Final Report for Research Project

LONG-TERM MAINTENANCE MONITORING DEMONSTRATION ON A MOVABLE BRIDGE

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A Report on a Research Project Sponsored by
Florida Department of Transportation
Contract No.: BDK78 977-07
Alberto Sardinas, Project Manager, FDOT

September 2011

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The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation.

UNIT CONVERSION TABLE

To convert from	To	Multiply by
inch	centimeter	2.54
square inch	square centimeter	6.4516
kip	kiloNewton (kN)	4.44747
kip/sq.in.	(ksi) kN/sq.m (kPa)	6,894.28
kip-foot	kN-meter	1.3556
btu	joule	1,055
btu/hr	watt	0.2931
degrees Fahrenheit – 32	degrees Celcius	0.5555
lb/cu.in.	kg./cu.m	27,680
Btu/sq.ft./min.	watt/sq.in.	0.122

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Long-term Maintenance Monitoring Demonstration on a Movable Bridge		5. Report Date September 30, 2011 6. Performing Organization Code
7. Author(s) Mustafa Gul, H. Burak Gokce, and F. Necati Catbas		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Central Florida Civil, Environmental and Construction Engineering Department Engineering Bldg Room 211 Orlando, FL 32816		10. Work Unit No. (TRAIS) 11. Contract or Grant No. BDK78 977-07
12. Sponsoring Agency Name and Address Florida Department of Transportation Research Center, MS 30 605 Suwannee Street Tallahassee, FL 32310		13. Type of Report and Period Covered Final Report January 6, 2011 – September 30, 2011 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The maintenance costs related to movable bridges are considerably higher than those of fixed bridges, mostly because of the complex interaction of the mechanical, electrical and structural components. A malfunction of any component can cause an unexpected failure of bridge operation, which creates problems for both land and maritime traffic. Maintenance processes associated with the operation system and mechanical parts require special expertise. A comprehensive monitoring system was implemented on Sunrise Bridge (Ft. Lauderdale) to track the behavior and condition of several critical mechanical, electrical and structural components. A number of tests and monitoring of the bridge yielded a wide variety of data, which were analyzed in detail with methods developed by the PI and his research team, and the results obtained at the end of the project were reported to FDOT in a detailed report. After the completion of this previous project, the bridge was already scheduled for painting; however, the monitoring system was significantly damaged during the preparation, sandblasting and painting despite the considerable efforts of FDOT personnel to protect the system. This extension project therefore focuses on repairing the monitoring system, which was affected by the painting operation, collecting and analyzing more data and preparing the system for FDOT. First, details of the field work conducted to repair the damaged monitoring system are presented. Then, analysis of data that were collected after the monitoring system was repaired is presented for different components. The baseline response and the thresholds for acceptable behavior were established. During this phase of the project, unanticipated behaviors were observed for two components (one at the span locks and one at the gearbox) at two different times. These findings indicating the unanticipated behavior using the monitoring system are also corroborated with the independent maintenance reports. These changes in behavior required maintenance work at the span lock and gearbox as given in the maintenance logs. Finally, recommendations are provided based on the findings and experiences from this project.

17. Key Word monitoring, movable bridges, maintenance, sensors, data acquisition, data analysis, signal processing, inspection, repair	18. Distribution Statement		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 70	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGEMENTS

This project is made possible through the support of the Florida Department of Transportation (FDOT). In addition, support from the Federal Highway Administration Advanced Exploratory Program was very instrumental. The suggestions and feedback of the FDOT district and central office engineers were very helpful in the development of this project. In addition, FHWA personnel and engineers made contributions on the use and implementation of monitoring systems in general. Both FDOT and FHWA's support are greatly appreciated.

Finally, several other graduate and undergraduate students were involved in this current project for different aspects of the studies from field work to data analysis. We would like to acknowledge these individuals in no particular order: Alex Hanhold, Tung Khuc, MJ Levi, Masoud Malekzadeh and Tom Terrell,. All of these research assistants made important contributions to the development work presented in this report, and they are greatly appreciated.

PREFACE

The report describes and presents the background, methodology, and results of a research project conducted by University of Central Florida researchers and funded by the Florida Department of Transportation.

EXECUTIVE SUMMARY

Background

The Florida Department of Transportation (FDOT) owns and operates the second largest number of movable bridges in the U.S. The maintenance costs related to these bridges are considerably higher than those of fixed bridges, mostly because of the complex interaction of the structural, mechanical and electrical components. A malfunction of any component can cause an unexpected failure of bridge operation, which creates problems for both land and maritime traffic. Maintenance processes associated with the operation system and mechanical parts require special expertise.

Therefore, a research project for the implementation and demonstration of monitoring technologies for proactive assessment and maintenance purposes was recently conducted by the PI and his research team for FDOT. For this project, the bridge on Sunrise Boulevard in Ft. Lauderdale was selected as representative. The bridge was constructed in 1989 and consists of two parallel spans.. A comprehensive monitoring system was implemented on the westbound span of Sunrise Bridge to track the behavior and condition of several critical mechanical, electrical and structural components. A number of tests and monitoring of the bridge yielded a wide variety of data, which were analyzed in detail with methods developed by the PI and his research team, and the results obtained at the end of project were reported to FDOT in a detailed report (BD548-23).

After the completion of the project, the bridge was already scheduled for painting. The monitoring system was significantly damaged during the preparation, sandblasting and painting despite the considerable efforts of FDOT personnel to protect the system. This extension project therefore focuses on repairing the monitoring system, which was affected by the painting operation, collecting and analyzing more data and preparing the

system for FDOT. More details about the objective and scope of the project are discussed below.

Objective and Tasks of the Extension Project

The main objectives of this project are (1) data collection and analysis, (2) maintenance of the monitoring system after the bridge was painted (3) replacement of critical monitoring components, and (4) final report documentation and submission.

The extension project consisted of these four main tasks. The first task was to check the status of the overall monitoring system that includes sensors, cables, data acquisition, network condition, etc. For this reason, one visit for mechanical room sensors and one visit for structural components were conducted and the status of the monitoring system was updated. In this task, needs for the monitoring system were identified, and future visits were planned.

Based on the first task, the second task was to repair the monitoring system where needed. Structural sensors and cables were damaged due to the painting of the bridge and, with the help of MOT (Maintenance of Traffic) and the snooper truck, the researchers tried to repair the damaged equipment. Malfunctioning mechanical sensors were replaced and detached sensors were reattached to the components. In addition, computer, network and software problems of the monitoring system were solved as part of this task.

After completion of the second task, data collection was started again. Triggers and scheduled time slots for data collection were re-configured. The third task was to obtain sensor baselines from the newest collected data. For each sensor on each component, the data baselines were obtained with statistical analysis. Moreover, the methodologies developed in the previous project were used for the newest data and results were presented. The fourth and final task of the project was documentation and submission of the final report with a transfer of the monitoring system to FDOT.

Findings and Results

In this report, methodologies developed in the previous project (Catbas et al., 2010) are used for the newest data collected during the extension project. Strain correlation based structural alteration identification is employed for identifying the structural changes in the bridge, such as SL (Span Lock) or LLS (Live Load Shoe) shims removal. This methodology is expected to reduce the number of visits for shim replacement at these locations as well as to evaluate the effectiveness of maintenance by checking the correlation levels of the baseline (well-maintained, proper operations) conditions to conditions with no maintenance or new maintenance. From the analysis of the new data, no significant change in the correlation coefficients is observed during the extension of the project.

Other methodologies developed for mechanical component assessment are an image-based analysis for open gears and an analysis based on artificial neural networks (ANN) that can be applied to both open gears and gearboxes. In the image-based analysis for the open gear, edge detection based computer vision techniques were used to identify whether the open gear was lubricated properly or not. Besides the image analysis, ANN-based oil level/lubrication analysis in which the data were reduced to “0” (healthy) and “1” values (unhealthy), showed that the oil level in gearbox and the grease level in open gear were adequate or not for the given period.

Furthermore, long-term monitoring can also provide important information about the effects of the temperature variations on the bridge balance, friction and structural strains. Bridge friction and temperature change were tracked for the extension project, and it was seen that the bridge friction numbers were in the 20-30 kip-ft range, and the temperature vs. friction numbers showed a steady behavior. On the other hand, studies for exploring the long-term environmental effects on structural and mechanical components were conducted. Daily strain variations due to temperature were observed to be on the order of 20-30 microstrain during the summer season.

In addition to data analysis methods, sensor baselines were identified for different component sensors based on statistical analysis of the long-term data collection. For each sensor on different components, maximum, minimum, standard deviation and maximum root mean square values were calculated. With the help of these values, baselines statistics and histograms were generated. Statistical analysis showed that the average vibration level on the gearbox was around ±0.2g with slight changes depending on the sensor location. Another sensor type on the gearbox is the microphone which showed an average sound pressure of ±3Pa. The motor accelerometers close to the gearbox side (mot-acc1 and mot-acc2) were vibrating at ±1g, whereas the accelerometers on the other side of the motor (mot-acc3 and mot-acc4) were vibrating at ±1.5g. It should be noted that the average levels were showing differences for east and west leaves.

Finally, the importance of the monitoring system is illustrated with two different case studies, which were presented in a comparative fashion with the maintenance reports provided by FDOT. In the first one, span lock trouble was identified by the maintenance crew during weekly inspection on 6/19/11. The researchers also investigated this event independently using the monitoring system. Pulling pressure is are also investigated using histograms, and the span lock trouble was identified on 6/13/11. Histogram analysis shows an increase in the coefficient of variation before the action taken by maintenance crew on 6/19/2011. It should be noted that the effectiveness of the maintenance can also be observed from the monitoring data. Finally, it is critical to note that the span lock problem initiation date (as structural changes detected from the different relevant sensors) is several days earlier than the maintenance work done on 6/19/2011.

The second case study is the gearbox shaft seal replacement on 6/28/11. In this case study, the effect of maintenance is evaluated with the help of monitoring data. Before this maintenance, the baseline acceleration level on gearbox was around ±0.2g but after the replacement of the shaft seal on gearbox, the acceleration level is increased to ±0.3g. Excessive vibrations are one of the main problems for machinery components, and the effectiveness of the maintenance was demonstrated with the help of the monitoring system.

Recommendations

The current system detected changes and problems effectively for the live load shoes, span locks, gearboxes, open gears, bridge friction, etc. The system behavior is now well-established with baselines and thresholds. Future monitoring application should utilize this information. A more compact data acquisition system can be designed, developed and used for future applications. Several commercial data acquisition and card providers can now supply smaller and more cost-effective systems. In addition, the data acquisition computers should be checked periodically since these computers and necessary hardware/software may require updates, which further improve the operation of the monitoring system.

Major bridge maintenance such as bridge sandblasting and painting may induce damage to sensors and cables. Such activities should be coordinated in such a way that the damage to the monitoring system, sensors and cables be minimized. Another rudimentary yet important recommendation is that power to the data acquisition system should be dedicated power since using the same power for other bridge operations and maintenance activities may induce interruptions and possibly damage to the monitoring systems. Use of uninterruptible power supply can be a solution to a certain extent.

For detecting structural problems as exemplified in this and previous reports, at minimum, live load shoe locations are to be instrumented. Similarly, the number of vibration sensors at the electrical motors and gearboxes can be reduced to two and three, respectively. This exploratory study required the use of a large number of sensors; however, a much reduced sensor count could be sufficient to obtain the most critical information. In addition, with the advances in sensors, more sensitive sensors can be employed for applications such as vibration, sound and temperature measurements.

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1. Introduction

1.1. Background

The Florida Department of Transportation (FDOT) owns and operates one of the largest number of movable bridges in the U.S. The maintenance costs related to these bridges are considerably higher than those of fixed bridges mostly because of the complex interaction of the structural, mechanical and electrical components. Recently, a Bridge Maintenance Monitoring System (BMMS) was developed and demonstrated for a District 4 movable bridge. In this study, a monitoring application demonstration is implemented to evaluate the performance of structural, mechanical and electrical components of movable bridges for proactive assessment and maintenance purposes by the PI and his research team (Project BD548-23).

The selected representative movable bridge is the West-bound span of two parallel spans on Sunrise Boulevard in Ft. Lauderdale (Figure 1). This span was constructed in 1989. It has double bascule leaves with a total span length of 117 ft and a width of 53.5 ft, carrying three traffic lanes. Each leaf is 70 ft long and 40 ft wide. The bridge can be opened every 30 minutes when requested. Depending on the boat traffic, the bridge opens usually about 10 to 15 times a day. A comprehensive monitoring system was implemented on Sunrise Bridge to track the behavior and condition of several critical mechanical, electrical and structural components. A number of tests and monitoring of the bridge yielded a wide variety of data, which were analyzed in detail with methods developed by the PI and his research team, and the results obtained at the end of project were reported to FDOT previously (Catbas et al, 2010).

Figure 1: Sunrise Bridge in Ft. Lauderdale, Florida

1.2. Issues Related to Movable Bridges

Movable bridge rehabilitation and maintenance costs are considerably higher than those of a fixed bridge mostly because of the complex interaction of the structural, mechanical and electrical components. A malfunction of any component can cause an unexpected failure of bridge operation, which causes problems for both land and maritime traffic. Maintenance processes associated with the operation system and mechanical parts require special expertise.

Although the moving condition of a movable bridge brings a lot of advantages, it is also the main reason for significant drawbacks and problems associated with the operation and performance. Deterioration and damage is usually observed due to moving parts, friction, wear and tear of the structural and mechanical components. Moreover, corrosion, deterioration and section losses are also concern since the movable bridges are located over waterways and often close to the coast. Reversal or the fluctuation of stresses as the spans open and close may create fatigue related problems.

1.3. Design of the Monitoring System and Instrumentation

Although monitoring of structural components is usually the only concern for fixed bridges, a properly designed monitoring system for a movable bridge should consider all critical electrical, mechanical and structural components. The components include electrical motors, gearboxes, drive shafts, open gears, rack and pinions, trunnions, live load shoes, span locks, main girders, floor beams and stingers. For this reason, the most common types of the problems related to these components were investigated. A series of meetings and field visits with bridge engineers, FDOT officials and consultants were also conducted to finalize the design of the monitoring system. The hardware and software components of the implemented monitoring system were designed to track the behavior of these components, detect problems and plan for corrective actions.

Two separate data acquisition systems (DAQ) were used to collect the data at the two separate and disconnected leaves. These two systems were connected and synchronized wirelessly. The final instrumentation plan consisted of an array of sensors, which includes accelerometers, strain gages, tiltmeters, pressure gages, strain rosettes, ampmeters, infrared temperature, microphones, environmental sensors, cameras, etc. It should be mentioned that the instrumentation plan is expected to be reduced significantly to an optimum level based on the findings of this research when monitoring systems are to be installed on several similar type bridges.

1.4. Findings of the Previous Project

After the monitoring system was designed and installed on the bridge, the data collection phase started. As part of the long-term monitoring, data was collected continuously on every single opening and during rush hours. Moreover, data was collected also during two special events: damage tests (Figure 2, Figure 3) and truck load tests (Figure 4). The data collected from the monitoring system through routine monitoring, as well as from the damage scenarios, were employed for developing and demonstrating methodologies to identify mechanical and structural alterations.

The researchers first developed methods and tools to efficiently analyze the data to extract useful information in a timely manner and to facilitate operation and maintenance by bridge engineers and constractors. Various algorithms were investigated by the researchers and then the most effective ones were employed to provide meaningful information about the condition of the structure. Excellent results were obtained using the methodologies developed for structural (Figure 5) and mechanical (Figure 6) monitoring of critical components of the movable bridge. The development of these methods and results were reported in the report of the previous project.

Figure 2: Damage tests (structural): removal of the live load shoe shims (left) and removal of the span lock shims (right)

Figure 3: Damage tests (mechanical): removal of gearbox oil (left) and removal of the open gear grease (right)

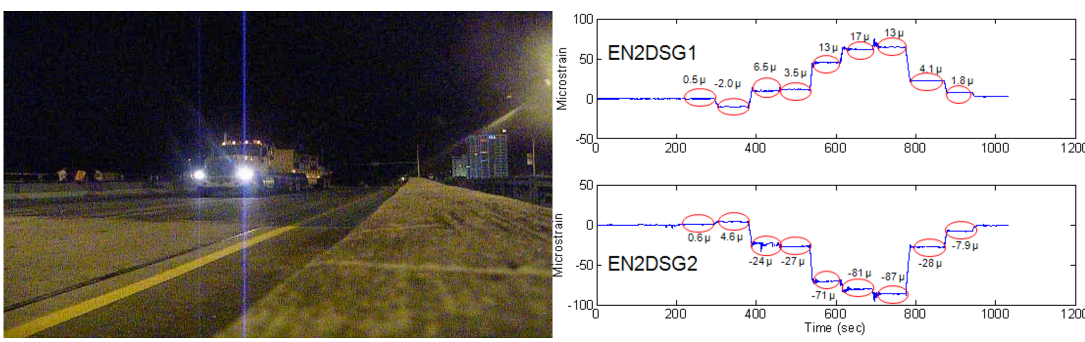

Figure 4: Truck load test and sample data

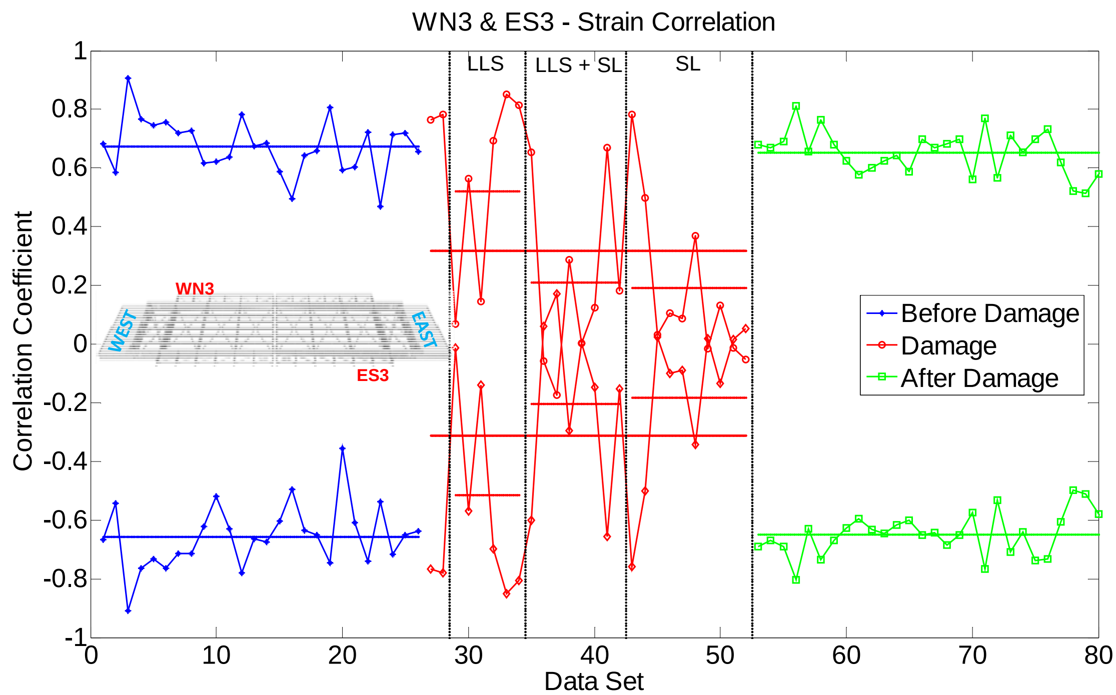

Figure 5: Structural damage detection based on strain correlation method developed by the researchers

