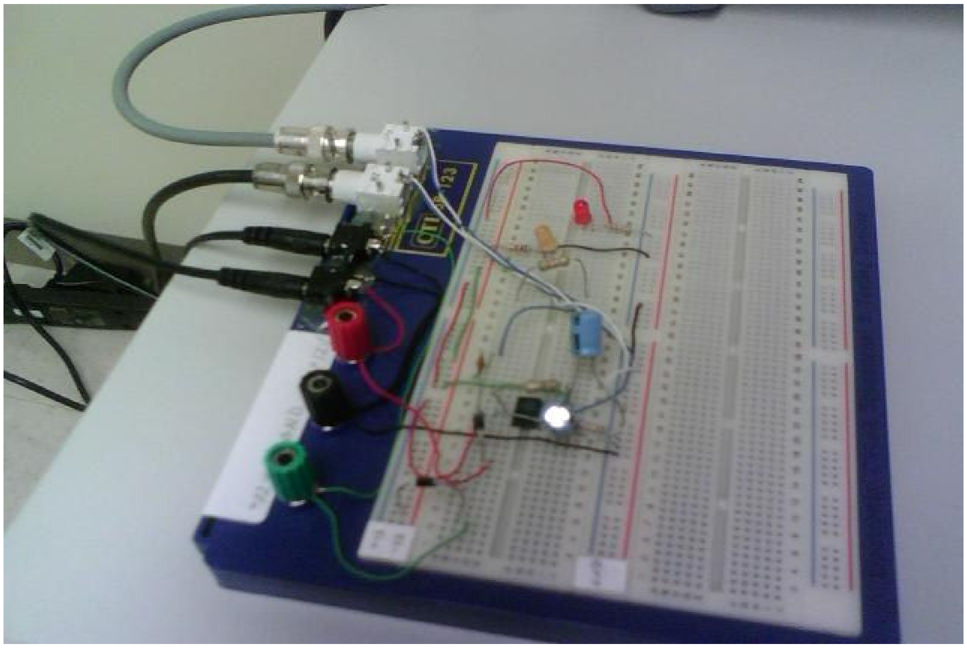

Figure 8: Practical implementation of the amplifier circuit

Figure 9 shows the simulated oscilloscope reading of both the input and output for this circuit, showing the amplifier gain of 2. Once the signal was amplified by the circuit, it was capable of being captured by the sound card.

