Heavy Movable Structure Health Monitoring: Case Study on a Bascule Bridge in Ft. Lauderdale

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Abstract

Heavy movable bridges have different design, operation and maintenance characteristics compared to fixed bridges. This is mainly due to the complex interaction between their structural, mechanical and electrical systems. Movable bridges are viable options in certain terrain conditions and their unique operation provides versatility. At the same time, their intricate interrelation also produces some operation and maintenance challenges. Deterioration, unexpected breakdowns, high maintenance costs and difficulty of repair are some of the issues related to movable bridges. In this paper, a Structural Health Monitoring (SHM) application demonstration on a bascule type movable bridge is presented. The ultimate objective of this on-going project is continuous assessment of the condition and improvement of the maintenance operations. The bridge that is presented as a case study is the Sunrise Boulevard Bridge in Fort Lauderdale, Florida. This bridge has one of the most comprehensive monitoring systems in terms of the different sensors installed to monitor different phenomena. The design of the monitoring system, selection and performance of the sensors, wireless communication between the two leaves, triggering and synchronization of the data acquisition systems on both sides are presented. In addition, sample data from various types of sensors for structural, mechanical and electrical systems are shown. Finally, some challenges encountered during the field implementation are discussed.

Introduction

The Florida Department of Transportation (FDOT) owns and operates one of the largest numbers of movable bridges in the U.S. According to National Bridge Inventory [1], there are 146 movable bridges (3 lift type, 133 bascule type, and 10 swing type) in Florida and these are complex structures utilizing machinery to open a portion of the bridge allowing for the passage of waterborne traffic. The majority of the movable bridges in Florida are of the bascule type, having interior spans called "leaves" that rotate upward and away from the centerline of the waterway thus providing clear passage.

Movable bridges are commonly used over the waterway especially in flat terrain. These bridges also present significant drawbacks and problems associated with the operation and performance. Movable bridge rehabilitation and maintenance costs are considerably higher than that of a fixed bridge. Deterioration is a concern since they are located over waterways, and often close to the coast, which constitute conditions suitable for corrosion, causing section losses. Deterioration and damage is also observed due to moving parts, friction and wear and tear of the structural and mechanical components. Fatigue can be a problem due to the reversal or the fluctuation of stresses as the spans open and close. If there are breakdowns, these cause problems for both, land and maritime traffic. Maintenance costs associated with the operation system and mechanical parts require special expertise, and may cause extensive repair work. Finally, difficulty in repair works is an issue for movable bridges. A minor or major malfunction of any component can cause an unexpected failure of bridge operation. Electrical and mechanical problems may require experts and may be difficult and time consuming to fix.

Structural Health Monitoring (SHM) can be considered as an approach to continuously monitor the structural, mechanical and even electrical components of a movable bridge mainly for bridge maintenance and predicting possible problems in advance. Such a monitoring program can generate flags and warnings for maintenance to indicate a worsening condition according to industry standards, manufacturer recommendations and/or pre-set thresholds. A monitoring system is an excellent tool for real-time asset management by infrastructure owners. Infrastructure owners may use flags and warnings as a mechanism to monitor/assess maintenance performance. The data may be used by the contractors in scheduling preventive maintenance to maximize the service life of the equipment and the structure. In addition, the root causes of the structural and mechanical problems can be determined, and future designs can be improved using the information generated using the monitoring system.

In this study, the writers present the monitoring design and implementation on a representative bridge in Ft. Lauderdale, Florida. First some of the critical structural, mechanical and electrical components will be described and then the issues related to these components will be defined. Finally, possible measurements to corresponding issues will be shown with some sample data. For this reason, a representative bridge which is the west-bound span of two parallel spans on Sunrise Boulevard in Ft. Lauderdale was selected. 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. Sunrise Boulevard Bridge is shown in Figure 1.

Figure 1: Sunrise Boulevard Bridge

Bridge Maintenance Monitoring System (BMMS)

Sunrise Bridge is the most common bascule type, with a rack-and-pinion mechanism. The bascule leaves are lifted horizontally at the point of the trunnions, which are the pivot points on the main girders. The weight of the span is balanced with a counterweight that minimizes the required torque to lift the leaf. The counterweight is made of cast-in-place concrete. In the closed position, the girder rests on a support called ‘Live Load Shoe’, or LLS, on the pier and traffic loads are not transferred to the mechanical system. The movable bridge also involves fixed components, such as reinforced concrete piers and approach spans. The counterweight of the main girder stays below the approach span deck in the closed position. When the bridge is opening, the leaves rotate upwards, and the counterweight goes down. The driving torque is generated by an electrical motor, which is then distributed to the drive shafts via the gear box. The gear box involves an assembly of gears operating similar to automobile differentials, and provides equal lifting of both sides. The drive shafts transmit the torque to the final gear called the pinion, engages the rack assembly which is directly attached to the main girder. The issues related to these components and possible measurements will be discussed in the following sections.