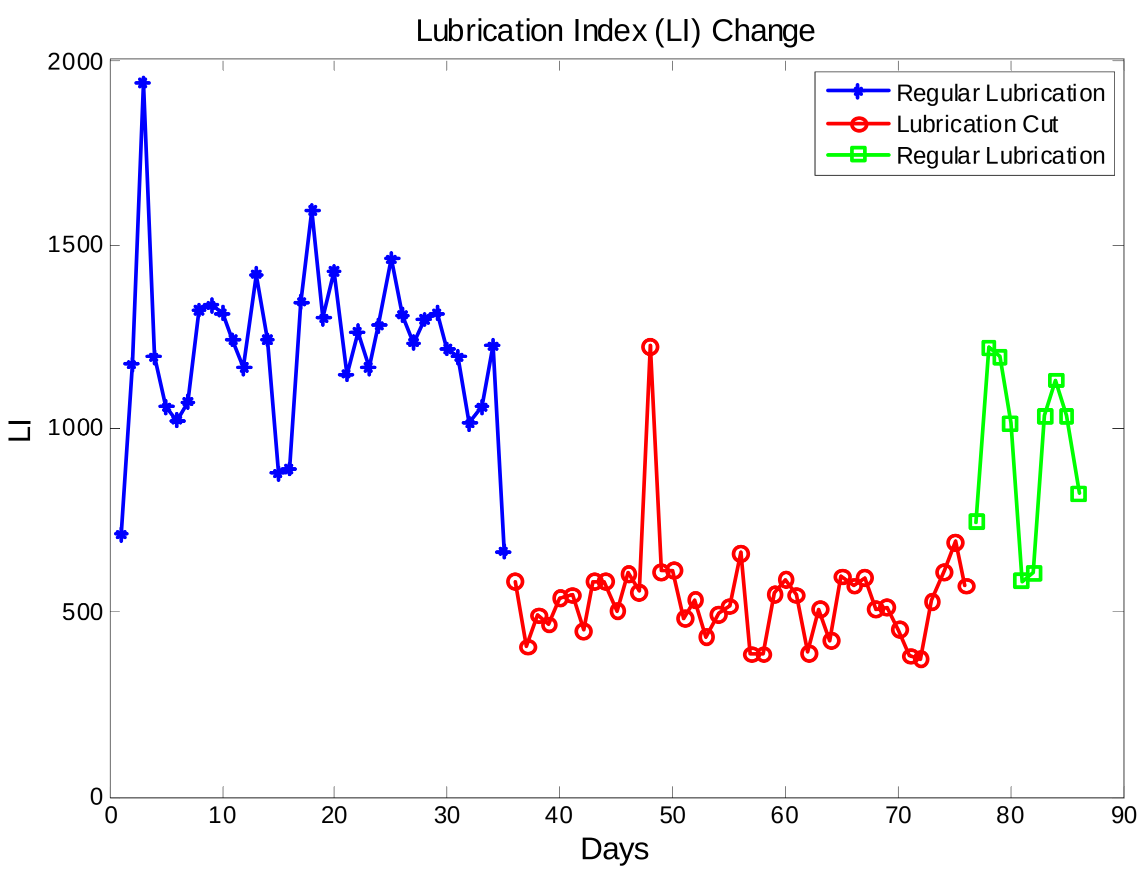

Figure 6: Open gear lubrication monitoring with computer vision based methods

1.5. Objectives of the Extension Project

The main objectives of the extension project are (1) data collection and analysis, (2) maintenance of the monitoring system after the bridge paint (3) replacement of critical monitoring components, and (4) final report documentation and submission. To achieve these objectives, the following work is undertaken.

- Repairing, replacing the sensors and cabling, maintaining the monitoring system: A few months after completion of the previous project, the bridge was painted by external contractors. Although a significant effort was expended by the FDOT personnel to keep the monitoring system as operational as possible, which is highly appreciated by the researchers, the sand blasting and painting operation caused major damage to the sensors and cabling of the monitoring system. Therefore, one of the major tasks of the extension project was to repair and replace the damaged sensors and cables. Several field visits were made for this purpose. As per FDOT request, failed components were replaced with the same kind that the initial monitoring design specifies, and additional upgrade to hardware and software were required.

- Data collection: During the previous project, data sets were collected (data during normal operation, data from threshold/damage tests and truck load tests), data analysis methods were developed and the results were reported. In this current project, data analysis continued and additional results were generated. These results were submitted in monthly reports as well as intermittent data analysis reports as requested by FDOT.

- Preparing final report and field visit at the conclusion of the project: A final report which is documenting the work done for this project is prepared. The report and the current status of the system is presented to FDOT officials. A site visit is to be conducted for a walk through/knowledge transfer of the monitoring system to the FDOT Project Manager.

2. Status of the Monitoring System

In this section, some technical problems encountered during the previous and extension project, the current status of the monitoring system, and possible improvements for future implementations are discussed.

2.1. Status of the Monitoring System at the End of the Previous Project

There were some technical issues encountered during the project. Following are a brief list of these issues, proposed and implemented solutions and suggestions for future implementations.

- Data acquisition hardware and computer: The number of sensors and where these sensors will be mounted were finalized by the researchers along with the FDOT engineers, personnel and consultants during a site visit to have a comprehensive instrumentation to explore different methods and technologies. As a result of this, higher number of sensors and channels were employed. Most of the hardware challenges and problems were caused by the fact that two separate wirelessly connected large-scale monitoring systems were implemented. Although much effort was expended to create the best system within the given budget limitations, it is observed that some higher-end components could increase the performance of the system considerably (for example using a National Instruments PXI system instead of the currently employed National Instruments SCXI system, which was chosen mostly considering the project budget). Furthermore, the limits of the SCXI system were forced since it is used to measure data from numerous structural, mechanical and electrical sensors. Currently, there are better sensors and compact DAQ systems available in the market with a much lower cost compared to the ones that were available at the time of design of the monitoring system. Such systems should be investigated for possible future implementation. Moreover, problems directly related to the computers were also encountered. A number of different hardware and software components in both of the computers were replaced. All of these issues are reasons for system halts and data losses intermittently.
- Software problems: A number of different software components, including the operating system of the computers, the Labview software, and the codes generated for the monitoring system, should be updated for better performance. Also, the Labview code

developed by the researchers can be further optimized for more efficient operation with the new developments of National Instruments Labview program over the last three years. In the case of implementation on another bridge, it is now possible to develop a very fast and efficient system based on the understanding of the researchers and current state of technologies.

- Operations at the bridge and environmental issues: The maintenance operations, work at the machinery room, loss of power (tripping at the outlets due to rain, or simply disconnected power cords also caused damage in some sensors, which have been replaced accordingly. This system halt caused some missing data from the electrical and mechanical components. The sand blasting and painting operation caused significant damage to the sensors and cabling of the monitoring system. Repairs and/or replacement of these components were attempted during the several field visits conducted during the extension project (details about these field visits are presented in the monthly reports). Some pictures showing damage to the monitoring system due to the sand blasting and painting are presented in the following (Figure 7).

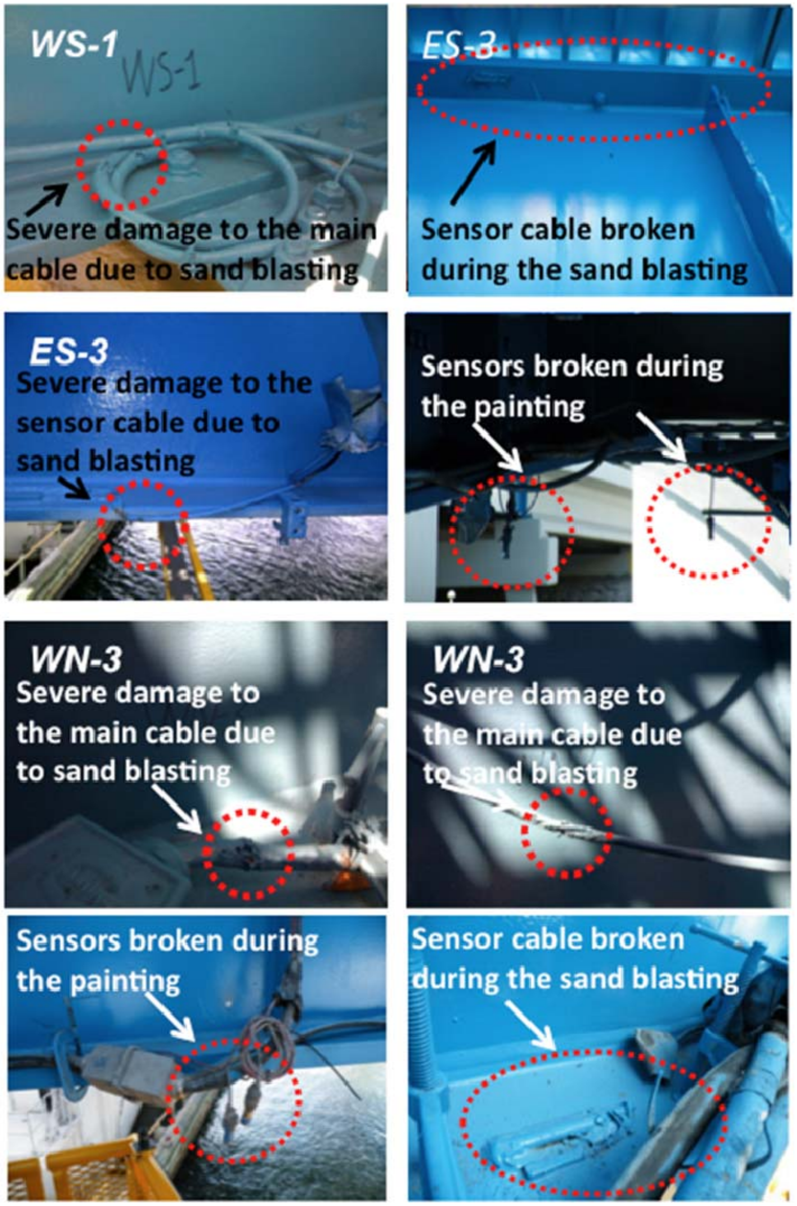

Figure 7: Sample pictures showing the severe damage to the monitoring components at different locations (WS: West-South, ES: East-South, WN: West-North)

2.2. Field Visits to Repair the System

As briefly discussed above, one of the main aims of the extension project was to repair the monitoring system and bring it to an operational condition. Six field visits were conducted during the extension project to pursue this aim. In general, the objectives of these field visits were to repair the monitoring system, solve software related problems and conduct different tests. Although the details are skipped in this report (discussed in the monthly reports) a list of the field visits are given below. Figure 8 shows sample pictures from one of the field visits.

1. Field Visit 1 (January 21-22, 2011): The main objectives of this visit were to investigate the condition of the monitoring system after the bridge painting operations by conducting a survey for the sensors and to solve software related problems related to the East leaf computer crash.

2. Field Visit 2 (February 11-12, 2011): The main objectives of this visit were to re-setup the internet/wireless connection of the computers due to the cancellation of the internet service and to repair the mechanical room sensors that were detached or dislocated.

3. Field Visit 3 (March 8-11, 2011): The main objectives of this field visit were to investigate the condition of the monitoring system at the structural elements which could not be checked without the help of a snooper truck and to repair/replace the damaged components during the scheduled time. Three days of MOT provided during this visit.

4. Field Visit 4 (April 20, 2011): The main objectives of this field visit were to re-install the west leaf computer, to connect associated hardware to west leaf computer and backing up the east leaf computer.

5. Field Visit 5 (May 12, 2011): The main objectives of this field visit were to investigate the west leaf remote computer connection problem, to re-install the Labview code and to re-arrange the data collection triggers in the Labview code.

6. Field Visit 6 (June 16-17, 2011): The main objectives of this field visit were to replace the malfunctioning sensors in the mechanical rooms, to conduct some sensor test for the mechanical components and to take the image of the computers for both sides.

7. Field Visit 7 (August 17-18, 2011): A field visit was made based on the invitation of the Project Manager, who was coordinating a meeting with company representatives and consultants. The objective of the visit was to fix the system halt on West side span, present the monitoring system to visitors and to attend the meeting on August 18. The researchers attended the meeting. The system halt due to tripping of GFI outlet possibly due to recent rains was fixed later.

8. Field Visit 8 (September 2011): A final visit will be scheduled to hand over the monitoring system to the bridge owners. The date of this visit has yet to be scheduled when this report is being prepared.

Figure 8: Sample pictures from the field work conducted during 3/8/2011-3/11/2011

2.3. Current Status of the Monitoring System

As discussed in the "Design of the Monitoring System and Instrumentation" section, the final instrumentation plan consisted of an array of 160 sensors (more than 200 channels) which are distributed on East and West leaf. In each leaf, the sensors can be divided into two groups as mechanical room and structural sensors. Currently, the system is operational (except some broken and malfunctioning sensors) on each leaf and data is being recorded regularly. Some of the broken/malfunctioning sensors due to bridge painting were repaired/replaced in conducted field visits. The sensors and cables under the bridge that were damaged during the painting required an MOT and a snooper truck for repair. The sensors that need to be repaired using snooper truck were under the bridge and were mainly the strain gages and accelerometers. In the third field trip, some of the structural sensors were repaired/replaced with the help of snooper truck whereas in the sixth trip the mechanical room sensors were repaired/replaced. After these actions, 75% of all channels are working properly, 16% of the channels have connections to the system but the sensors are malfunctioning, however, additional snooper truck and MOT was not available after Field Visit 3 to fix these sensors. The rest of the channels, which corresponds to 9% are showing no reading due to disconnection. This requires additional debugging and possible changing damaged sensor cables (also sensors) and/or main cables.

These observations lead to the conclusion that field operations and major maintenance work such as sandblasting and painting should be better coordinated with the owners, contractors and the researchers. In future applications, monitoring system can be implemented after such major work, or the sensor/cable/connector/main cable system can be made more modular in such a way that damaged parts can be replaced more easily.

3. Data Analysis Results

The monitoring of the Sunrise Bridge is quite comprehensive in the sense that structural, mechanical and electrical components were instrumented with a variety of sensors. Different methods and approaches were developed to analyze the data from these sensors as discussed in the previous report. In this chapter, threshold levels indicating pre-established limits for each component during normal operation are defined and presented in time and frequency domain. The methods that were investigated, developed and implemented to track the performance and possible damage/deterioration of the movable bridge are discussed in next sections with some case studies which integrates maintenance reports.

3.1. Analysis Results of the Data Collected during the Extension Project

In this section, data analysis results from the long-term Bridge Maintenance Monitoring System (BMMS) are presented for different components. Data from the sensors on mechanical components are analyzed statistically in time and frequency domains to obtain the baselines. Maximum, minimum, standard deviation and maximum root mean squares (RMS) are extracted to track any change in the operation. In addition, frequency domain analysis is conducted to obtain the modal frequencies. It should be noted that analysis of the data sets collected during this phase of the project are presented in this section.

3.1.1. Gearbox

The gearboxes contain the assembly that transmits the torque generated by the motor to the shafts (Figure 9). When the gearboxes experience deterioration or lack of lubrication, some change in the vibration and sound characteristics during operation should be noted. Abnormal vibration is an indicator of wear in the gears. Oil viscosity is also an important parameter for proper functioning of the gearbox. Considering these issues, the monitoring system included accelerometers to measure the vibration on the gearbox during openings and closings. Furthermore, microphones were also included within the gearbox vicinity to determine the acoustic print corresponding to normal/abnormal lubrication. Sample data from gearbox accelerometer and microphone are shown in Figure 9 and Figure 10, respectively.

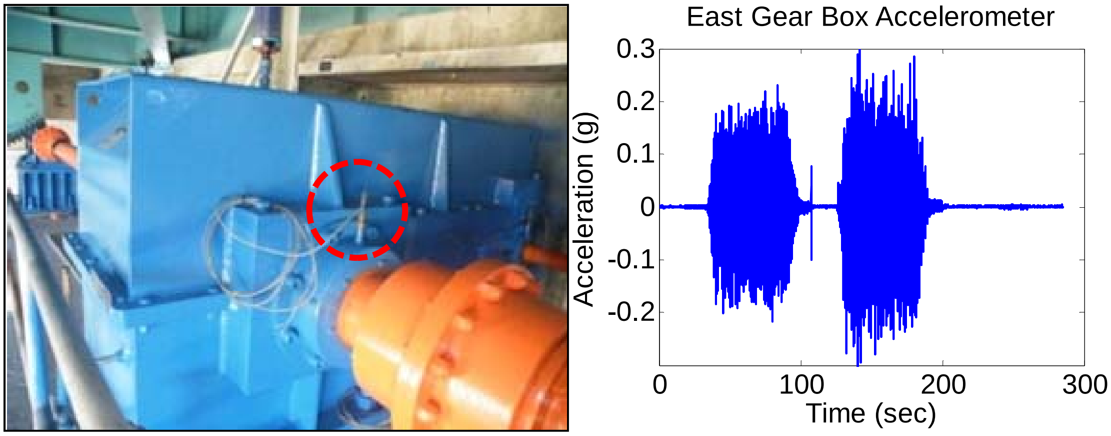

Figure 9: Gearbox accelerometer and sample data

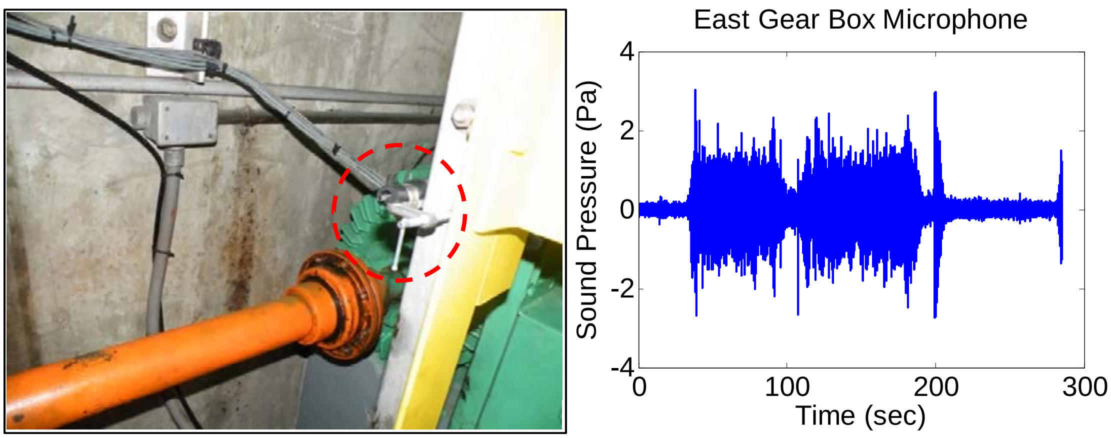

Figure 10: Gearbox microphone and sample data

Baseline information for gearbox accelerometers and microphones are obtained from statistical analysis from the several opening and closing of the bridge. For each opening during this period; 30 maximum, 30 minimum, standard deviation and maximum RMS values are collected and the histograms for maximum values and minimum values are generated. In addition, frequency domain analysis is also conducted for both types of sensors. For the sake of brevity, representative results for East gearbox accelerometer (Figure 11), West gearbox accelerometer (Figure 12), East gearbox microphone (Figure 13) and West gearbox microphone are presented (Figure 14).