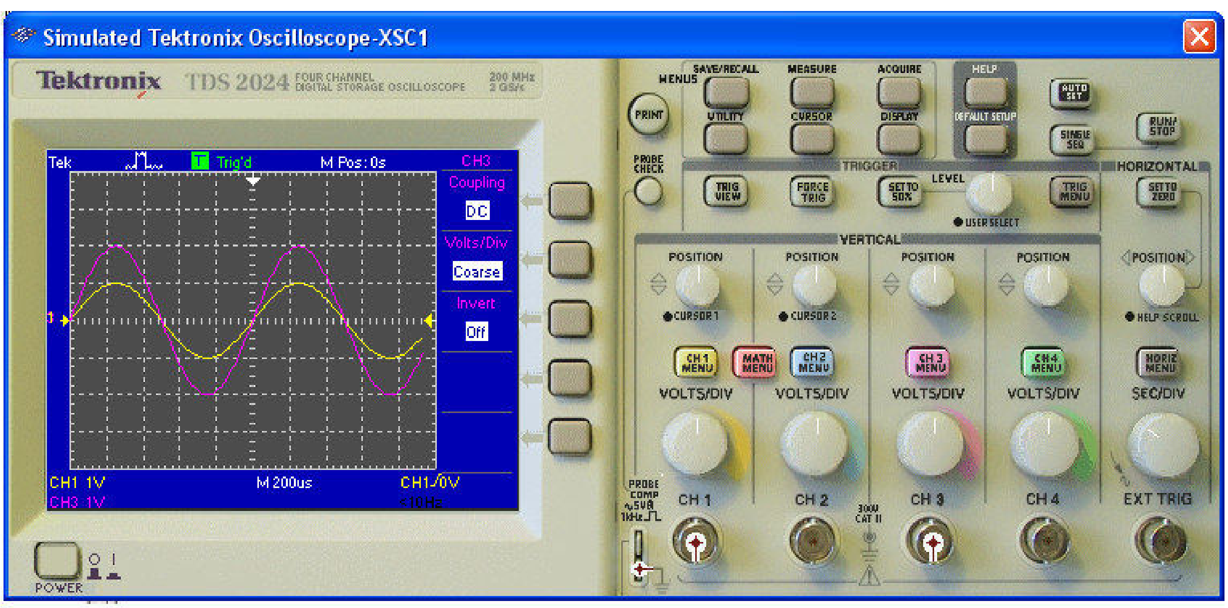

Figure 9: Amplifier circuit verification

Figure 10 is the basic design of the bridge architecture. Attached to the pin joints are the accelerometers, which will detect any displacement in the x, y, or z, directions.

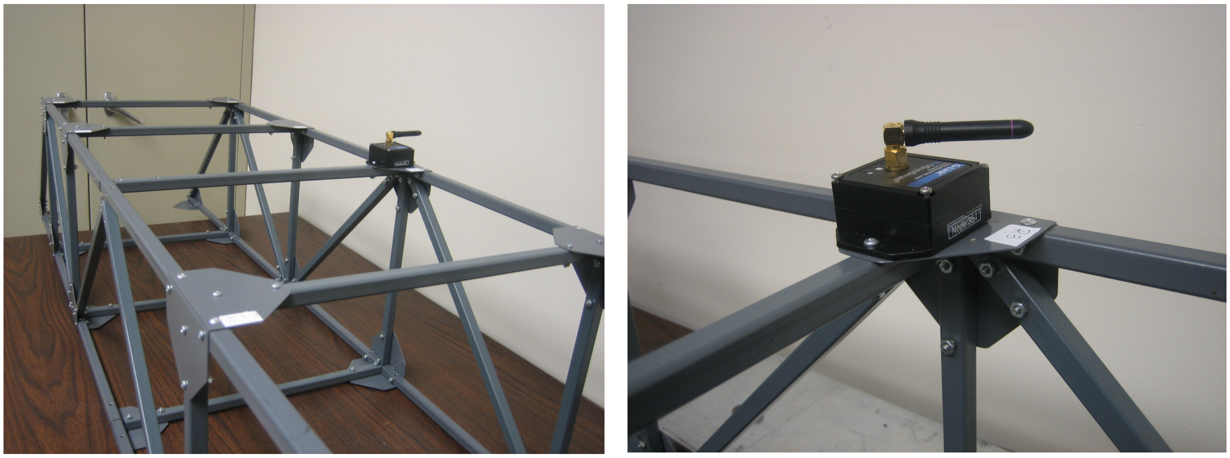

Figure 10: Bridge architecture with wireless accelerometers attached

Experimental Results

The final verification of the bridge design was accomplished by first collecting and analyzing the signal from the structurally sound bridge and then loosening some of the gusset plate’s nuts and bolts to emulate a damaged bridge and collecting the response of the weakened structure. By comparing the two cases, differences in the FFT spectrum were analyzed as indicators of bridge structural deficiency.

The results for the structurally sound bridge, with the accelerometer location R3, Impulse location R4 and no damage, are shown in Figures 11. A gusset plate was loosened at location L3 to simulate a structurally compromised damaged bridge; with the accelerometer location at R3 and the hit location at R4, the damaged bridge spectrum was obtained and compared with the safe bridge spectrum, as shown in Figure 12. A comparison of the FFT spectra of the compromised versus safe bridge demonstrates that there are frequency shifts due to loosening of the bridge trusses, indicating a compromise of its structural integrity. Thus the wireless signal analysis system has been demonstrated as a possible indicator of bridge structural integrity.