Structural Components

Main girders floor beams and stringers form the frame of the spans. They are made from both rolled and built-up sections with welded plates. The frame is generally manufactured at the shop and then installed at the site. Corrosion is a main concern on the bridge girders, especially on exposed surfaces that leads to section loss and reduced capacity. Additionally, any misalignment, bending, or deformation can also cause an increased strain on the structure. Therefore, these components were instrumented with strain gages to detect these anomalies and to trigger preventive maintenance to avoid catastrophic failures. Instrumentation with strain rosettes is also crucial because panel shear is the most likely cause of excessive stresses. Main girder failure modes will be tracked considering bending and web shear. Accelerometers can be used to register the vibrations caused by vehicular traffic. Vibration frequencies also indicate if there is change in structural system such as due to imbalance or due to span lock failure. Figure 2 shows sample data from a strain gage, strain rosette and accelerometer under traffic loading.

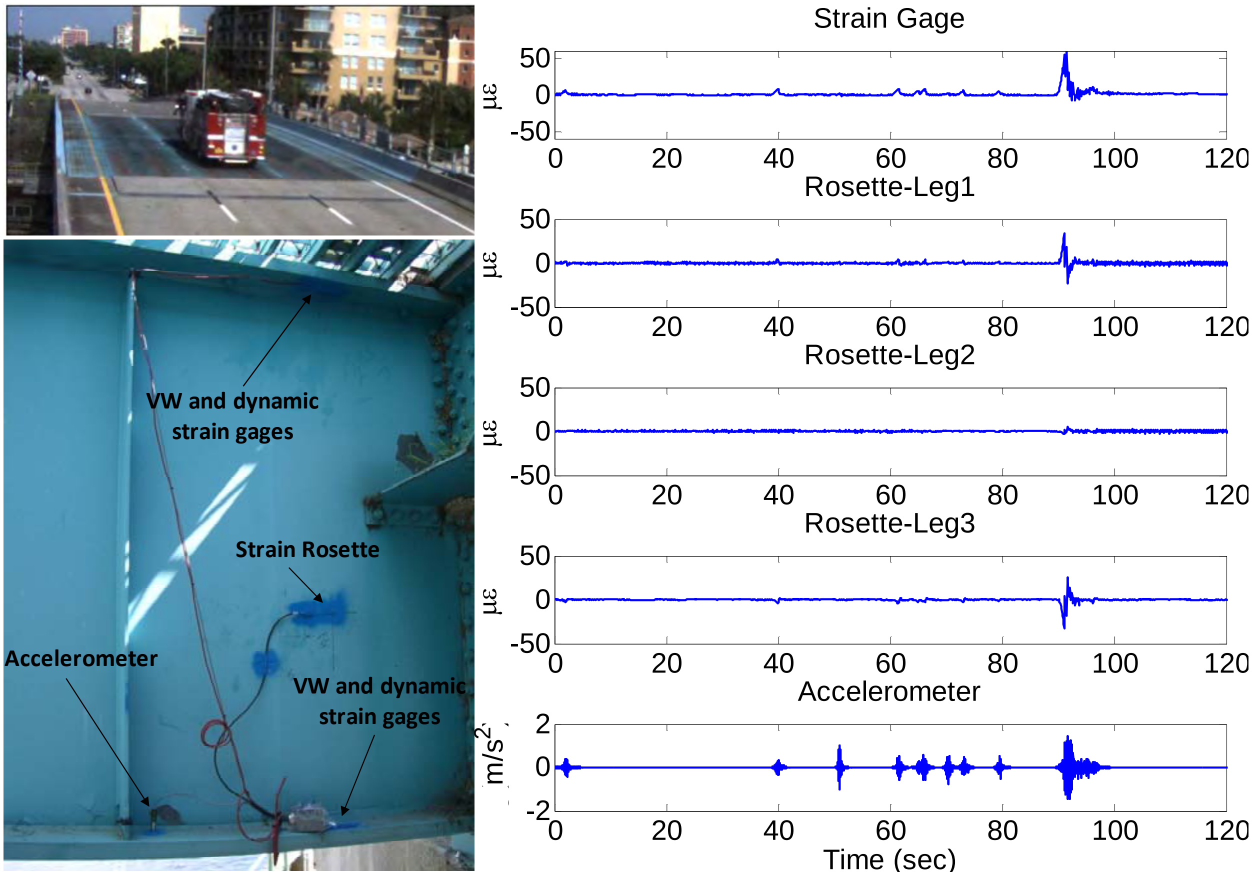

Figure 2: Strain, rosette and accelerometer sample data under traffic

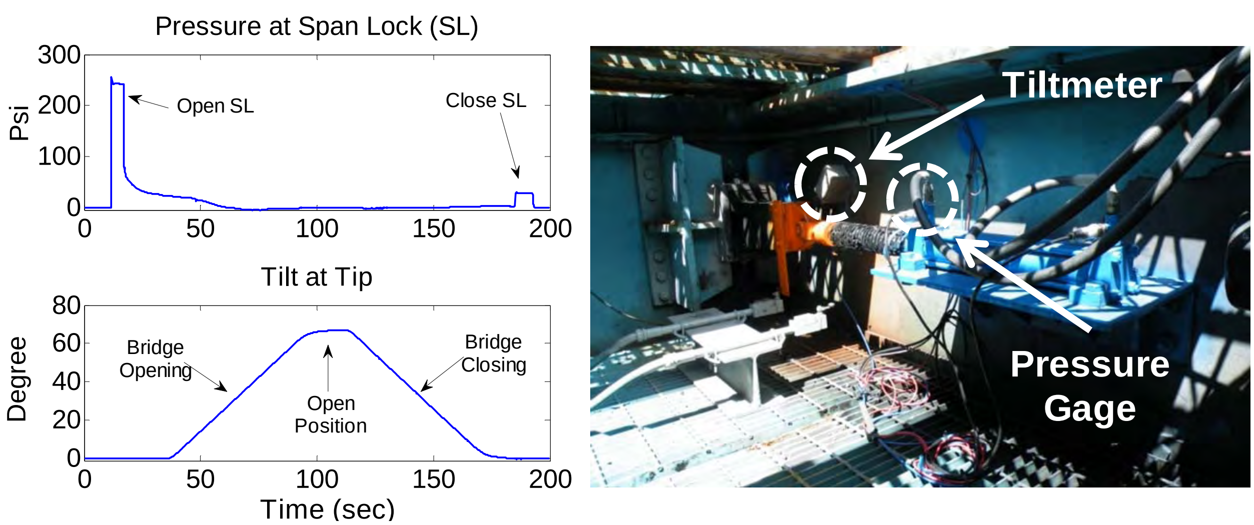

Figure 3: Pressure gage and tiltmeter data during opening

Tiltmeters provide monitoring of the angle of rotation at the tip of the span. The tiltmeter readings will serve two functions: checking the leveling between girders on both sides for alignment during opening/closing and ensuring that the tips are in correct position for the locking maneuver. During an opening, sample tiltmeter data from the tip of the main girder can be seen in Figure 3. The same figure also shows the pressure gage readings from the span lock.