East gearbox vibration levels are identified as ±0.15 g with a coefficient of variation of 10% and frequency domain analysis shows that the modal frequencies are around 15 Hz, 45 Hz and 55 Hz. For the west gearbox, the vibration levels are ±0.12 g with a coefficient of variation of 10% and the modal frequencies are around 6 Hz, 17 Hz and 54

Hz. These differences can be due to the different boundary conditions or stiffness parameters.

Microphone data over long-term monitoring shows that the baseline level for east gearbox microphone is 2.0 Pa and for west gearbox 2.4 Pa. Frequency domain analysis of the east gearbox microphone identifies two modes at 45 Hz and 55 Hz but for the west gearbox microphone 4 modes which are at 6 Hz, 16 Hz, 46 Hz and 57 Hz can be identified.

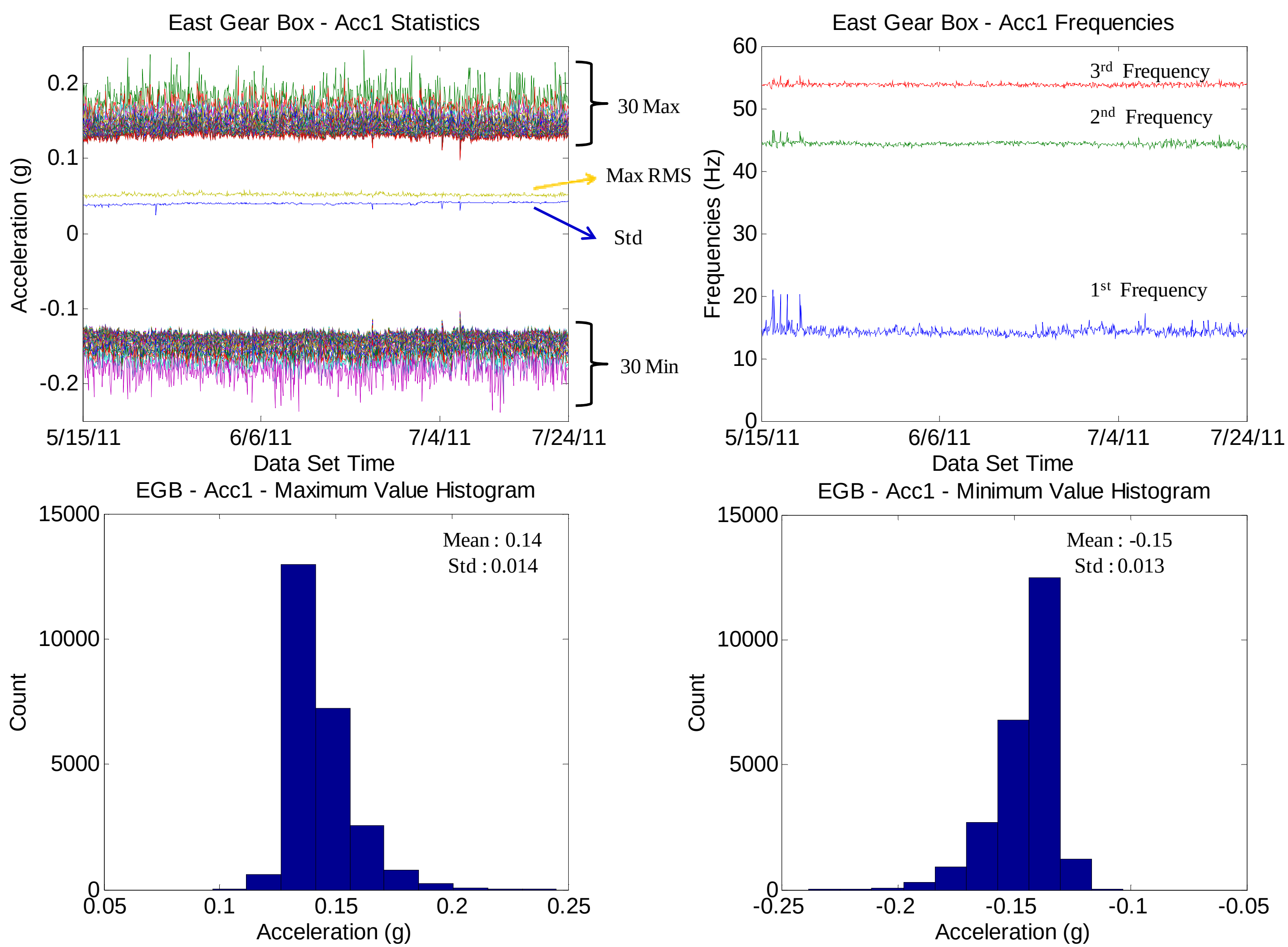

Figure 11: East gearbox accelerometer statistics (max, min, standard deviation and max RMS), accelerometer frequency domain results and accelerometer maximum and minimum value histograms

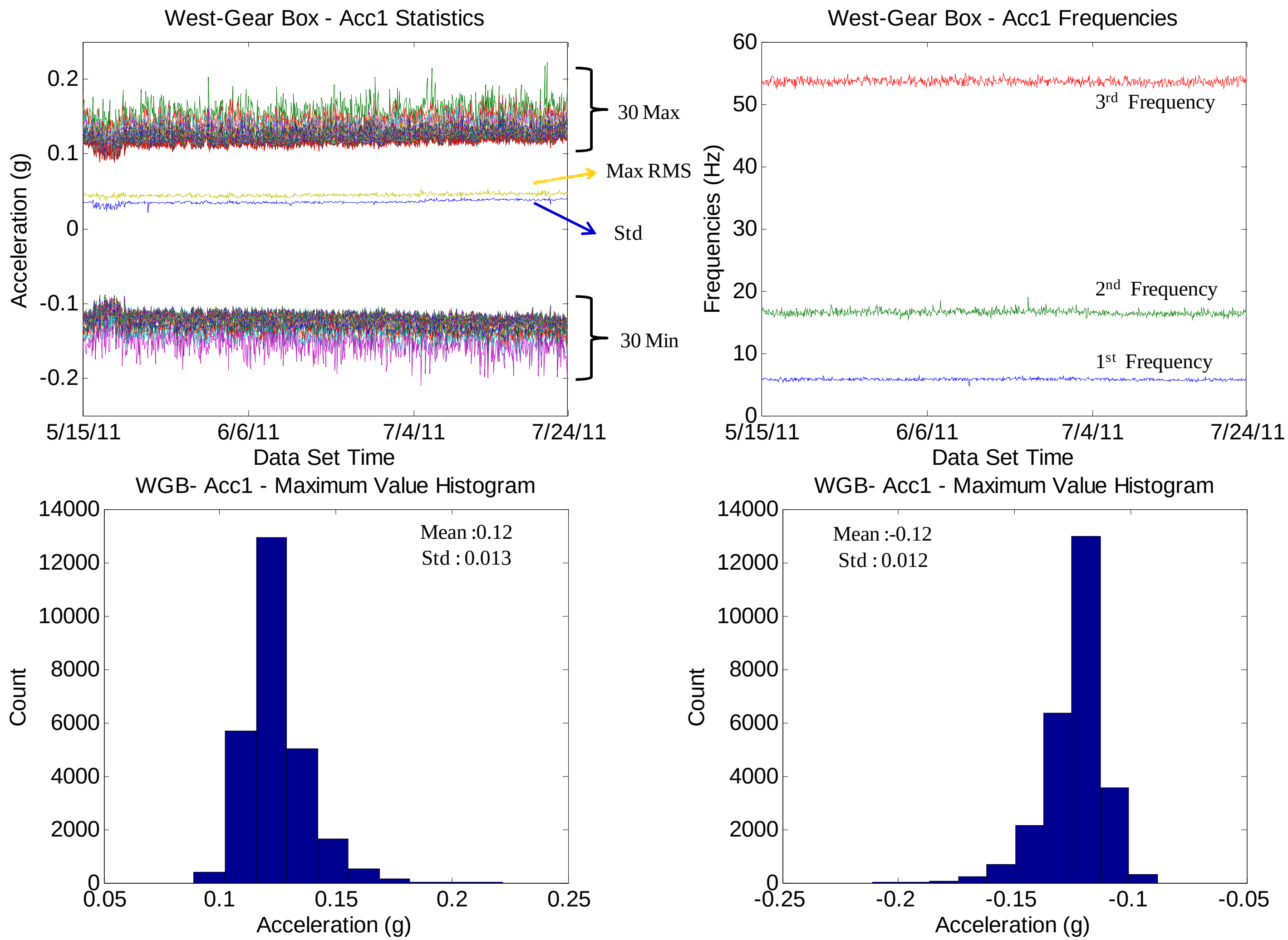

Figure 12: West gearbox accelerometer statistics (max, min, standard deviation and max RMS), frequency domain results and maximum and minimum value histograms

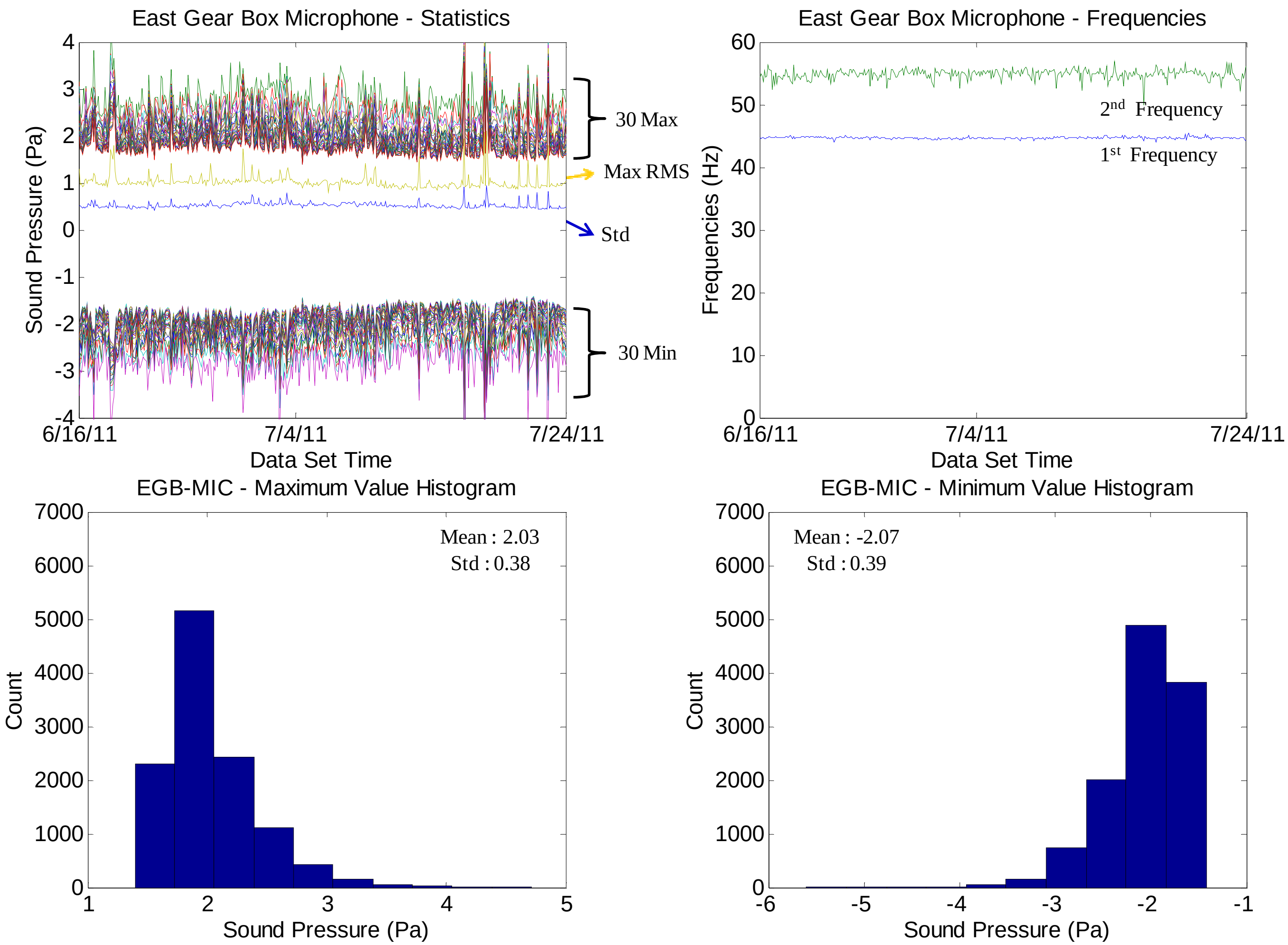

Figure 13: East gearbox microphone statistics (max, min, standard deviation and max RMS), frequency domain results and maximum and minimum value histograms

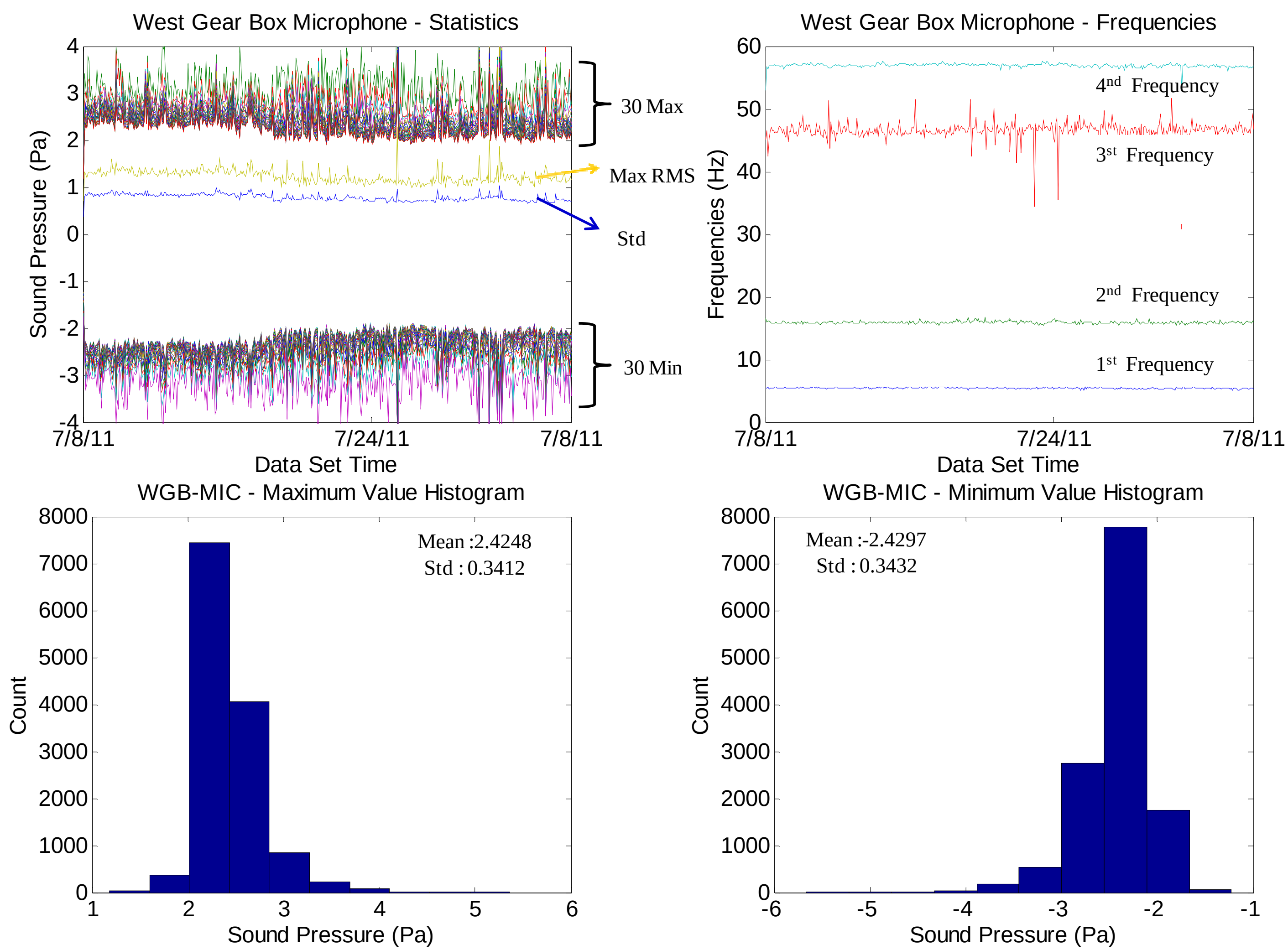

Figure 14: West gearbox microphone statistics (max, min, standard deviation and max RMS), frequency domain results and maximum and minimum value histograms

3.1.2. Electrical Motor

The electrical motors generate the torque required for the opening and closing of the bridge. Some of the indicators for improper functioning are high amperage, high temperature, vibration and high revolution speed. Therefore, it was decided that the monitoring system would include ampmeters to measure the amperage levels for each one of the electric motor phases (Figure 15), accelerometers to measure the vibration on the motor during opening and closings (Figure 16), and infrared temperature sensors to check the temperature of the electrical motor (Figure 17).