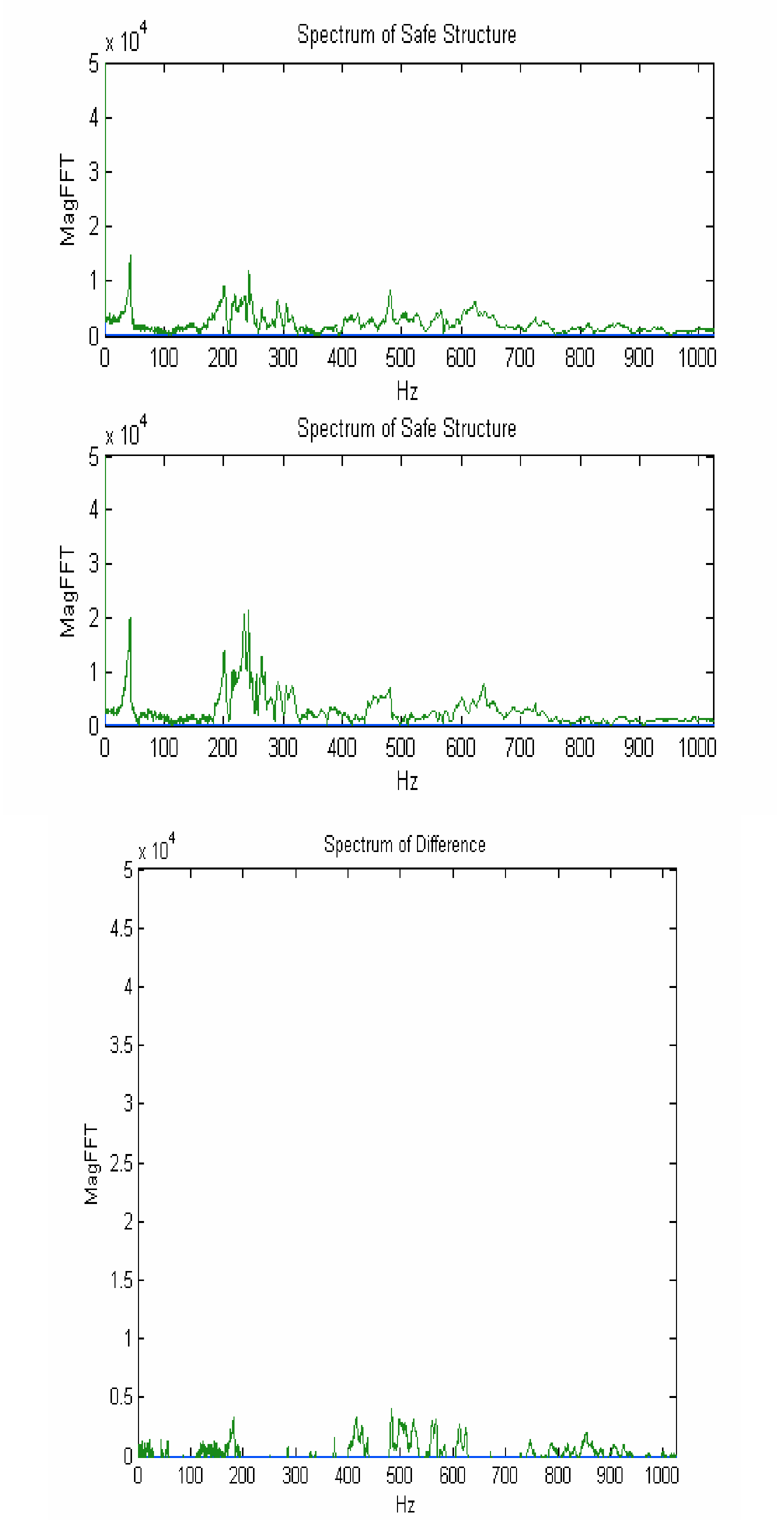

Figure 11: Spectrums of accelerometer response placed at R3 without compromise.