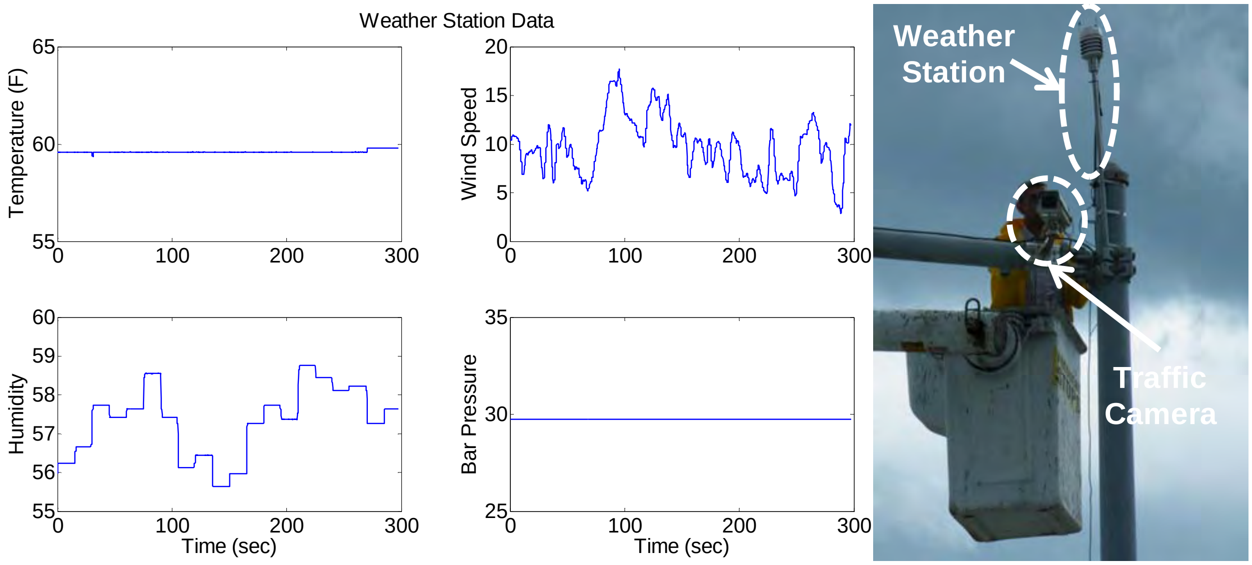

Figure 4: Weather station data & location and traffic camera

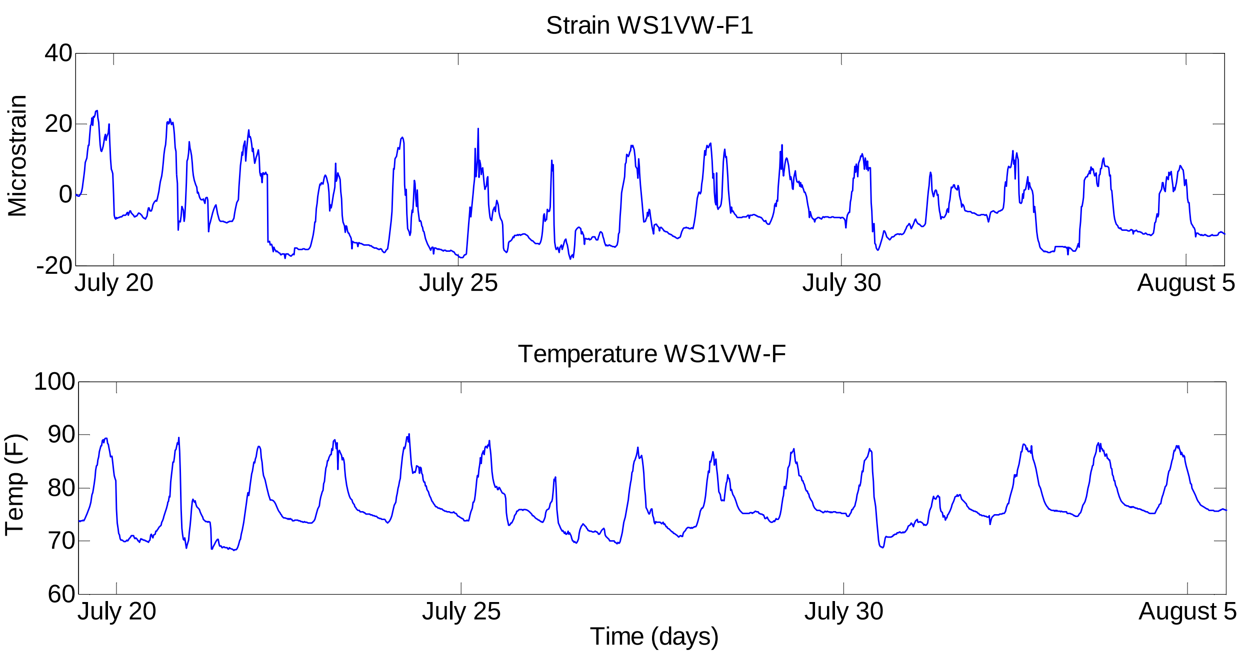

Figure 5: Sample data from vibrating wire strain and temperature readings

Wind monitoring will be used for determining the input load on the structure caused by air currents. Bascule bridges are slender and lightweight, and are significantly affected by strong wind forces, especially when they are open. Measured wind speed and direction will also be useful during hurricane-strength winds, indicating excessive force on the girders. In addition to wind, ambient temperature and structural member temperatures need to be monitored. A typical wind station data is shown in Figure 4. Furthermore, past studies have shown that temperature differentials can cause considerably higher stresses than stresses induced by vehicular traffic [2]. For this reason, vibrating wire gages were installed to the bridge to track the temperature induced strain cycles. Vibrating wire strain gage data between 7/20/2009-8/5/2009, which includes strain and temperature can be seen in Figure 5. From this figure, daily strain cycle due to temperature can be easily seen.

Finally, a video camera can be a complementary element as providing vehicular traffic data to be correlated with other sensor readings, informing bridge owners about accidents and suspicious activities. In addition, computer vision can be employed for purposes such as tracking corrosion of the gears. The location of the traffic camera can be seen in Figure 4 whereas sample video image from this camera can be seen in Figure 2.

Mechanical and Electrical Components

The electrical motors generate the torque required for the opening and closing of the bridge. High amperage, high temperature, vibration and high revolution speed are indicators of improper functioning. Excessive or abnormal vibration can be detected by accelerometers attached on the motor case. To detect the malfunctioning of the electrical motor, accelerometers were installed in horizontal and vertical directions as seen in Figure 6. Moreover, amperage can be measured with electrical current measurement. Therefore, electric box was instrumented with three ampmeters and sample data from ampmeters can be seen in Figure 7. Temperature probes may be used to detect overheating on the brakes of the motor and for this issue an infrared temperature sensor was installed.