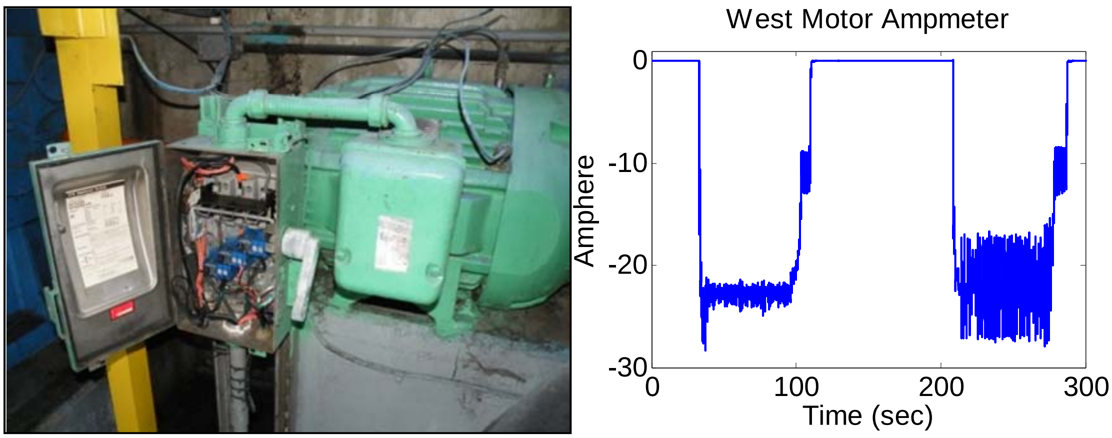

Figure 15: Electrical motor ampmeter and sample data

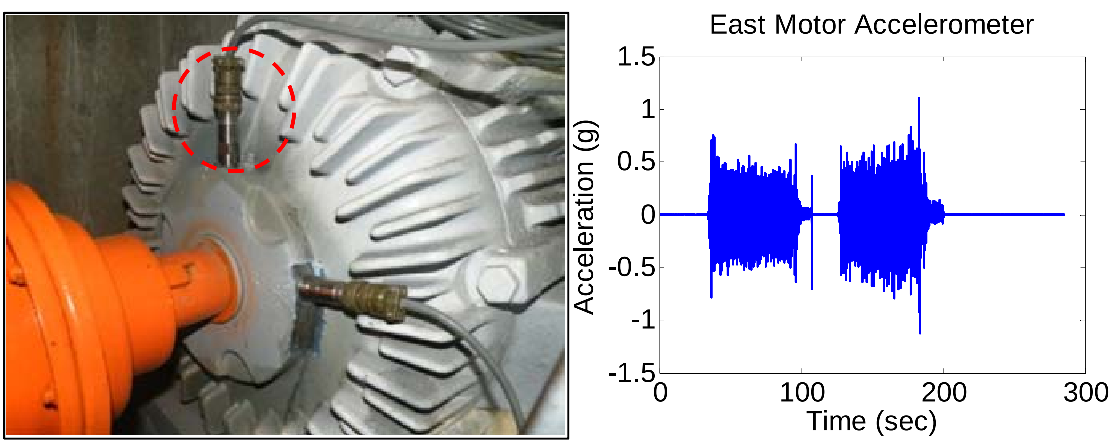

Figure 16: Electrical motor accelerometer and sample data

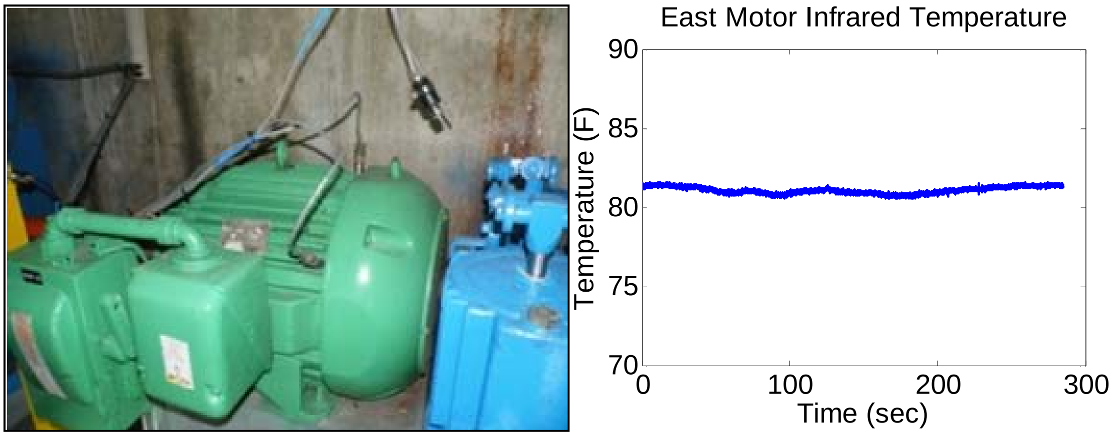

Figure 17: Electrical motor infrared temperature sensor and sample data

From the long-term data collection, no significant change is observed from infrared temperature gages. The deviation is only 1-2 Fahrenheit during opening and closing. Another type of infrared temperature gage (with a different resolution etc.) may give better results and can be investigated for future applications.

West side ampmeter readings are collected between 5/15/11-7/24/11, which is presented in Figure 18. The average readings are calculated around 24 amperes and the corresponding reading in June 2011 maintenance report are around 24-25 amperes (Figure 19).

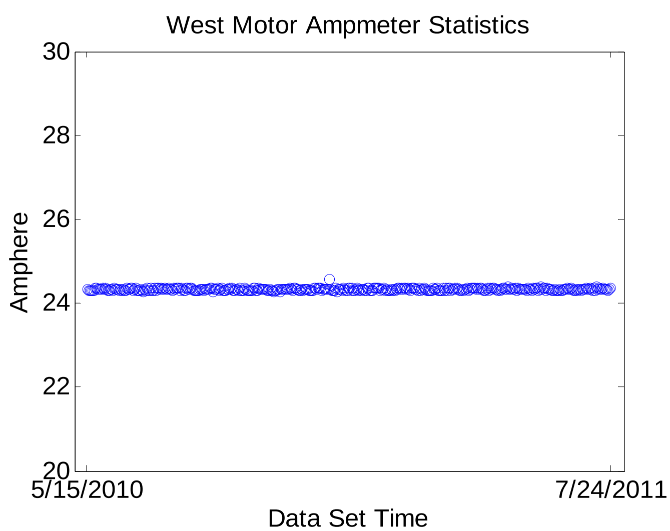

Figure 18: Electrical motor ampmeter mean readings

AMPERAGE READINGS SUNRISE 2011

EQUIPMENT	DATE	2/15	3-29	4-26	5-16	6-28	
SPAN MOTORS							
NA	A	25	25	25	25	25	
	B	25	24	24	25	25	
	C	25	22	22	23	25	
ND	A	23	26	26	26	26	
	B	23	26	26	26	26	
	C	23	17	24	23	24	
FA	A	21	20	26.6	26	27	
	B	22	20	27.7	28	28	
	C	21	18	27.3	28	28	
FO	A	23	13	24.	24	24	
	B	23	10	23	23	23	
	C	23	10	24	24	24	

Figure 19: Electrical motor ampmeter mean readings from June 2011 maintenance report

Baseline information for electrical motor accelerometers is obtained from statistical analysis of the long-term data collection between 5/15/11-7/24/11. For each opening, 30 maximum, 30 minimum, standard deviation and maximum RMS values are collected and the histograms for maximum values and minimum values are generated as in the gearbox case. In addition frequency domain analysis is also conducted. For the sake of brevity representative results for East motor accelerometer (Figure 20) and West motor accelerometer (Figure 21) are presented.

The average vibration level of the east and west motors are close and around ±0.6 g but the frequency domain characteristics shows different values due to different boundary and stiffness conditions. On East motor the first and second frequencies are 10 Hz and 46 Hz whereas on West motor 6 Hz and 53 Hz.

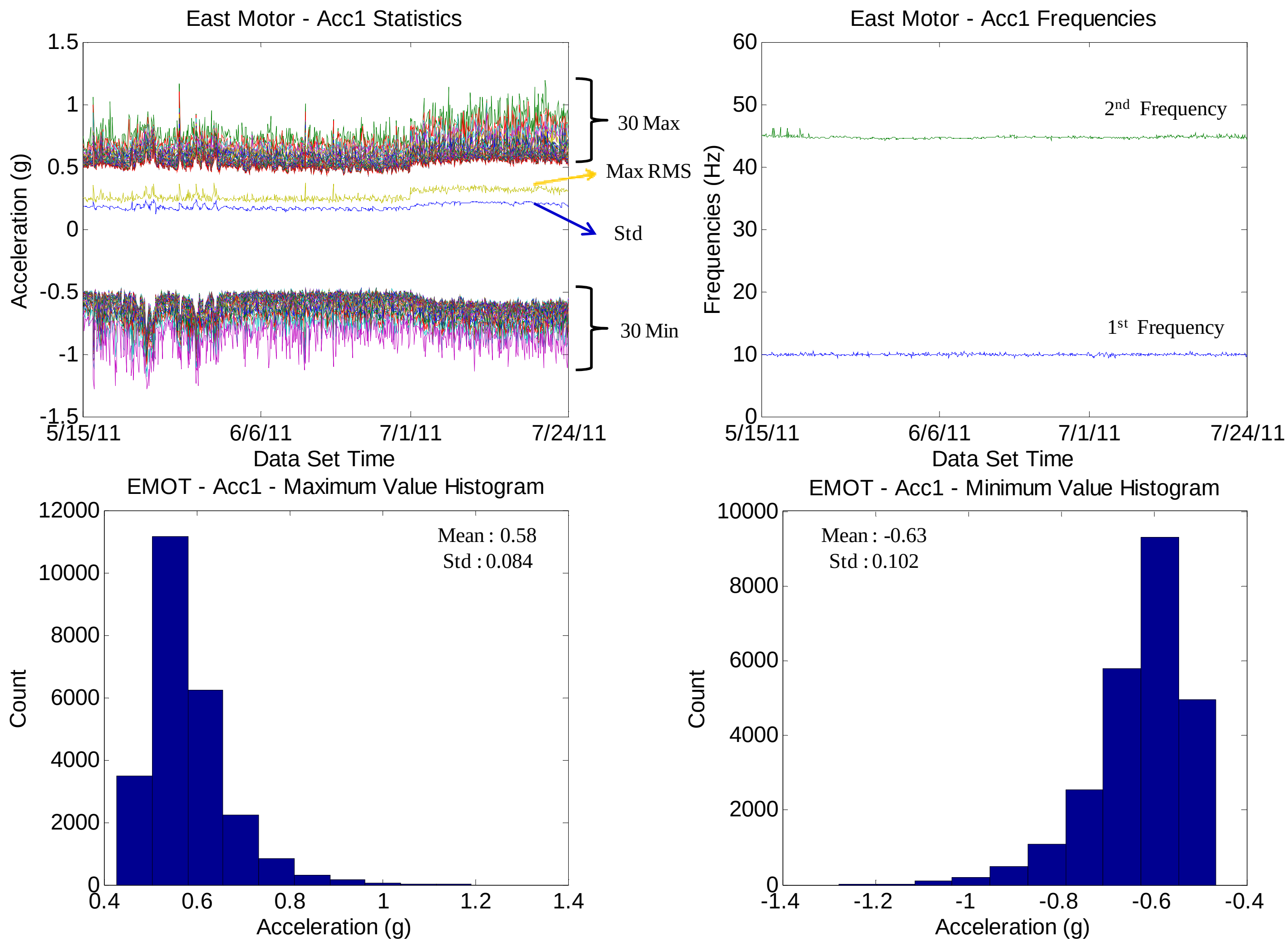

Figure 20: East motor accelerometer statistics (max, min, standard deviation and max RMS), frequency domain results and maximum and minimum value histograms

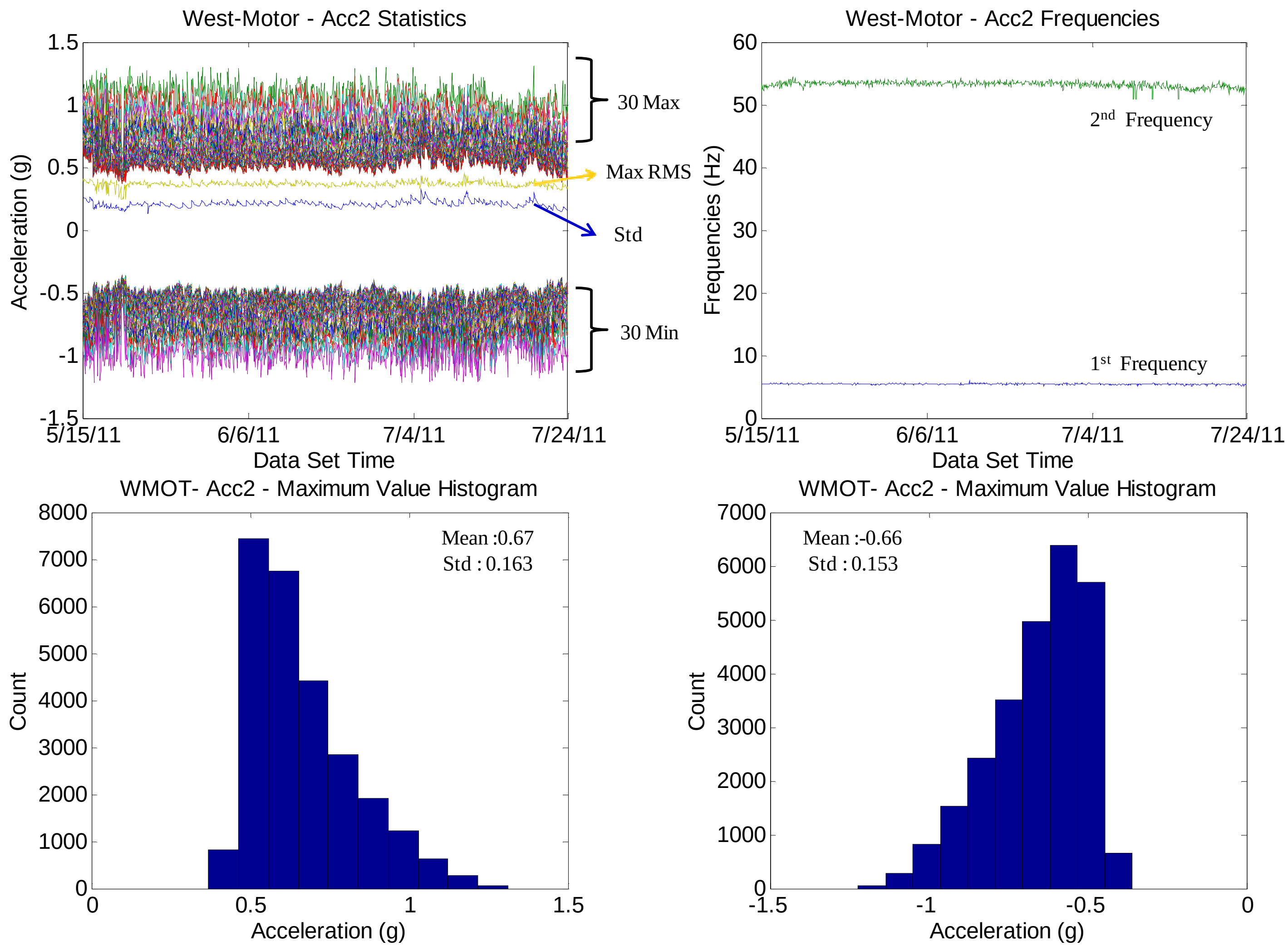

Figure 21: West motor accelerometer statistics (max, min, standard deviation and max RMS), frequency domain results and maximum and minimum value histograms

3.1.3. Open Gear and Rack & Pinion

The open gears are the main gears, which are part of the leaf main girder and receive the torque from the rack and pinion assembly. Corrosion due to lack of lubrication, excessive strain, out-of-plane rotation and misalignment are common problems for open gears. Another concern is loading sequence problems, which mean that the drive shafts begin rotation in delayed sequence. This has an adverse effect on the condition of the open gears, usually by causing impact loading. Routine maintenance is required on the gear teeth. Unless they are kept lubricated at all times, wear and corrosion due to grinding of the rack and the pinion will occur.

To monitor the condition and maintenance needs of the open gears and rack and pinions, accelerometers installed to the rack and pinion base to check the vibrations were included in the instrumentation plan (Figure 22). A FireWire camera was also installed facing the open gear for the use of computer vision algorithms to detect the corroded and/or non lubricated areas as discussed in previous report (Figure 23).

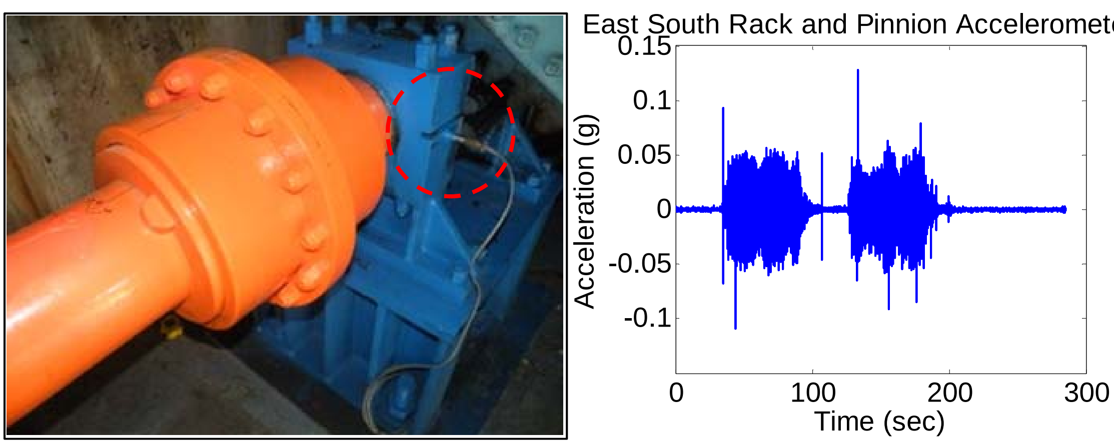

Figure 22: Rack and pinion accelerometer and sample data

The lack of lubrication of the open gear is one of the mechanical alterations, which was discussed in previous report. The results of lubrication index (LI) from approximately two month window are shown in Figure 24. It should be noted that the threshold level was defined as 500 based on the duration without lubrication in 2009 as explained in the previous report (Catbas et al, 2010). In Figure 24, it is seen that the lubrication index reaches the threshold level time to time but never drops to a lower level in this two month period.

Figure 23: Open gear and video camera

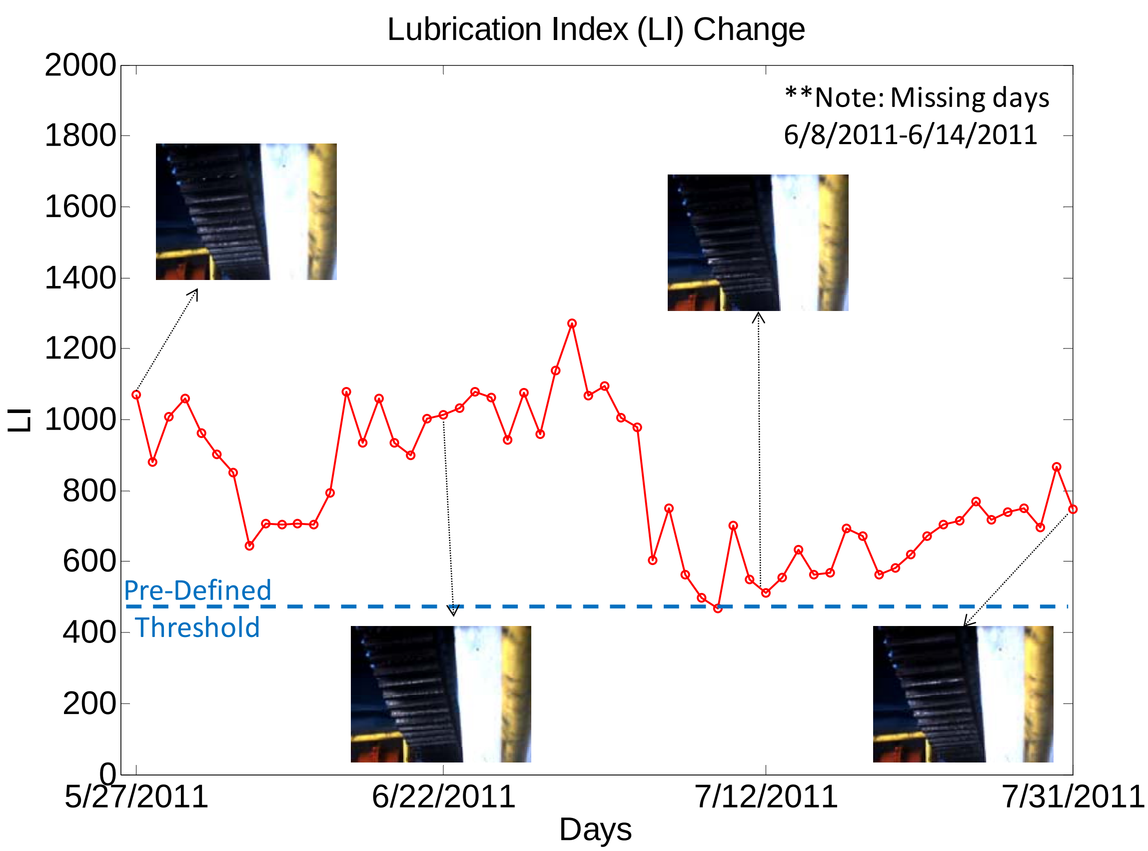

Figure 24: Monitoring and tracking lubrication index (LI) over long-term

3.1.4. Bridge Balance

The shaft is the connecting element between the gearbox and rack pinion, and it is responsible for transmitting the required power for opening and closing operations. Its condition is directly related to the structural integrity and proper functioning of the movable bridge. Any unanticipated distress on the shaft will indicate either degradation on the shaft, motor, gears, rack, or overloading of the bridge during operation.