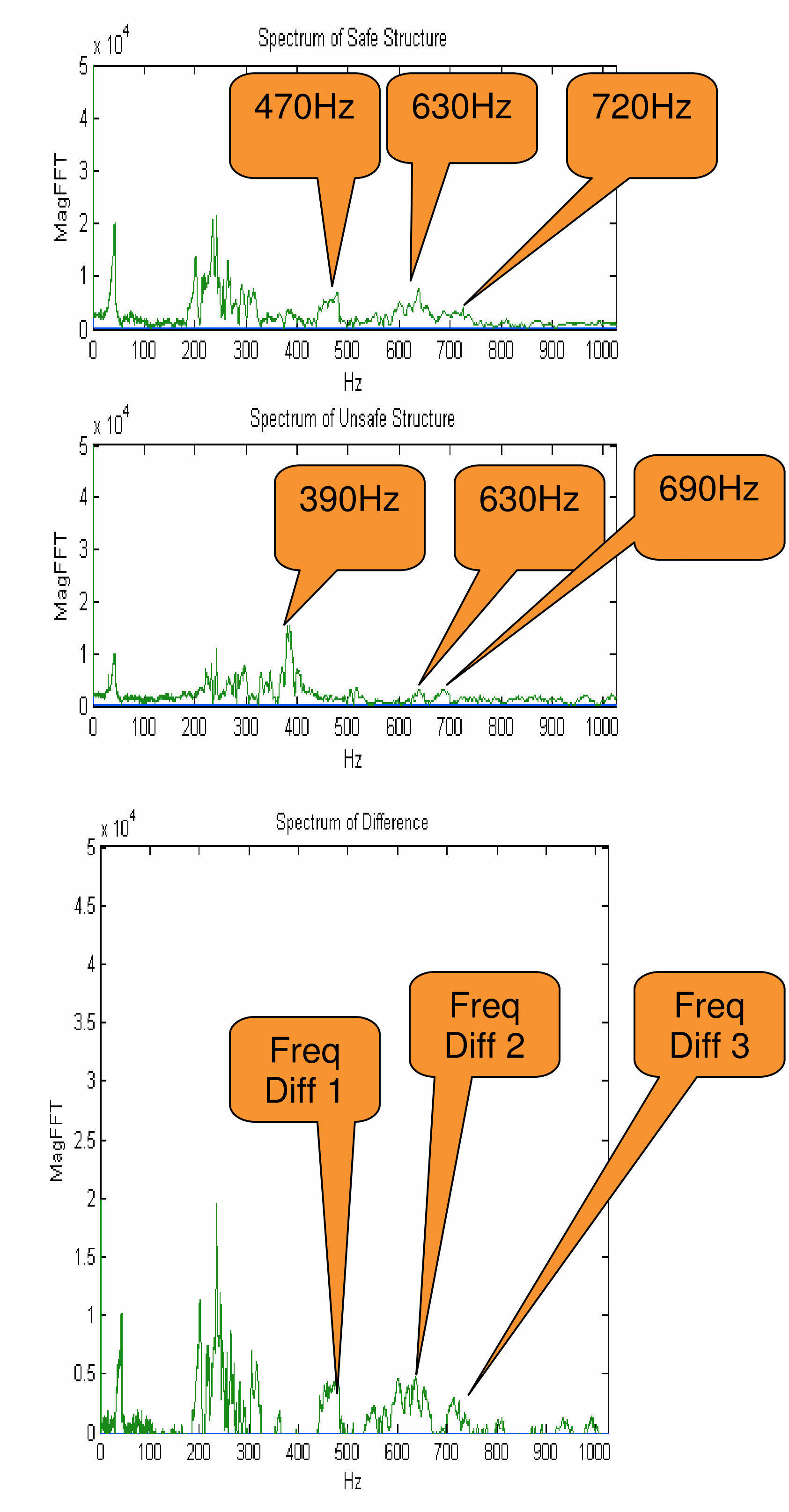

Figure 12: Comparison of safe and damaged bridge spectra

Future Work

The bridge monitoring system is a convergence design that provides a better design solution to existing monitoring systems. The design plan implements vibration analysis to detect structural deficiencies throughout a structure. The system is composed of wireless nodes[7] and accelerometers that are to be placed at each pin joint of the gusset plate. Each of these accelerometers is responsible for calculating displacement that may occur at its respective gusset plate.

The concept of using accelerometers ensures that the gusset plates are structurally sound. Cracks in the center of the bridge could be detected using ultrasonic sensors[8, 9]. An integrated interface of the accelerometers with the ultrasonic sensors, with both sensors communicating with the same base station might be feasible.

Conclusions

A wireless triple axes accelerometer based signal analysis system was demonstrated to provide indicators for bridge structural integrity using a small metal truss bridge model. MATLAB software algorithms were developed using Fast Fourier transforms to analyze the frequency domain signals. Such a system could easily be implemented by municipalities and engineering firms to periodically monitor the safety and security of bridges or other civil structures.

The design of bridge monitoring system allows computer engineering students to weave together the knowledge gained from several courses in the curriculum, such as Electronics, Signal Analysis in time and frequency domains, Communications, Applied Physics, and high-level technical programming. The system also provides students real-world examples of Computer Engineering applications. This helps students learn how to integrate hardware and software to fabricate a functional system. In addition, it provides a hands-on experience for the students to gain abilities to design a system to meet desired needs within practical constraints.

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