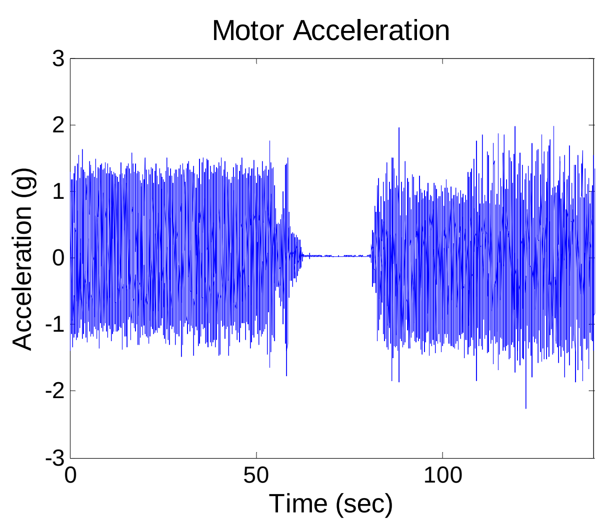

Figure 6: Electrical motor, installed accelerometers and sample acceleration data

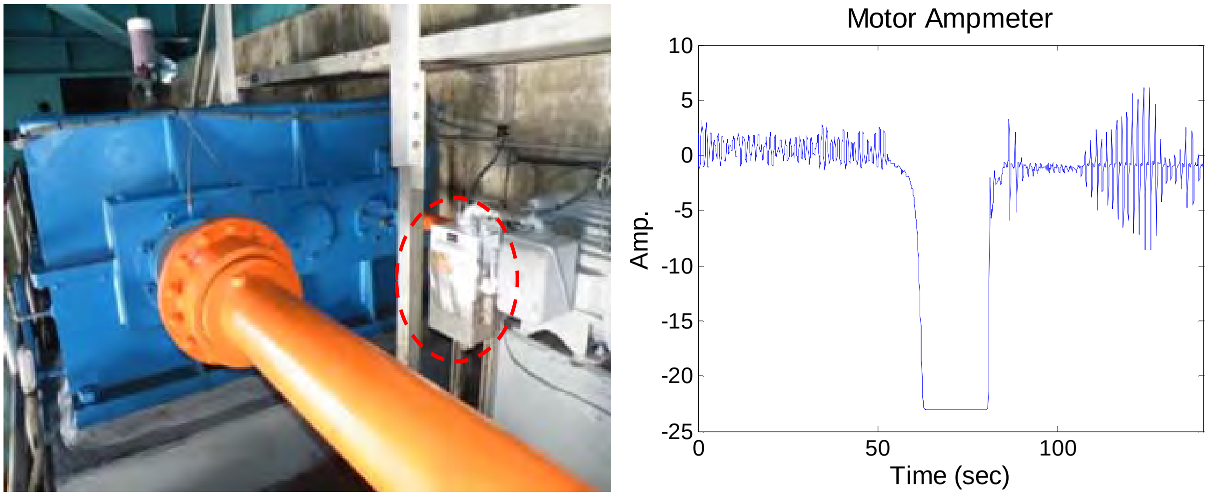

Figure 7: Electric box of the motor ampmeter and sample data from the ampmeter

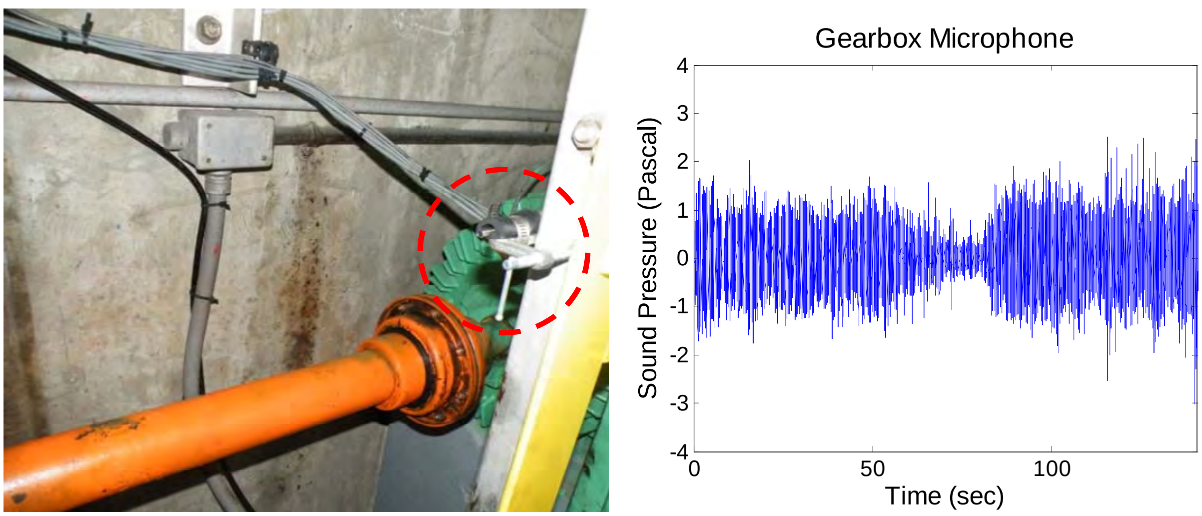

Figure 8: Gearbox microphone and sample sound pressure data from the microphone

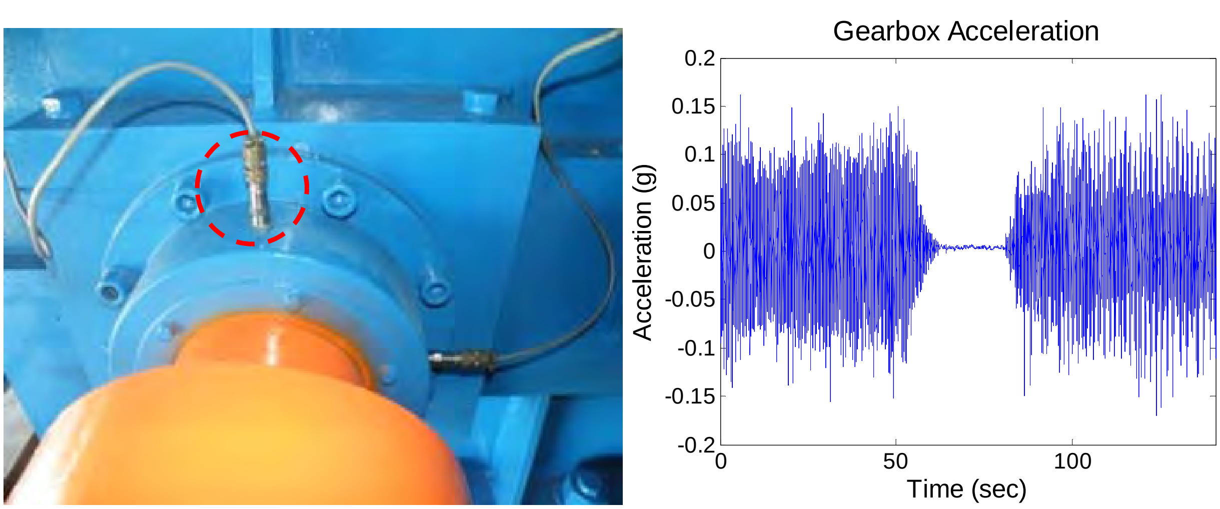

Figure 9: Installed gearbox accelerometer and sample data from vertical accelerometer

The gear boxes contain the assembly that transmits the torque generated by the motor to the shafts, similar to a differential. When the gear boxes suffer deterioration, or lack proper lubrication, some change in the sound during operation is noted and to detect this specific anomaly a microphone is used (Figure 8). Oil viscosity is also an important parameter for the proper functioning of the gear box. Similar to the electrical motors, abnormal vibration is an indicator of wear in the gears. In Figure 9, installed gear box accelerometer and sample data is shown.