The drive shafts can be monitored for the total torque, friction of the system, as well as for the center of weight, by means of a balance test, which is a common method for detecting changes in the opening/closing operational characteristics. During the test, torsional strain measurements are collected using strain rosettes mounted on the shaft (Figure 25). The torque on the drive shafts can be determined from these torsional strain measurements using the procedure given by Malvern et al. (1982), which is discussed in detail in the previous report. In addition, tilt data is provided from the tiltmeters installed on trunnions Figure 26.

Figure 25: Strain rosette on the drive shaft

To monitor the shafts continuously, the monitoring system included strain rosettes at both shafts on each leaf. The instrumentation of both shafts enables a comparison of data an indicator of shaft condition/deterioration. The implemented monitoring system is capable of performing a balance test for each opening/closing operation. This continuous monitoring offers numerous advantages. Tracking of the torque and friction number with time can help to apply corrective/preventive maintenance on time, establish power/imbalance relationships and prevent failures of motor, shaft, gearbox and trunnion. Savings in technical labor and repairs are anticipated benefits of the system.

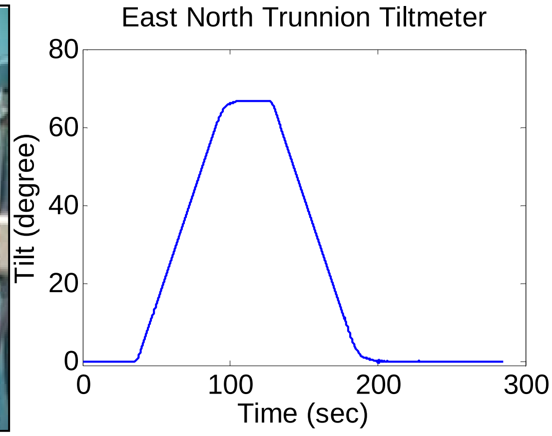

Figure 26: Trunnion tiltmeter and sample data

In this report, the opening and closing operation data collected from 5/15/11 to 7/24/11 from the West leaf was analyzed to obtain friction numbers. The friction and temperature trends are presented in Figure 27. From this figure a steady trend in the friction number can be seen during this period.

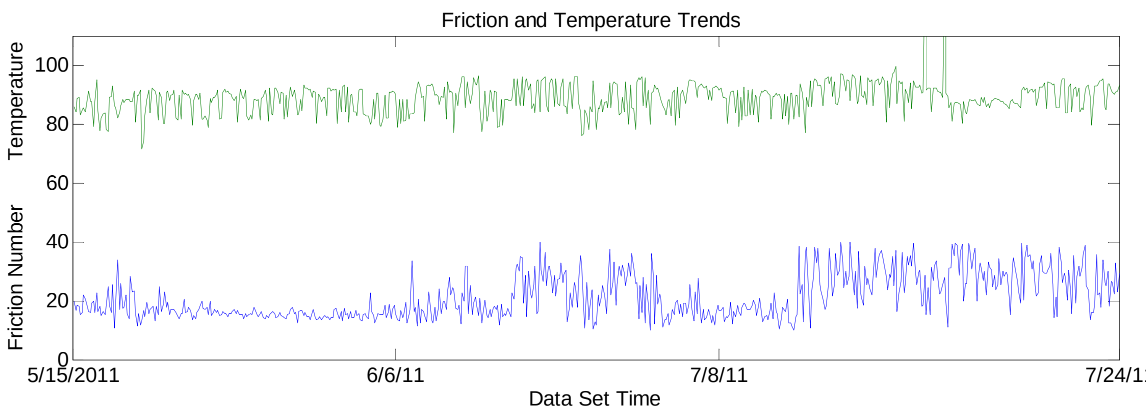

Figure 27: Friction and temperature trends over long-term

3.1.5. Span Lock (Pressure)

Span locks tie the tip ends of the two cantilevered bascule leaves together and force the leaves to deflect equally and prevent a discontinuity in the deck as traffic crosses the span. The span locks consist of a rectangular lock bar supported by a pair of guides on one leaf that engages a single receiver on the opposite leaf. During operation, the lock bar slides across bronze shoes mounted in the rectangular guide and receiver housings. Lock bars are driven or retracted directly using a hydraulic linear actuator.

Span locks are one of the members that fail the most. Deterioration or incorrect operation can cause failure, which disrupts function of the bridge. Based on the discussions with bridge engineers, it was decided to install two pressure gages at each span lock to measure the hydraulic pressure of the span lock to detect any leak or other anomalies with the pressure applied to span locks. In Figure 28, the span lock, pressure gage and sample data are shown. From the statistical analysis of the pressure gage data during 5/15/11-6/25/11, it is observed that pulling (pulling the lock bar out of the receiver before a span opening) pressure has a mean of 321 psi and a standard deviation of 33 psi whereas driving (driving the lock bar into the receiver after a span opening) pressure has a mean of 58 psi and a standard deviation of 15 psi (Figure 29).

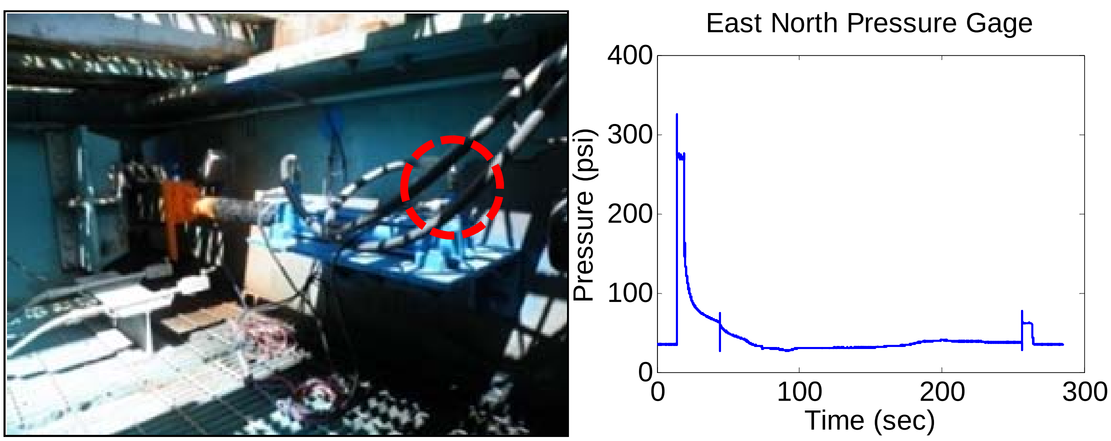

Figure 28: Span lock, pressure gage and sample data

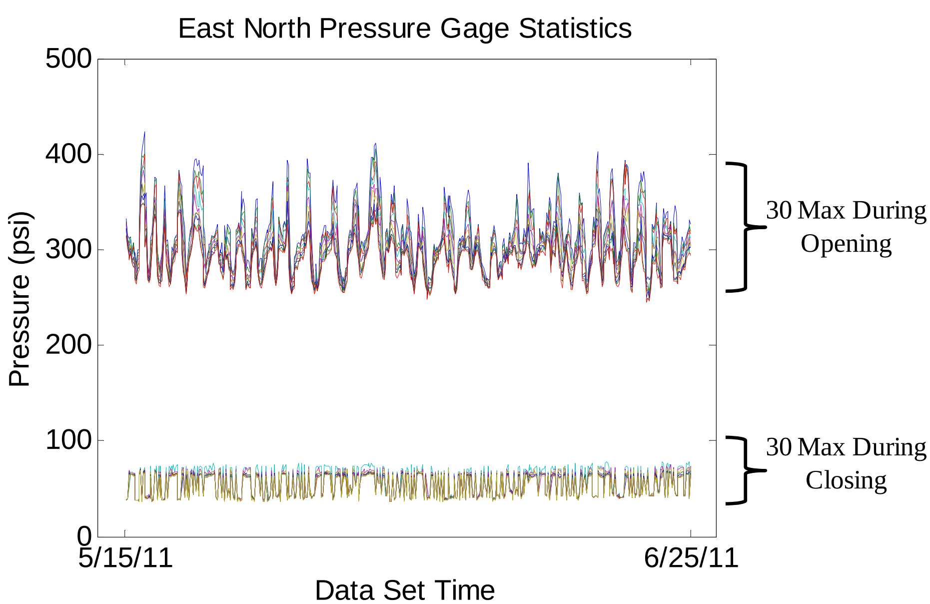

Figure 29: Span lock pressure statistics

3.1.6. Structural Components

Main girders, floor beams and stringers form the main frame of the spans. They are made from both rolled and built-up sections with welded plates. Corrosion is one of the main concerns on the bridge girders, floor beams, and stringers, especially on exposed surfaces. Corrosion leads to section loss and reduced capacity. Any misalignment, bending, or deformation can cause increased strain on the structure. Deformation or thermal effects can cause misalignment of the girders, leading to operation malfunction. The selected sensor layout provides the distribution of stresses on the girders and is expected to provide information regarding damage and deterioration for preventive maintenance purposes. In Figure 30, structural components of the Sunrise Boulevard Bridge are shown.

Figure 30: Structural components of Sunrise Boulevard Bridge

After several discussions and careful investigations, it was decided that the instrumentation plan of the main girders would include accelerometers, dynamic strain gages, and vibrating wire strain gages. Corresponding sample data and analysis methodologies are presented in next sections.

3.1.6.1. High Speed Structural Data

In this section, sample data from various sensors at different structural elements will be shown. The important boundary and continuity elements for the movable bridge are the Live Load Shoes (LLS) and the Span-Locks (SL). LLS are support blocks that the girders rest on while in the closed position. They can be located forward of the trunnions, holding the main girder up, or behind the trunnions resisting the upward movement of the counterweight. The former type is the most common type, and is the type used for the Sunrise Boulevard Bridge. This location was instrumented with accelerometers to see the impact loading due to pounding and with strain gages to observe the excessive strains on the cross section and strain rosettes to see the shear effects of the traffic loading. Sample data for acceleration (Figure 31), sample data from EN3 strain gages (Figure 32) and sample data from WS1 strain gages (Figure 33) can be seen in the following figures.

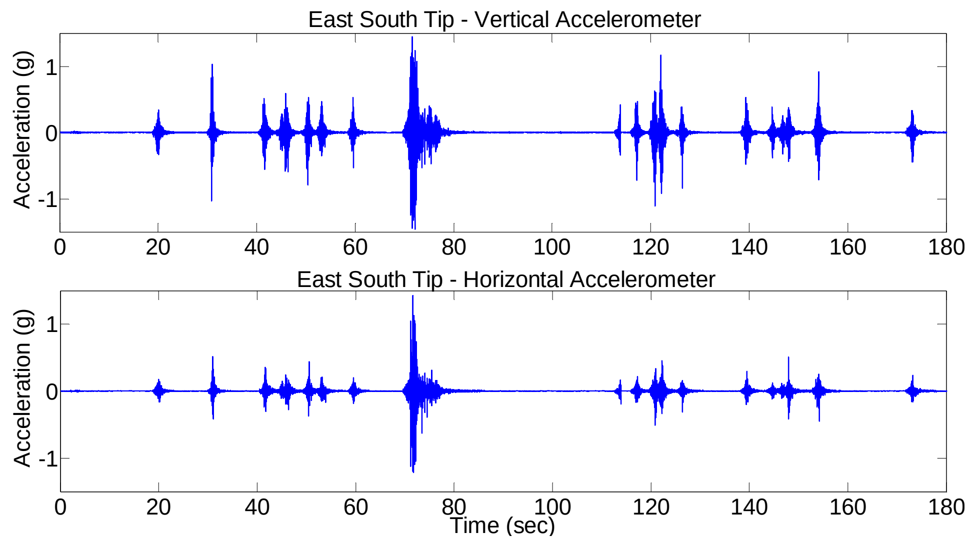

Figure 31: ES1 vertical top and bottom flange dynamic strain gage sample data

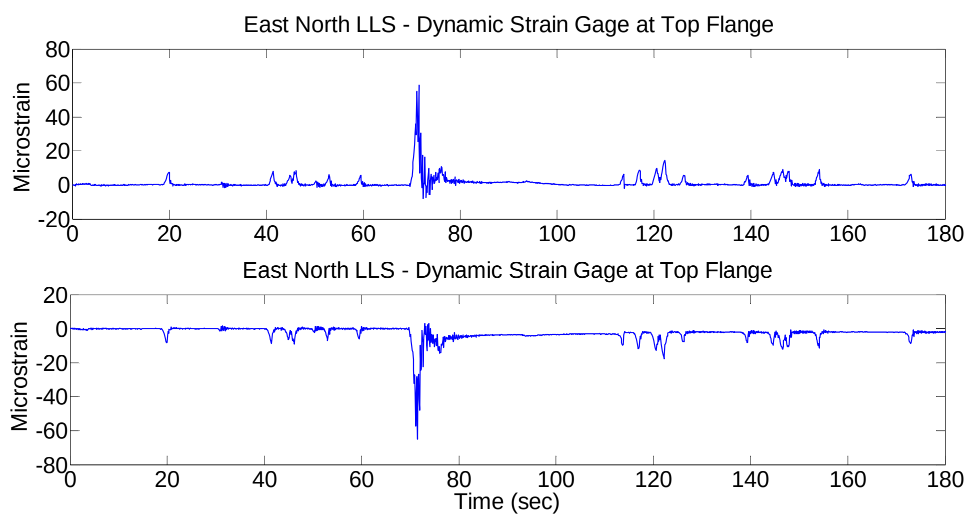

Figure 32: EN3 top and bottom flange dynamic strain gage sample data

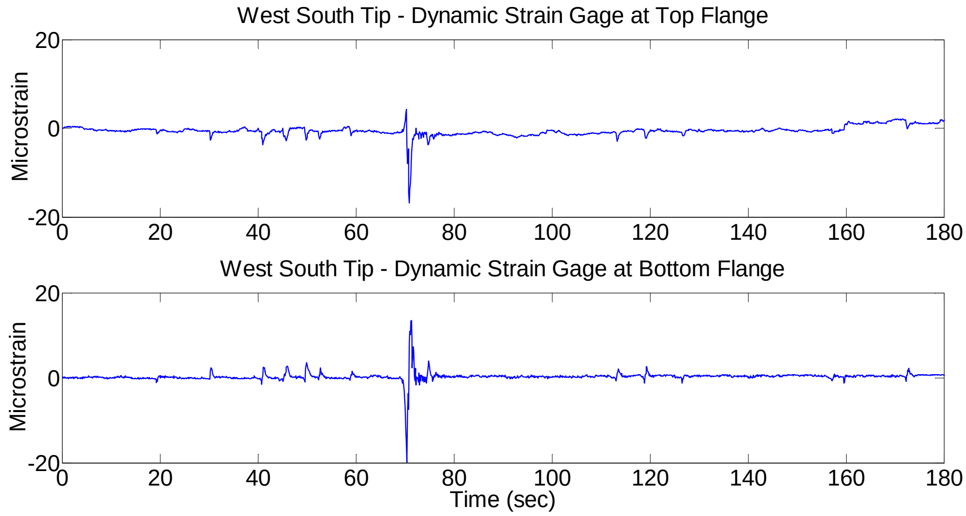

Figure 33: WS1 top and bottom flange dynamic strain gage sample data

Long-term traffic monitoring is very important to collect statistical parameters. Therefore traffic induced strain data over two months is employed for demonstration. More than two months (5/15/11-7/24/11) traffic induced strain data histograms and traffic induced acceleration data histograms can be seen in Figure 34 and Figure 35, respectively.

These histograms are generated from the maximum observed values from the collected data during the pre-defined rush hours. For strains, it is seen that the critical locations are LLS areas, but for accelerometers, tip and mid areas of the main girders have the highest vibrations.

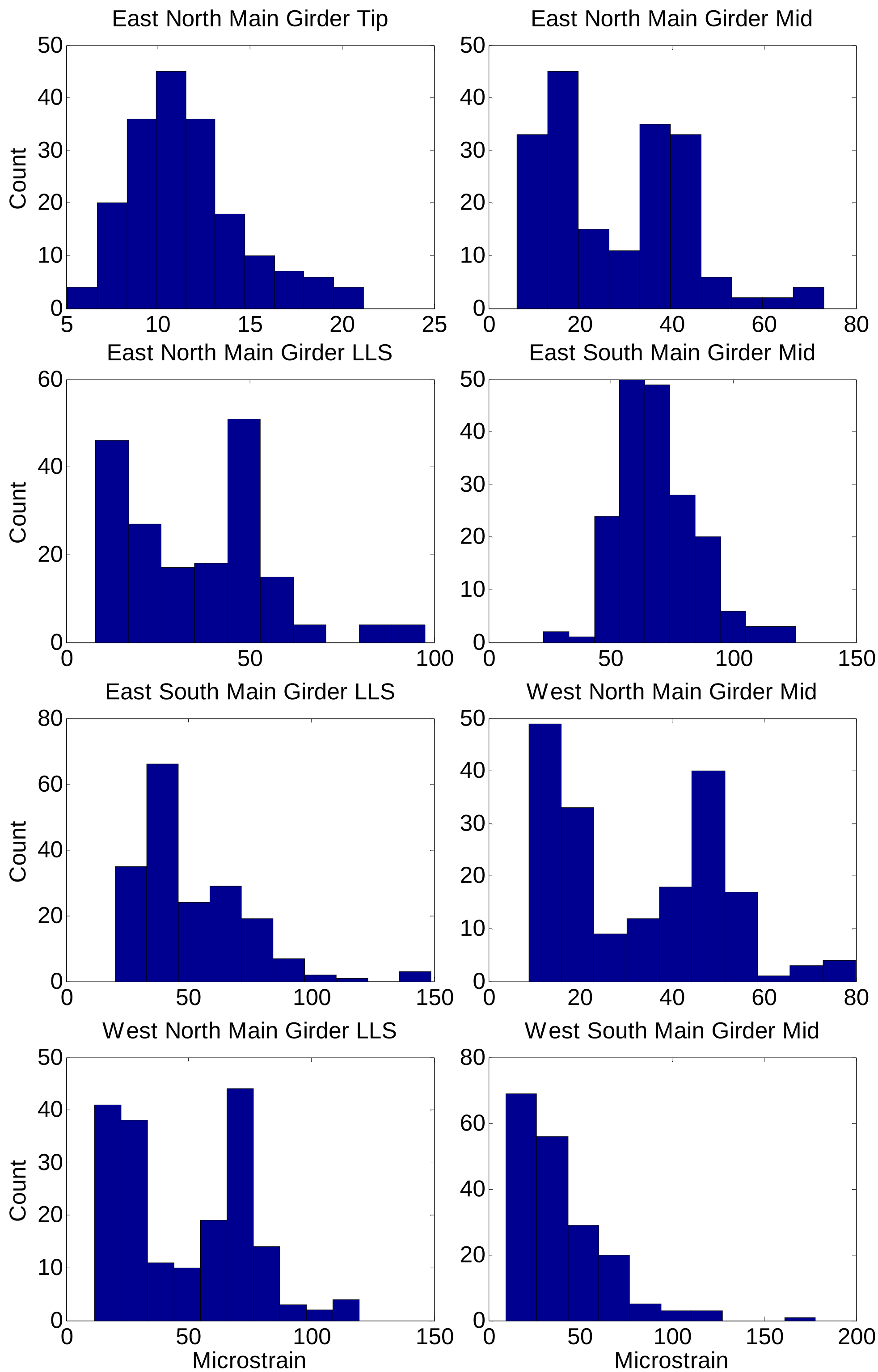

Figure 34: Traffic induced extreme strain distributions for different components

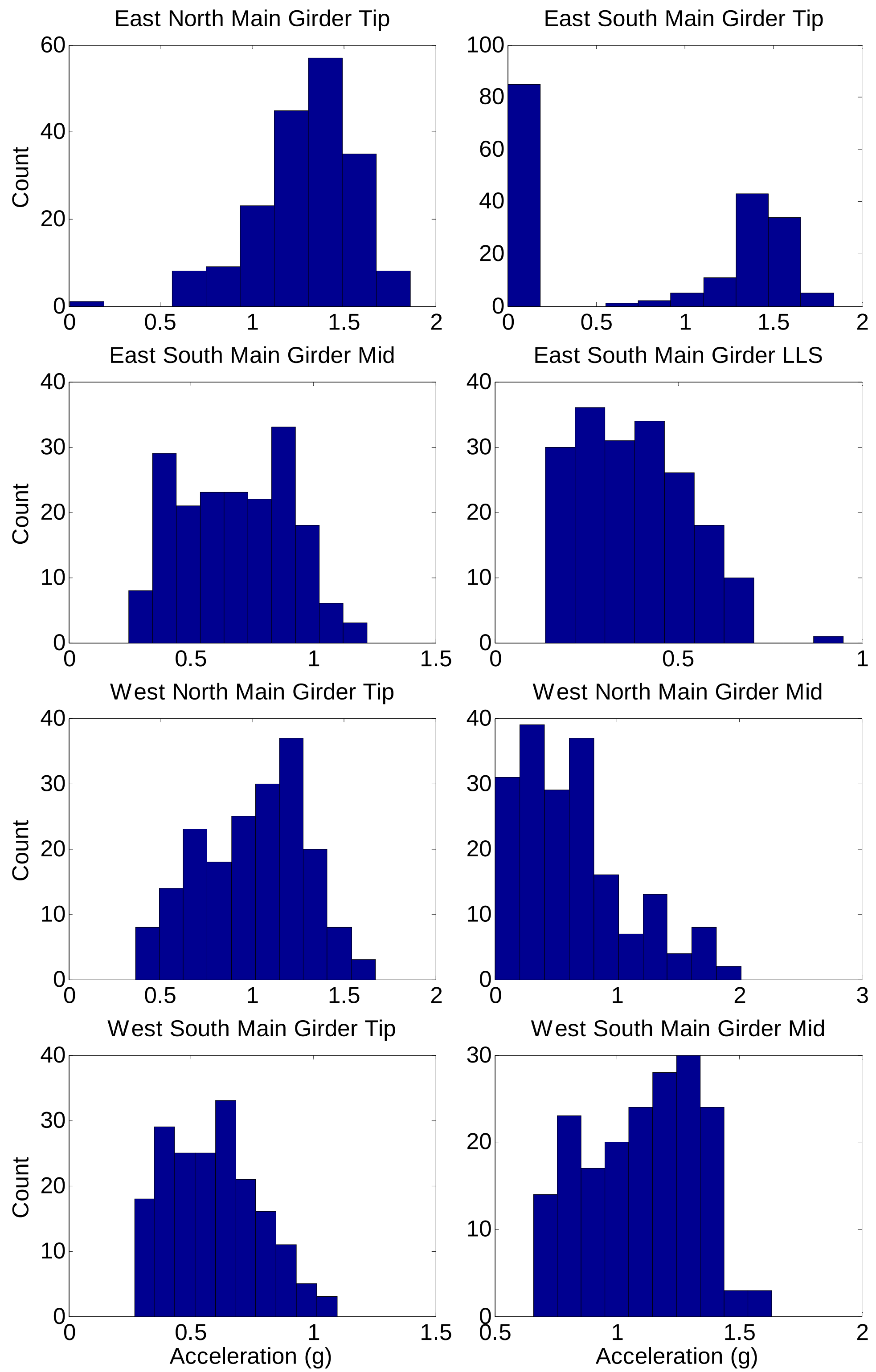

Figure 35: Traffic induced extreme acceleration distributions for different components

3.1.6.2. Slow Speed Structural Data

The temperature induced effect on a structure is best observed through the long-term monitoring. Seasonal and daily temperature induced changes, as well as sudden temperature shocks need to be captured to establish the effects on different components of the bridge. Depending on the material type and boundary conditions temperature induced stresses may vary. In order to explore the effects of temperature, different windows of data such as 3-months, 1-month and 1-week are investigated. For the sake of brevity, only one location from each leaf is presented in this report. Figure 36 shows the East North Mid vibrating wire data for different windows and it is seen that for this location the daily strain cycles are around 25 microstrain and range of the temperature cycles are around 15 degrees.

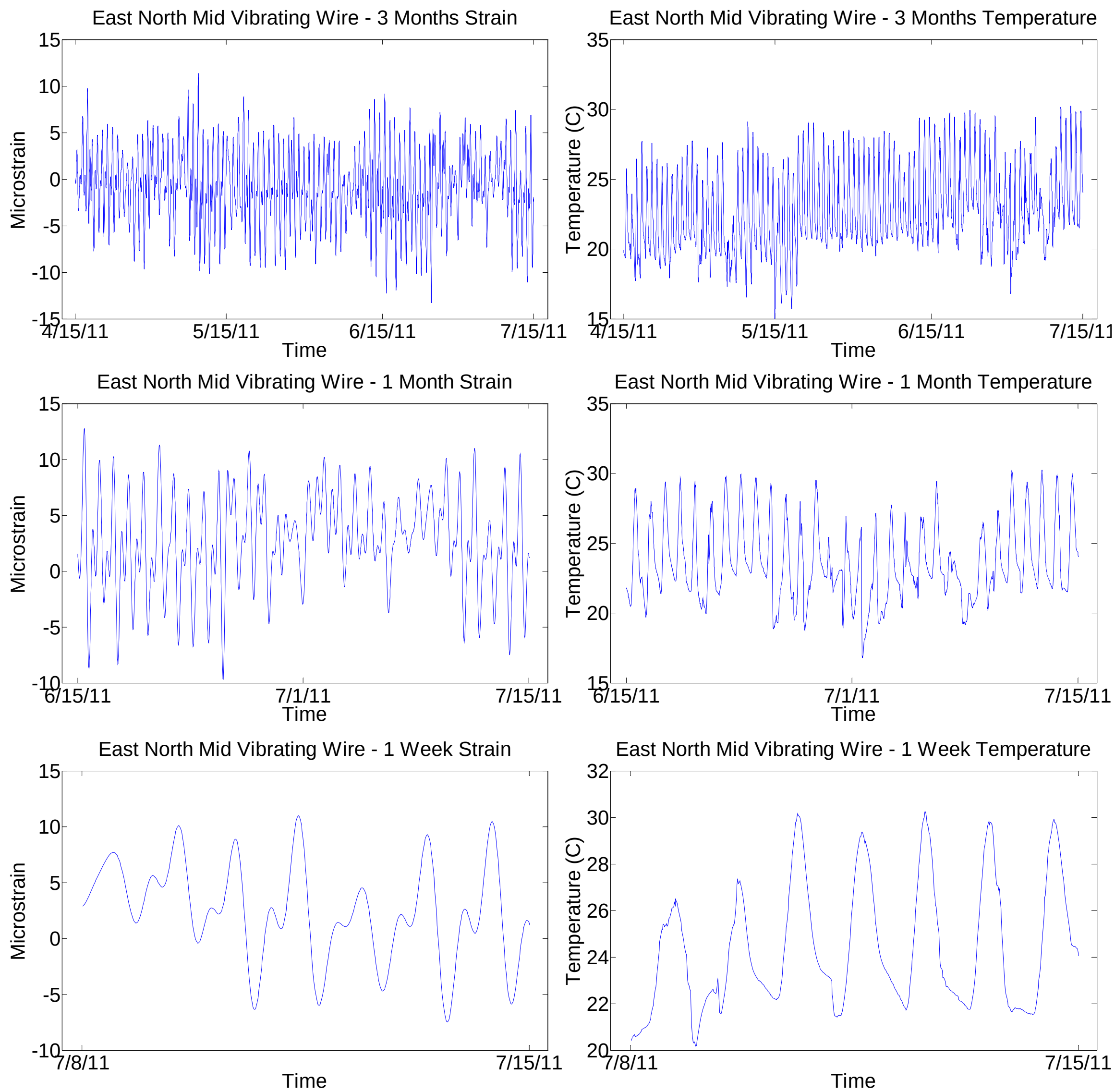

Figure 36: EN2 vibrating wire 3-months, 1-month and 1-week strain and temperature readings

For the west leaf representative data West South LLS area is selected and the data for different periods of this location is presented in Figure 37. It is seen that the strain cycle level is higher at LLS regions. For West South LLS region the strain cycles are around 50 microstrains whereas the temperature cycles are around 15 degrees.

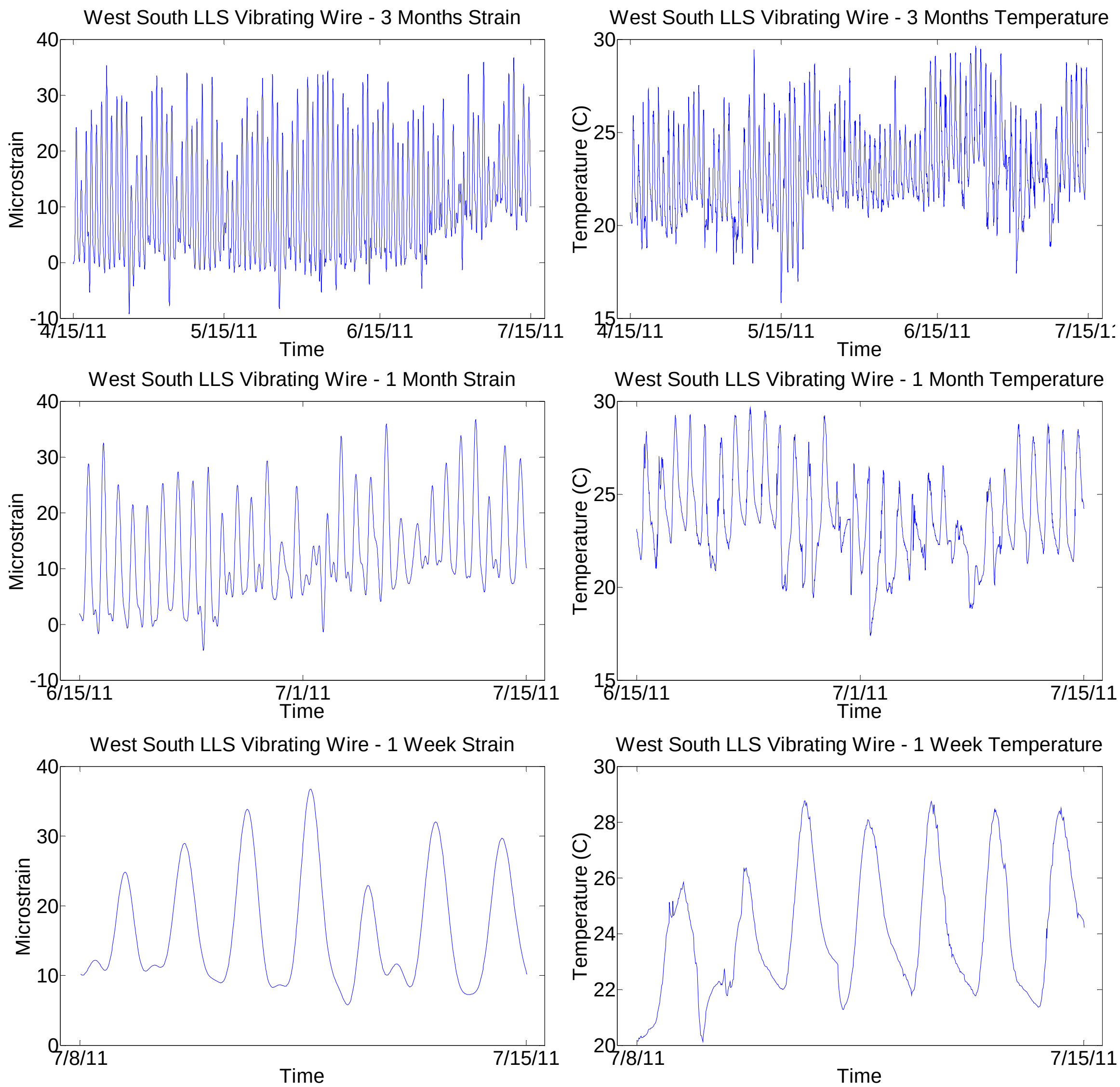

Figure 37: WS3 vibrating wire 3-months, 1-month and 1-week strain and temperature readings

3.1.6.3. Environmental Data

Bascule bridges are slender and lightweight, and are significantly affected by strong wind forces, especially when they are open. In addition to wind, ambient temperature, humidity and rain related information need to be monitored. Therefore, the instrumentation plan consisted of a weather station to measure wind speed, wind direction, temperature, humidity, and rain quantity, duration and intensity. Wind monitoring can be used for determining the input load on the structure caused by air currents. Measured wind speed and direction can also be useful during hurricane-strength winds, indicating excessive force on the girders. Wind station and sample data are presented in Figure 38.

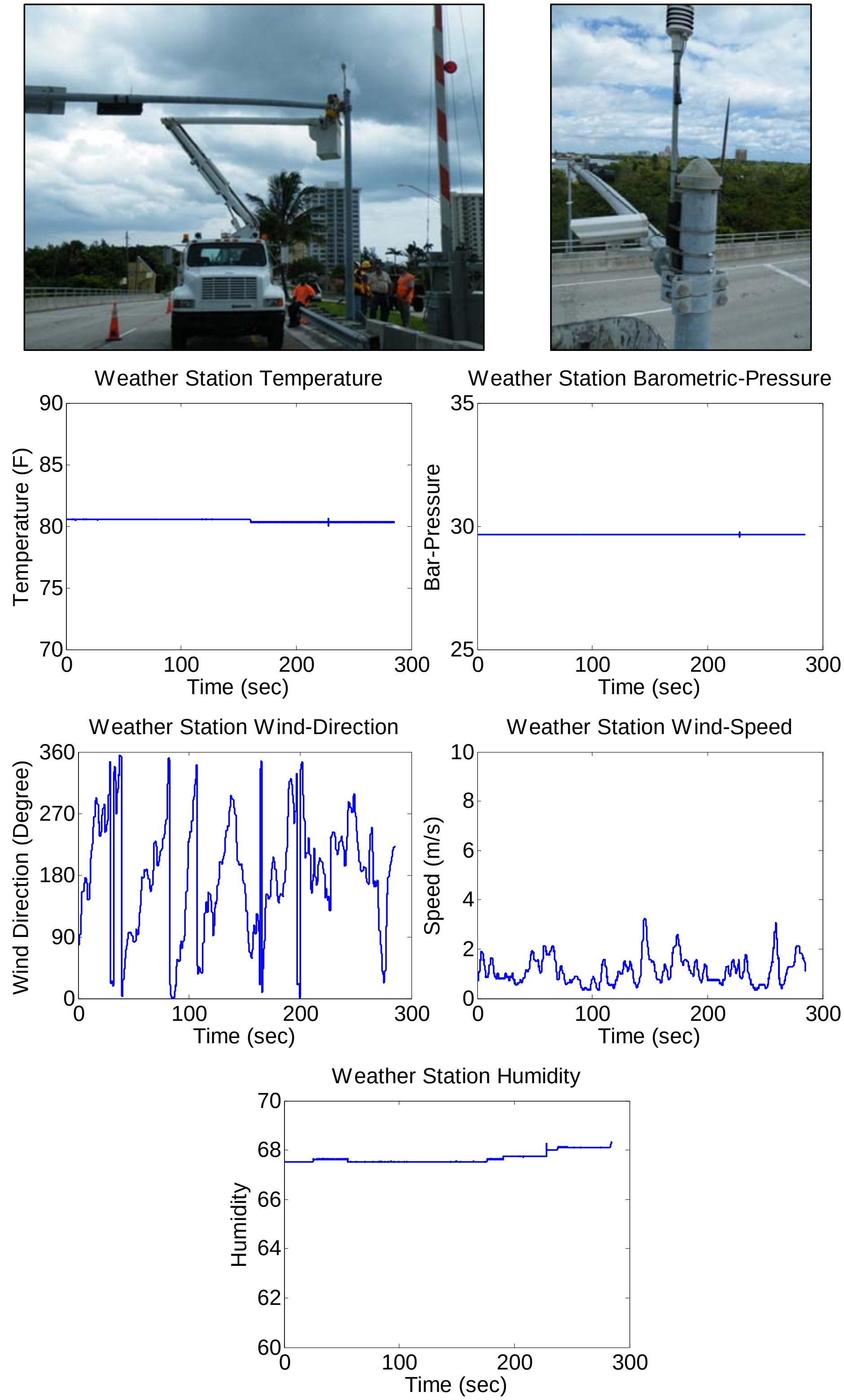

Figure 38: Weather station and sample data

3.1.7. Correlation Analysis Results for Span Lock and Live Load Shoe Shims

Based on the findings for span lock and live load shoe shims removal summarized in previous report, the correlation coefficients are also tracked to identify any structural boundary change. It was shown in the previous report that structural change (or simulated damage) can be detected by means of strain measurements, and more specifically, strain correlations of strain monitoring under any traffic loading. Individual strain measurements can be analyzed and checked; however, these measurements will vary due to loading magnitude and placement. Although maximum measurement can be an indicator for the stress levels due to traffic, any change of structural configuration due to damage cannot be easily detected by just looking at the strain levels. Cross correlations of the measurements, however, indicate a level of correlation when monitored over long-term. The cross correlation trends of different sensor couples for east leaf are presented in Figure 39 whereas the same trends for west leaf are presented in Figure 40. No significant change in the cross correlation trends is seen for both figures during 5/15/11-7/24/11.