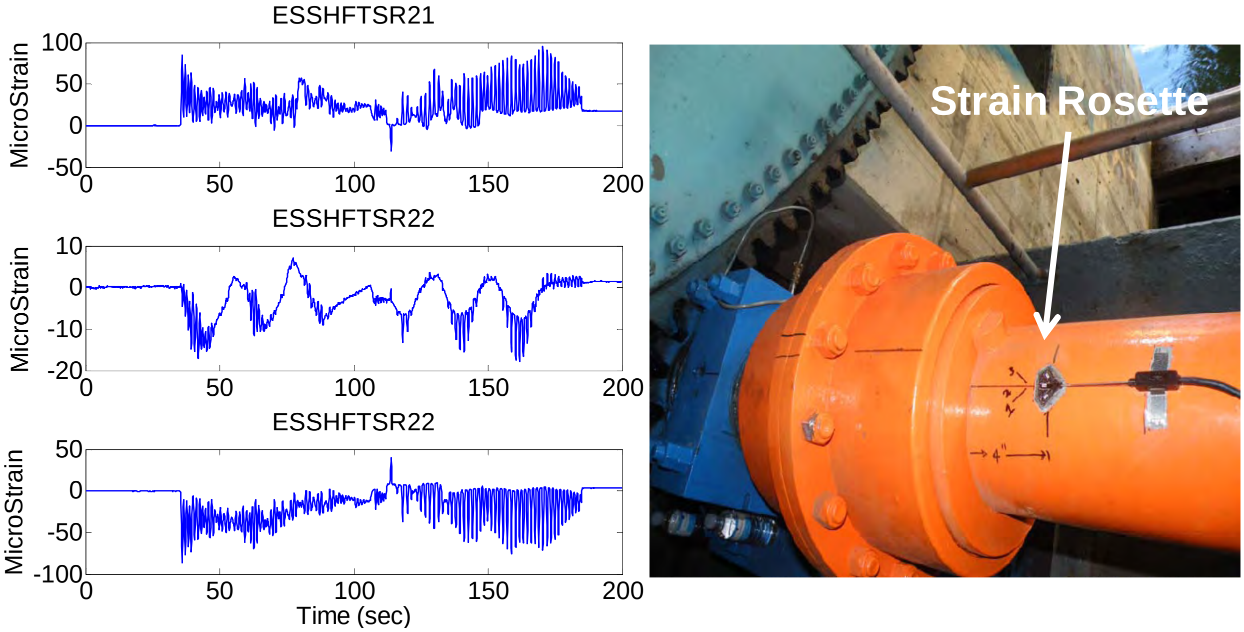

Figure 10: Strain rosette on the shaft and sample data from strain rosette

The gear box torque is transferred to the pinion, the final gear on the mechanical assembly, through the drive shafts. Opening and closing torques are critical for balance problems. Strain rosettes were installed to these drive shafts to calculate the friction numbers [3]. Typical strain rosette data during opening/closing can be seen in Figure 10. Another important part for friction calculation is the rotation. Trunnions are the pivot points of the leaves; therefore, for their operation they need proper lubrication at all times. During opening and closing, even a perfectly tuned and maintained leaf is expected to show some friction. FDOT maintenance engineers indicated that by experience, trunnion lubrication is a major factor for friction. Sample tilt data can be seen in Figure 3.