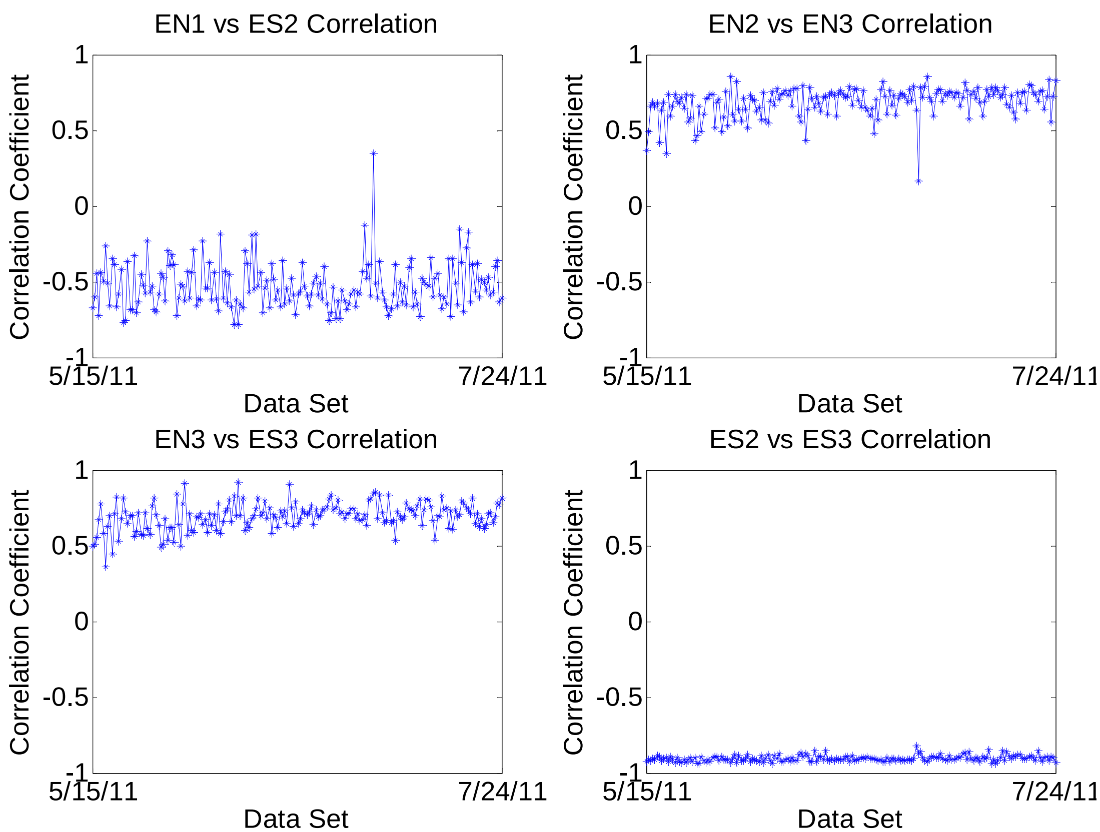

Figure 39: East leaf strain data correlations

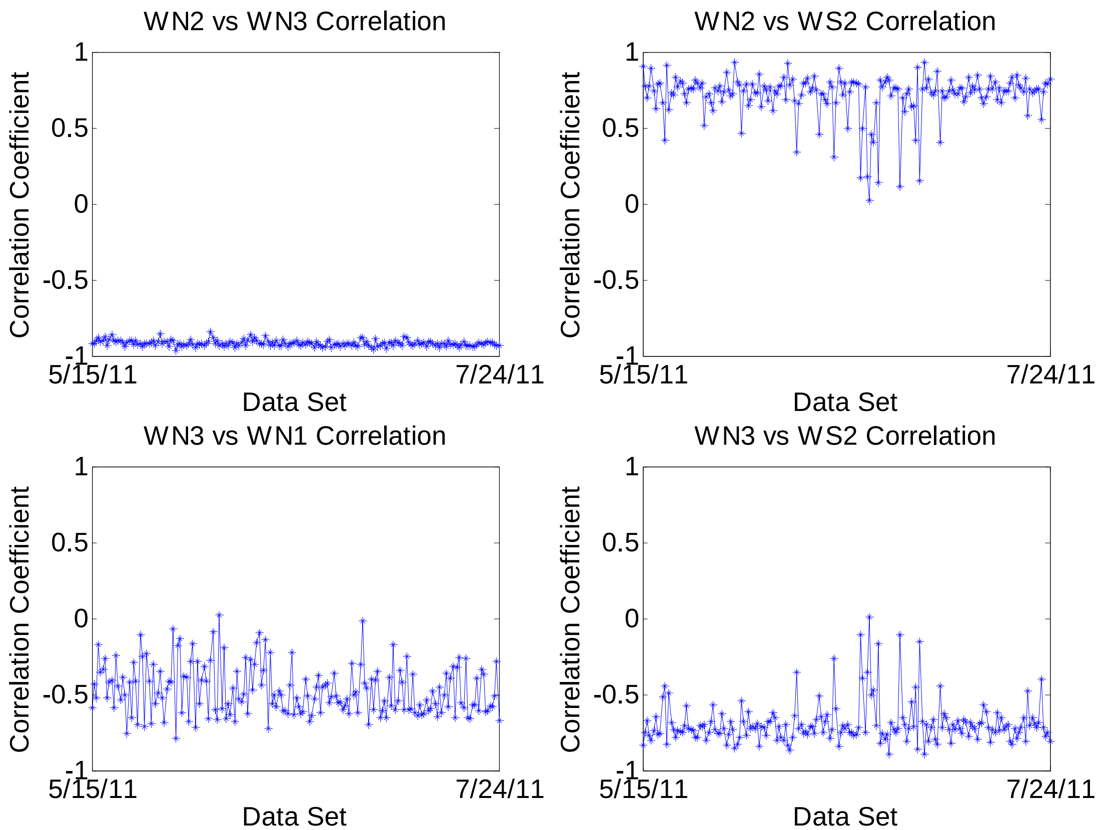

Figure 40: West leaf strain data correlations

3.1.8. Artificial Neural Network Analysis Results for Gearbox Oil Level and Open Gear Grease Level

As discussed in the previous report, an artificial neural network (ANN) approach was used for determining the gearbox oil level and open gear grease level. The inputs to this ANN are the statistical characteristics such as maximum, minimum and standard deviation of the gearbox accelerometer and rack and pinion accelerometer whereas the output of the network is either 0 or 1. "0" corresponds to adequate oil level for gearbox and adequate lubrication of open gear whereas "1" corresponds to unhealthy levels.

ANN results for gearbox oil level and open gear grease level are illustrated in Figure 41 and Figure 42, respectively. It is seen that ANN produces zero values for the openings between 5/15/11-7/24/11 which concludes both components have healthy levels of oil and grease.

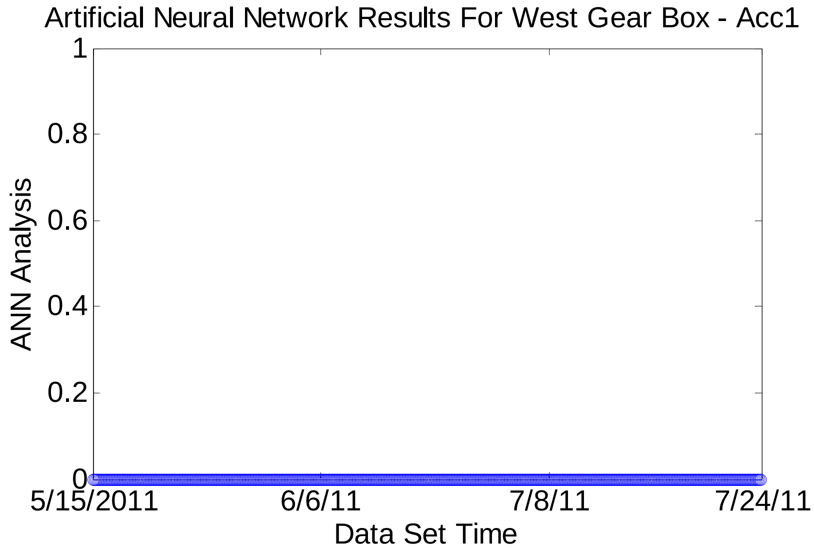

Figure 41: ANN results for gearbox oil level

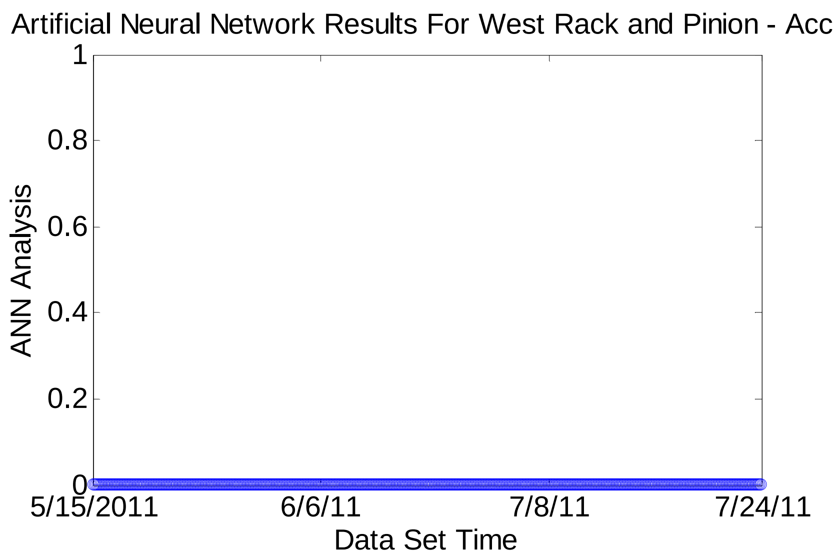

Figure 42: ANN results for open gear grease level

4. Case Studies: Anomalies Observed at Span Lock and Gearbox

Span locks are one of the critical components of the operation. The issues related to the span locks and the problems that can be observed due to its malfunctioning are explored in the previous report. The general behavior of the span lock pressure data in which a single peak is followed with an almost flat region is given in Figure 43.

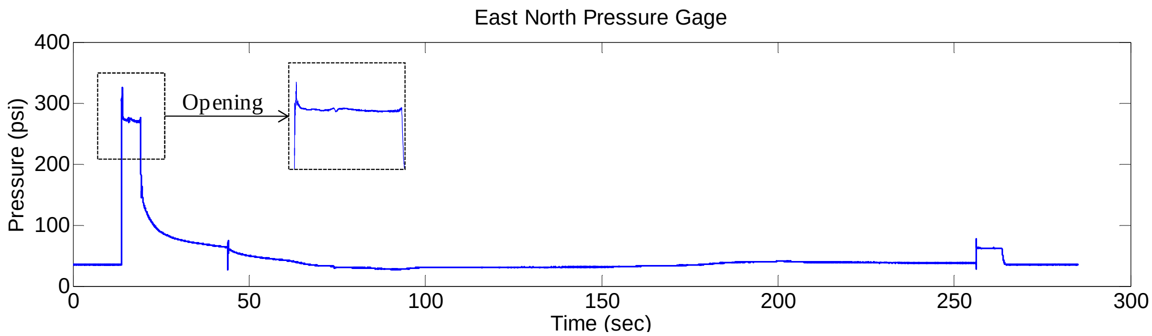

Figure 43: Typical span lock pressure gage behavior

After identification of this behavior, researchers created a basic code to extract features based on the statistical information for the pulling part of the pressure data. When the long-term data was analyzed, an increase in the coefficient of variation of the pulling pressure was detected between 6/13/2011 and 6/19/2011. Afterwards, a more detailed analysis was conducted for these dates as discussed below. Sample snapshots from these dates and corresponding behavior along with the extracted statistical information are illustrated in Figure 44.

It is observed that, on 6/12/2011 (7:03 PM) the span lock operates similar to previous established behavior based on the pulling and driving pressure levels and characteristics. On 6/13/2011 (11:00 AM), it is seen that the first peak is followed by another ~25 psi secondary peak which was not observed before. On 6/16/2011 (9:58 AM), the secondary peak level increased to a ~30 psi level. On 6/20/2011 (8:59 PM), span lock seems to be operating normal again based on the pressure data.

In addition to pressure data, changes in the acceleration and rosette strains during this period are also investigated. The accelerometers at the tip at North and South tip near the span lock are evaluated. After 6/7/2011, higher levels of vibrations are observed at both (Figure 45). It should be noted that while the increase in acceleration and strain levels corroborate with the changes observed at the span lock pressure gages, these are also affected by the traffic on the bridge.

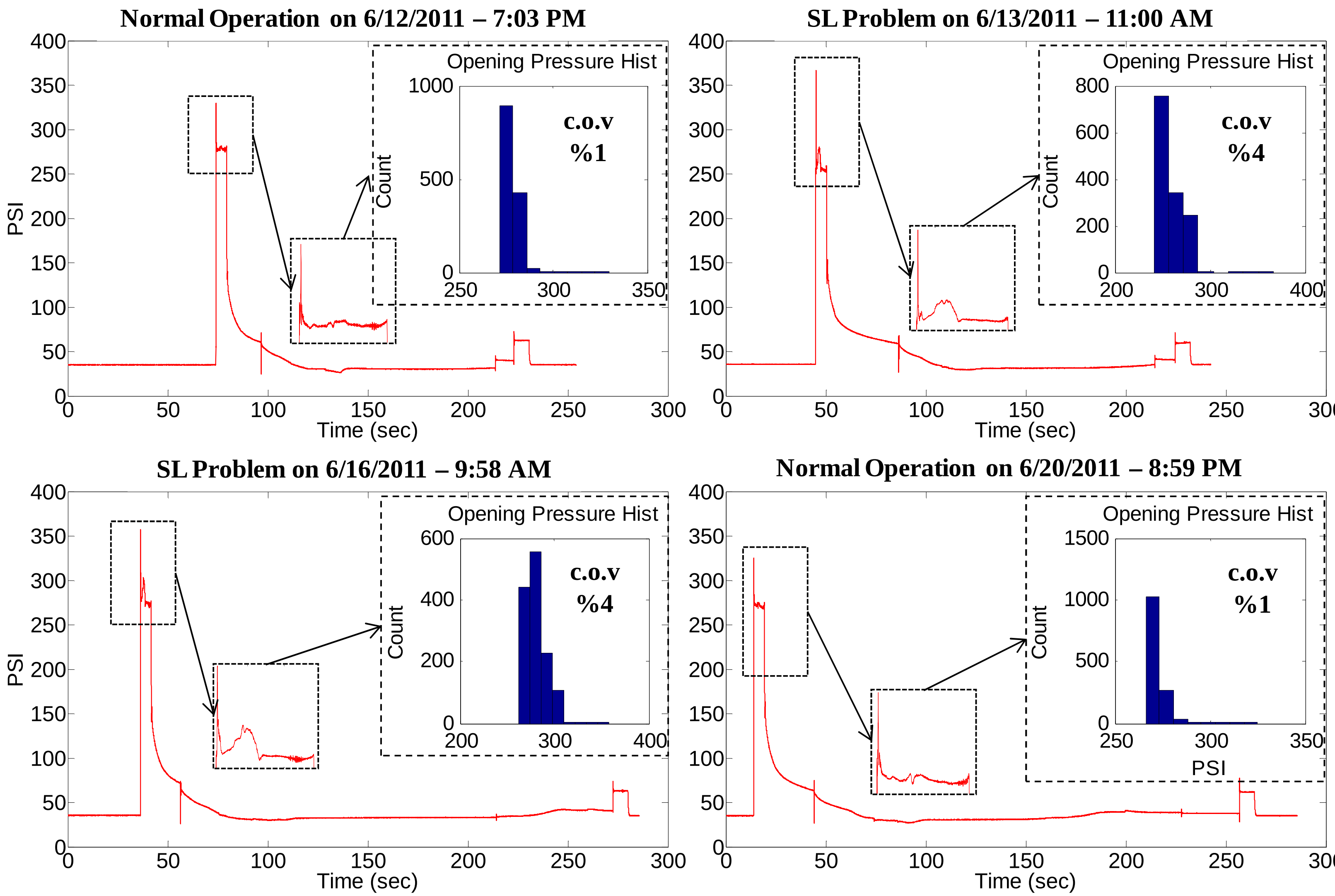

Figure 44: Behavior change of the pressure gage data

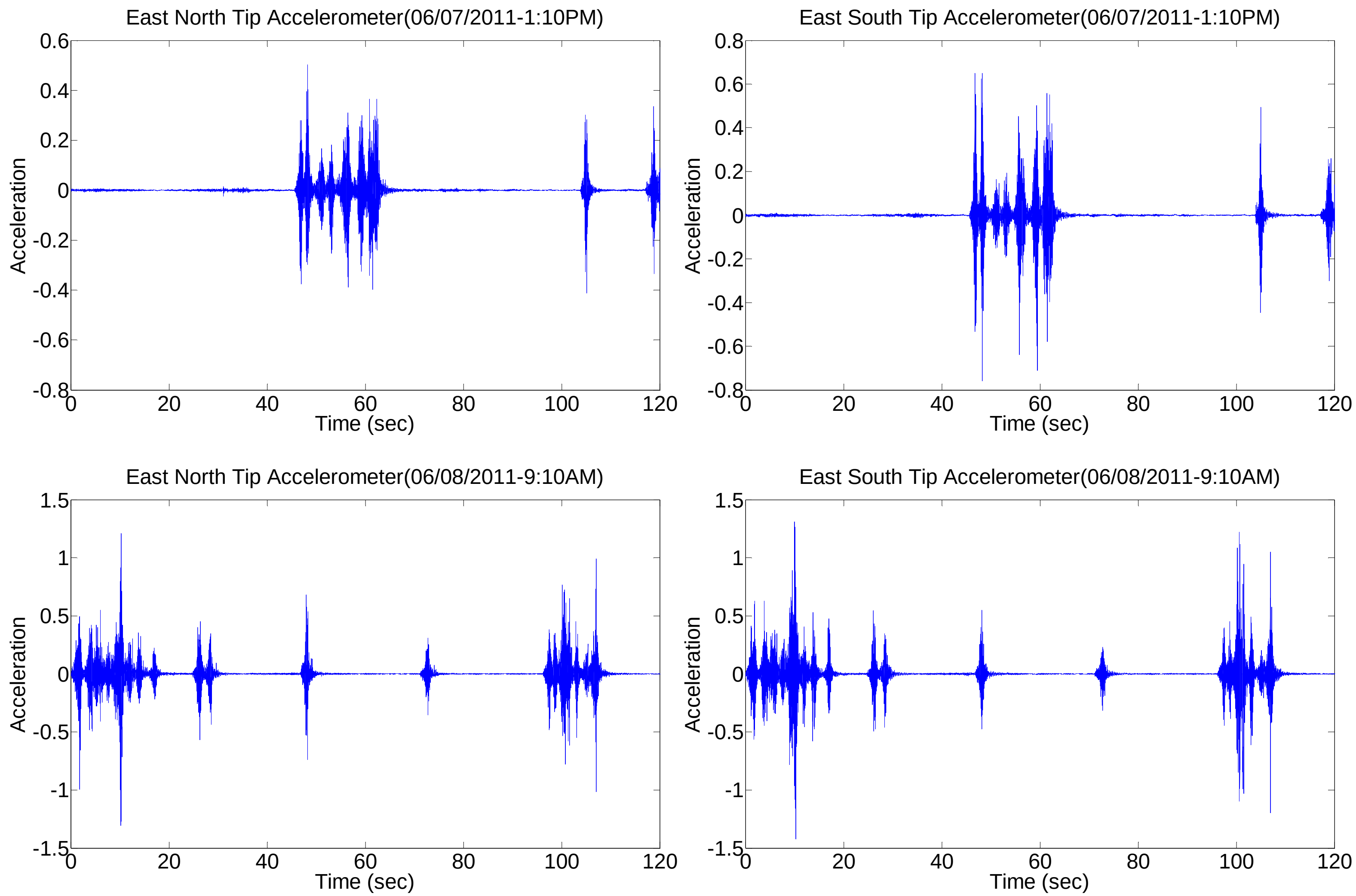

Figure 45: Vibration recorded at the tips of the main girders

The strain gage at the top of the receiver is evaluated. In Figure 46, daily mean of 30-Max and mean of 30-Min readings for East South tip strain rosette are presented. In east south tip strain rosette (change starts at 6/7/2011 5:10 PM). This comes back to normal to around 6/19/2011.

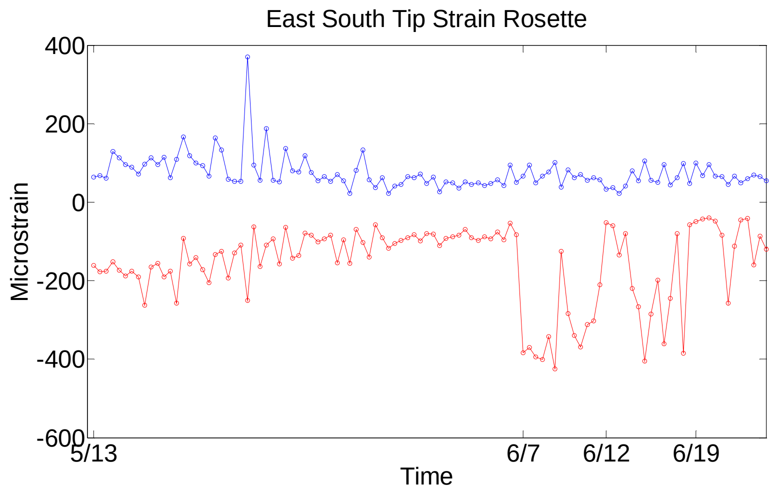

Figure 46: East South tip strain rosette data trend

Due to this unexpected behavior, the writers also investigated the maintenance reports for the corresponding month (June 2011). According to this report (Figure 47), maintenance crew troubleshoots the span lock system and fixes the issue on 6/19/2011. In addition, it is seen in the maintenance reports that the normal preventive maintenance frequency for span lock system is one week. This example shows the importance of an integrated BMMS system because span lock problem is observed to have occurred on 6/13/2011 and the preventive action is taken on 6/19/2011, which can cause an unexpected load distribution in the structural components during this time. As a result, the span lock problem initiation date (as structural changes detected from the different relevant sensors) is several days earlier than the maintenance work done on 6/19/2011. After the maintenance as reported in the maintenance reports, the span lock behavior was observed to come back to its original expected levels.

STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION
BRIDGE MAINTENANCE LOG

FORM 850-010-
MAINTENANC
01/

BRIDGE NO.: 860466 -7 MONTH: JUNE YEAR: 2011

DATE	TYPE OF CREW	TIME IN	TIME OUT	TENDER'S SIGNATURE	CREW LEADER SIGNATURE
6-13	GSI	7am	11 30	[signature]	Jason Cunningham
NOTES:					
6-15	GSI	1:45p	2:00p	[signature]	FRANK MAROTTA
NOTES:					
6.16	Transfield	9:00	12:30	[signature]	[signature]
NOTES: welding on the Deck					
6-19	GST	11:45p	3:00A	Natacha Bode	FRANK MAROTTA
NOTES: Trouble shoot NOB span lock system. ReplacED Time Delay Relay.					
6/19	GSI	1 30 Am	300 Am	Natacha Lodie	Orlando Cruz
NOTES: Assist w/ lock trouble					
6-20	GST	6 20 A	9:15	[signature]	FRANK MAROTTA
NOTES:					

Figure 47: Sunrise Boulevard Bridge maintenance log for 6/13/11-6/20/11

Another critical component of the movable bridge operation system is the gearbox, which transfers the power to the shafts. The main issues regarding to gearboxes are lubrication problems, speed reducers wearing and load transfer problems due to shaft seals. Accelerometers are installed on gearbox for tracking the vibration characteristics to determine if the gearbox condition is satisfactory. While tracking the statistical properties of the gearbox accelerations, a significant increase in the vibration levels is seen on 6/28/2011 which is shown in Figure 48. Before this date, the maximum vibration levels are slightly higher than 0.2 g whereas the vibration levels increased to 0.3-0.5 g after 6/28/2011. The change in the standard deviation characteristics is also shown in Figure 48.

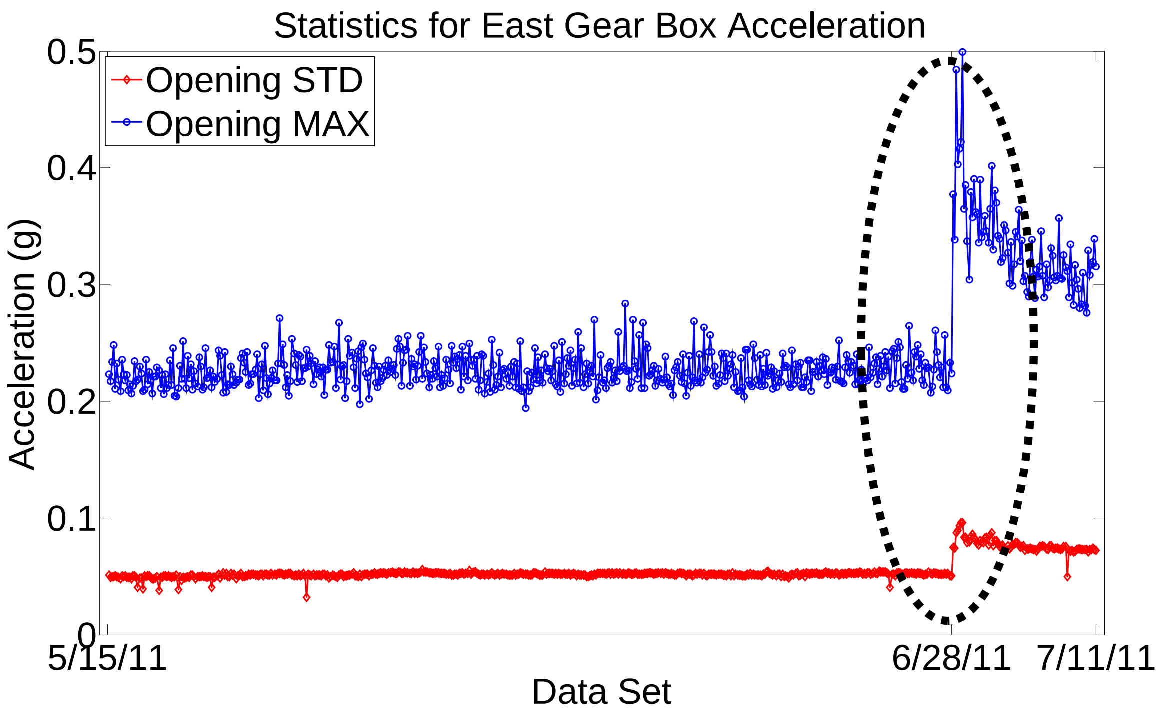

Figure 48: Gearbox acceleration statistical trend

After this observation, authors investigated the frequency domain results of some data sets from 5/23/2011, 6/29/2011 and 7/11/2011 to see the change in vibration characteristics. In Figure 49, a change in dynamic response of the east gearbox is observed especially around 10-20 Hz bandwidth. The change starts on 6/28/2011 and this effect can be observed from the power spectral density plots. By 7/11/2011, the change is getting back to its “normal” condition. The peaks observed around 10 Hz of the gearbox might be attributed mostly to its own dynamic characteristics (mass, stiffness, damping, connection to the concrete etc.).

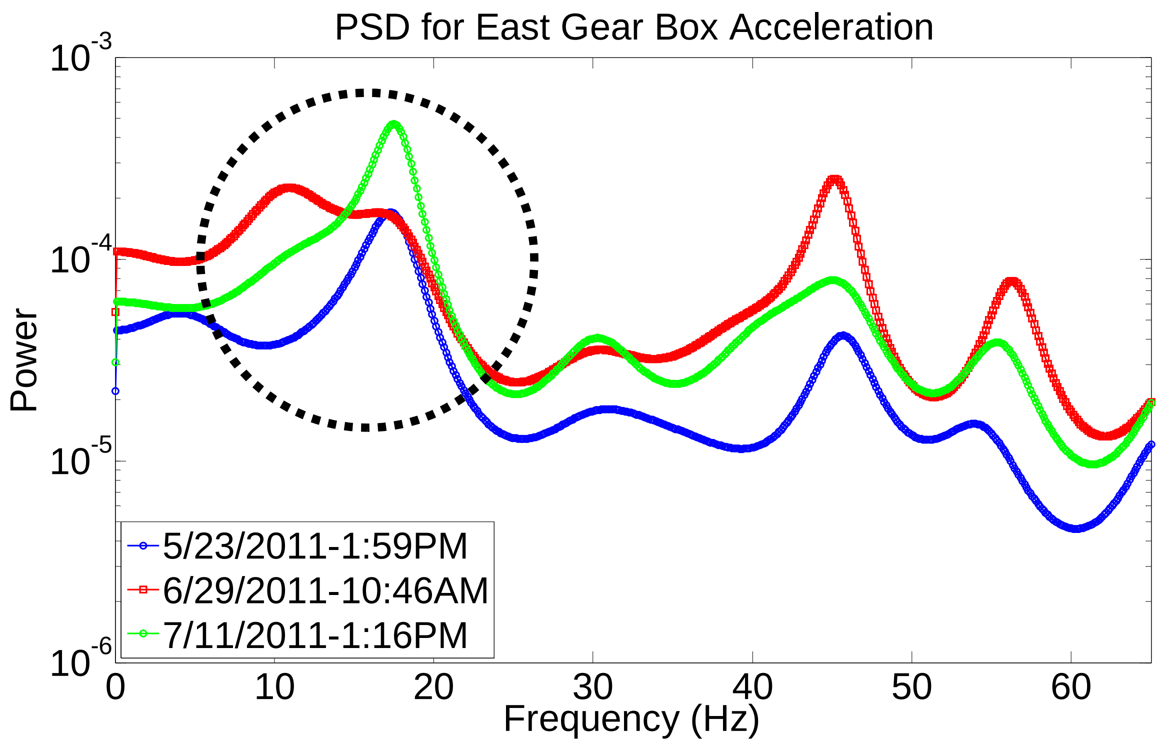

Figure 49: Gearbox acceleration frequency domain analysis of three different data sets

In addition to monitoring data analysis, June-2011 maintenance reports are also examined (Figure 50) and it is seen that on 6/28/2011 during the scheduled inspection, maintenance crew replaced the output shaft seal on gear-box, which most probably changed vibration characteristics at this location. It is also noteworthy to indicate that this preventive maintenance action increases the vibration levels and this may directly affect the movable bridge operation. This case also shows that incorporation of monitoring technologies with maintenance can also provide information about the effectiveness of the maintenance. It should be also noted that these technologies can provide information for sensor baseline behaviors as illustrated for gearbox accelerometer. Finally, redundant sensors can be identified based on the findings for an optimized sensor design for future implementations. It is obvious that the data from inspections, maintenance and BMMS can serve in complementary manner, even cross-checking each other.

STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION

BRIDGE MAINTENANCE LOG

FORM 850-010-25
MAINTENANCE
01/95

BRIDGE NO.: 860466-7 MONTH: June YEAR: 2011

DATE	TYPE OF CREW	TIME IN	TIME OUT	TENDER'S SIGNATURE	CREW LEADER SIGNATURE
6-20	GSI	700	9:15	[illegible]	[illegible] THREIKELD
NOTES: WEEKLY					
6-20	GSI	7am	9:15	[illegible]	Jason Cunningham
NOTES: WEEKLY					
6-27	GST	5:30A	7:05A	[illegible]	FRANK MAROTTA
NOTES: Weekly					
6:28	GST	6:13AM	10:15 AM	[illegible]	[illegible]
NOTES: wkly PM + Replace output shaft seal on W/E gear box					
6-28	GST	6:15AM	10:15A	M. [illegible]	FRANK MAROTTA
NOTES: Weekly PM REPAIRE OUTLET IN NEAR SIDE MACHINERY ROOM.					
NOTES:					

Figure 50: Sunrise Boulevard Bridge maintenance log for 6/20/11-6/28/11

5. Summary and Conclusions

5.1. Summary

The main objectives of this project are (1) data collection and analysis, (2) maintenance of the monitoring system after the bridge was painted (3) replacement of critical monitoring components, and (4) final report documentation and submission. A critical consideration of this extension project was to repair and maintain the monitoring system, which was significantly affected by the bridge painting operation. Other considerations included collection and analysis of additional data with the specialized methods and approaches that have been developed by the researchers.

Considering the large population of movable bridges and the costly maintenance issues, a research project was initiated by FDOT and UCF to implement a comprehensive monitoring system to a movable bridge for exploring improved decision making using monitoring data for maintenance and management (Catbas et al, 2010). For this previous study, the monitoring system was designed and implemented on a representative bridge in District 4 in Ft. Lauderdale, Florida. The selected representative movable span was the west-bound span of two parallel spans on Sunrise Boulevard in Ft. Lauderdale. This span was constructed in 1989. It has double bascule leaves with a total span length of 117 ft and a width of 53.5 ft, carrying three traffic lanes. Each leaf is 70 ft long and 40 ft wide. The bridge opens 10 to 15 times a day.

After the monitoring system was designed and implemented, monitoring data was collected continuously as well as for different events, such as truck load test and damage tests where certain components of the bridge were altered for a short period of time to demonstrate technologies and methodologies. After completion of the project, the bridge was painted as previously scheduled, which damaged the monitoring system significantly. Therefore, the extension project was initiated to bring the monitoring system to an operational condition. The first phase of the extension project included investigation of the condition of the monitoring system after painting of the bridge. Then, researchers started fixing the sensors and cabling systems that were affected during the painting as much as they can with the available access especially under the bridge. A number of field visits were made for repairing and replacing the sensors in the mechanical rooms and on the structural elements with the help of a snooper truck. Moreover, a number of fixes to the hardware and software of the DAQ system and computers were also accomplished during these visits.

After bringing the monitoring system to an up and running condition, continuous data collection started again. The data was analyzed with the methods developed in the previous project to monitor the condition of the critical components. The analysis results, which are discussed in the next section, showed that the monitoring system can be a significant component of the decision making strategy. Visual inspection, maintenance and monitoring data can be used in a complementary way to make better decisions, take precautions before unexpected malfunctions and to cross-check the quality of the maintenance operations.

5.2. Conclusions and Findings

Effective and unique data analysis methods were developed and reported to FDOT previously by the researchers. These methods are also used for data analysis in the extension project. One of these methods was the cross correlation based damage detection technique for structural assessment which can be used to identify the structural changes in the bridge, such as SL or LLS shims removal. This approach is expected to help the bridge engineers and maintenance personnel to reduce the number of maintenance visits for shim replacement at these locations and for other maintenance operations at the structural components. This method can also be used to evaluate the effectiveness of maintenance by checking the correlation levels of the baseline (well-maintained, proper operations) conditions to conditions with no maintenance or new maintenance. The analysis with the new data has indicated no significant change in the correlation of strain sensors.

For the assessment of mechanical components, two different data analysis techniques are employed for the new data. One method is the image-based analysis for the open gear in which edge detection based computer vision techniques were used to identify whether the open gear was lubricated properly or not. Results of the open gear image analysis show that the lubrication index is higher than the pre-defined threshold level during the period under investigation.

The other mechanical assessment method was identification of the oil level change in the gearbox oil and open gear grease removal. For identification of these damage scenarios, an Artificial Neural Network (ANN) based technique was used where the data was reduced to “0” (healthy) and “1” values (unhealthy) for simplicity and demonstration of the approach. The results of the analysis for latest data sets show that the oil level in gearbox and the grease level in open gear are adequate. This can also be used to cross-check the image-based analysis results, which also indicated that the open gear was properly lubricated.

Moreover, long-term monitoring can also provide important information about the effects of the temperature variations on the bridge balance and friction. In the previous report, the long-term monitoring studies showed the correlation between the mechanical friction and environmental effects. The most critical environmental effect was found to be due to temperature. Friction and temperature data presented in this report shows a steady behavior for the extension period. The friction numbers are in the 20-30 kip-ft range.

In addition to data analysis methods described in the previous report, sensor baselines are identified for different component sensors based on statistical analysis of the long-term data collection. For each sensor on different components; maximum, minimum, standard deviation and maximum root mean square values are calculated. With the help of these values, baselines statistics and histograms are generated. Statistical analysis shows that the average vibration level on gearbox is around ±0.2 g with slight changes depending on the sensor location. Another sensor type on the gearbox is the microphone which shows an average sound pressure of ±3 Pa.

For the electrical motor, vibration levels are changing based on the sensor locations. For example, the motor accelerometers close to the gearbox side (mot-acc1 and mot-acc2) are vibrating with ±1 g whereas the accelerometers on the other side of the motor are vibrating with ±1.5 g. It should be noted that the average levels are showing differences for east and west leaves. Motor temperature is also tracked with the help of infrared temperature but no significant temperature change on the motor could be observed with the installed sensor type. Amperage readings from the motor are showing consistent readings with maintenance reports.

Two different case studies in correlation with maintenance reports are investigated in this report. First one is the span lock trouble identified by the maintenance crew during weekly inspection on 6/19/11. The researchers also investigated this event independently using the monitoring system. Span lock pressure gage data statistical analysis shows that pulling pressure has a mean of 321 psi and a standard deviation of 33 psi whereas driving pressure has a mean of 58 psi and a standard deviation of 15 psi. In addition to this information, the characteristics of the pulling pressure are also investigated with histograms and the span lock trouble was identified on 6/13/11. Histograms show an increase in the coefficient of variation before the action taken by maintenance crew on 6/19/2011. It should be noted that the maintenance effects can also be observed from the monitoring data. Finally, it is critical to note that the span lock problem initiation date (as structural changes detected from the different relevant sensors) is several days earlier than the maintenance work done on 6/19/2011.

Second case study is the gearbox shaft seal replacement on 6/28/11. In this case study, the effect of maintenance is evaluated with the help of monitoring data. Before this maintenance, the baseline acceleration level on gearbox was around ±0.2 g but after the observed problem until the replacement of the shaft seal on gearbox, the acceleration level was increased to ±0.3 g. Detection of these problem was done by means of descriptive statistics of the time domain data as well as the frequency domain data. Excessive vibrations are one of the main problems for machinery components and with the help of BMMS system effectiveness of the maintenance is demonstrated.

All in all, these effective and unique methodologies can be employed for proactive maintenance, operation and safety. For instance, a refined monitoring system with such data analysis capabilities is expected to help to reduce the costs, to better understand the root causes and improve new designs.

5.3. Recommendations

Monitoring of a movable bridge provides an excellent opportunity to increase the safety and reliability and to reduce the maintenance costs. The current system proved to detect changes and problems effectively as exemplified for the live load shoes, span locks, gearboxes, open gears, open gear, bridge friction etc. The system behavior is now well-established with baselines and thresholds. Future monitoring applications are recommended to utilize this information.

A more compact data acquisition system can be designed, developed and used for future applications. Several commercial data acquisition system and card providers can now supply smaller and more cost effective systems.

The writers developed Labview codes for collecting data from the extensive monitoring system. As per FDOT recommendation, the researchers did not update and/or revise the existing programs; however, it is recommended that newer versions of software are utilized. In addition, the data acquisition computers should be checked over time since these computers and necessary hardware/software updates be conducted.

Major bridge maintenance such as bridge sandblasting and painting may induce damage to sensors and cables. Such applications should be coordinated in such a way that the damage to the monitoring system, sensors and cables are minimized.

Another rudimentary yet important recommendation is that power to data acquisition system should be dedicated power since using the same power for other bridge operations and maintenance applications may induce interruptions and possibly damage to the monitoring systems. Use of uninterruptible power supply can be a solution to a certain extent.

For detecting structural problems as exemplified in this and previous reports, at minimum, live load shoe locations are to be instrumented. Similarly, the number of vibration sensors at the electrical motors and gearboxes can be reduced to two and three, respectively. This exploratory study required the use of a large number of sensors; however, a much reduced sensor count could be sufficient to obtain the most critical information. In addition, with the advances in sensors, more sensitive sensors can be employed for applications such as vibration, sound and temperature measurements.

6. References

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