The open gears are the main gears, which are part of the leaf main girder and receive the torque from the pinion. The usual rack-pinion type bascule bridges have the rack assemblies directly below the main girder. Excessive strain, out-of-plane rotation and misalignment are common problems for open girders. The loading sequence problems mean that the drive shafts begin rotation in delayed sequence. This has an adverse effect on the condition of the open girders, usually by causing impact loading. Rack and pinnion was instrumented with an accelerometer (Figure 11).

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. Lack of lubrication and areas of corrosion can also be determined through use of computer vision algorithms. A video camera was positioned within sight off the teeth of the open gear (Figure 12). Different computer vision algorithms can run in real time to process the image and detect regions lacking lubrication or showing corrosion.

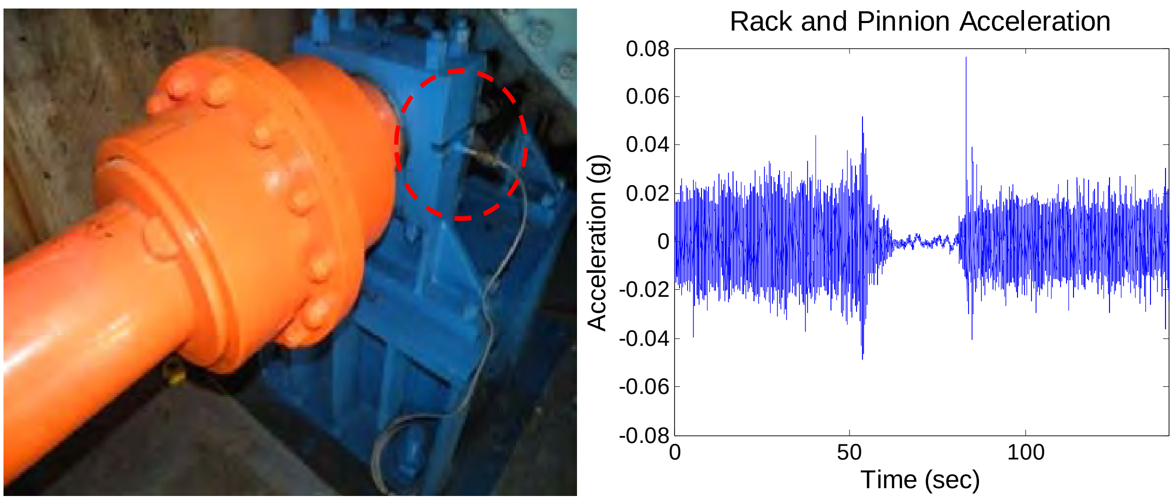

Figure 11: Rack and pinnion and the sample acceleration data

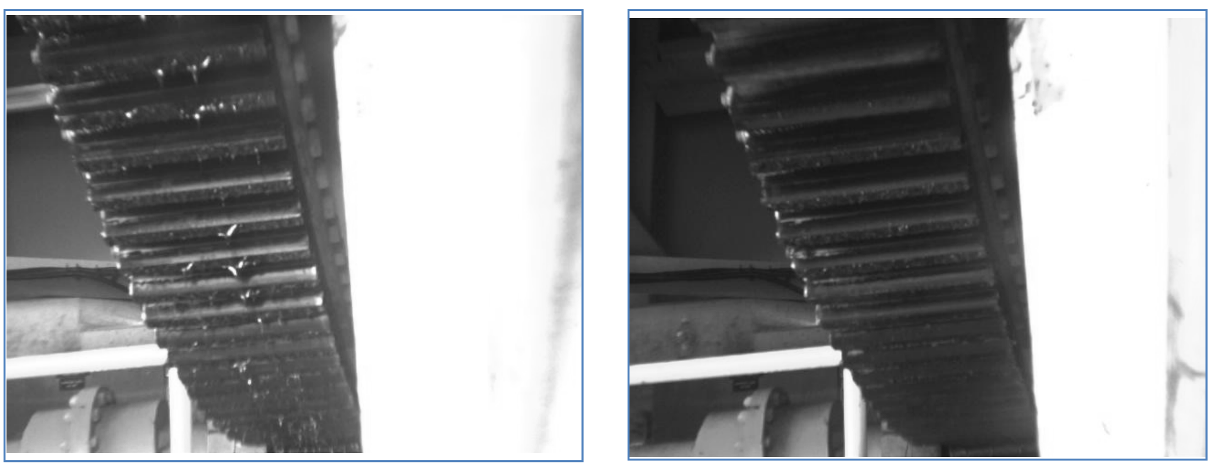

Figure 12: Open Gear with proper lubrication (left) and with lack of lubrication (right)

Data Acquisition and Communication

The data acquisition system (DAS), which includes sensors, data acquisition systems, signal processing, synchronization, and storage of the data, is a critical component of a structural health monitoring system. The data from the sensors is transmitted either with a cable or wireless connection to the data acquisition unit. The goal is to have good quality data to be received without any time delay or loss of information. One of the most challenging aspects of data acquisition is handling different types of sensors, rates, and signals at the same time. DAS varies depending on the monitoring objectives and applications.

In this application, the data acquisition equipment is installed in permanent protective and temperature-humidity-controlled-enclosures located in both machinery rooms at each side of the bridge. The sensors are connected by weather proof cables and specially designed connectors. Since the two leaves of the movable bridge are physically separated from each other, wireless communication is provided to ensure the data transmission between the leaves of the bridge, and two GPS units are used for synchronization. Figure 13 shows the scheme used for the data transmission.

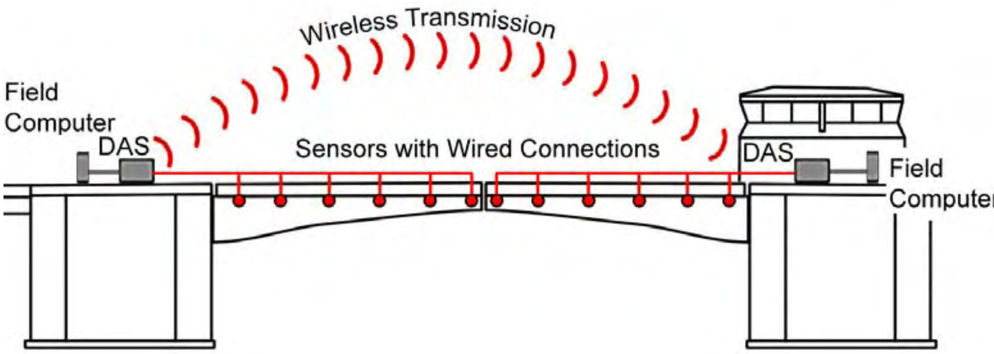

Figure 13: Scheme used for data transmission

Table 1: Summary of the Sensors

Sensor type	Structural Sensors	Mechanical and Electrical Sensors	Total
High-speed Strain Gage	36	0	36
Vibrating Wire Strain Gage	36	0	36
Strain Rosette	6	16	22
Tiltmeter	4	4	8
Accelerometer	16	24	40
Pressure Gage	0	4	4
Microphone	0	6	6
Infrared Temperature	0	2	2
Video Camera	1	1	2
Ampmeter	0	3	6
Weather Station	1	0	1
Total	100	60	160

The instrumentation plan is designed to monitor the most critical electrical, mechanical, and structural components. The current installation consists of an array of 160 sensors which add up to 200+ channels. In addition, a weather station to monitor the environmental factors is also installed. A summary of the sensors used in the study is shown in Table 1.

Field Implementation and Challenges

The technical challenges associated with field implementation of a SHM program for bridges are commonly related to installation, operation, and maintenance of the various components of the monitoring system as well as the coordination and cooperation with the bridge owners, coast guards, contractors, and users. Ideally, an SHM system should be designed to operate accurately and reliably with minimal maintenance for the entire duration for which the bridge will be monitored. Meeting this standard requires a careful consideration of the various issues and incorporating some degree of flexibility and redundancy to the system during its initial design. Another major challenge in the implementation of SHM system in real life is the coordination of fieldwork with infrastructure owners in such a way that the sensors and cables installation impacts the land and maritime traffic minimally. Since it is a movable bridge application, the sensor installation was delayed many times by the bridge openings (Figure 14). FDOT engineers have facilitated the coordination of the field work among several agencies.

Figure 14: Instrumentation under the bridge and a bridge opening

Conclusions and Recommendations

The structural health monitoring system presented in this paper serves as a demonstration of an integrated system that is designed to monitor structural, mechanical and electrical components of a movable bridge. Such an implementation offers promise for improved condition assessment and can complement current bridge management systems. After monitoring the bridge for a sufficiently long period of time (e.g. a year or more), we expect to identify and reduce the overall instrumentation to the most critical measurements so that an optimum monitoring system can be developed for a system-wide application to movable bridges in Florida. An application such as described in this paper can be expected to mitigate both problems and maintenance costs. Further studies and pilot applications are necessary to evaluate the real life performance of technologies and methods as well as to quantify the cost-benefit ratio of integrated SHM applications.

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