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Self-Contained Structural Health Monitoring System for Repairing Bolted Connections

Mana Afshari, Dao Zhou, Guillaume Verdier, and Daniel J. Inman
Railway Technologies Laboratory, Center for Vehicle Systems & Safety, Virginia Tech

Summary

The feasibility of autonomous monitoring and repair of bolted connections in railway applications was evaluated by Virginia Tech University under sponsorship of the Association of American Railroads' Technology Scanning Strategic Research Initiatives Program. This method of monitoring was shown to be self-contained; i.e., it is sensitive to the damage in the structure, is capable of self-diagnosing and self-repairing, and provides the required power for the system.

In laboratory simulations, switch throw rod bolts were monitored for changes in clamping force. Using shape memory alloy washers, loosened bolts were retightened (i.e., clamping force was restored) by the monitoring system. This type of monitoring system has the potential advantages of improving system safety and reliability by monitoring and automatically repairing essential bolted connections.

The integrity of bolted connections on the railroad is essential for safe and reliable operations. Today these connections are typically inspected visually. For track components, these inspections are done every few days during track inspections as required by Federal Track Safety Standards. Under train operations and weather conditions found in the field, these connections can be loosened over time and with accumulated tonnage.

As a demonstration, a switch throw rod connection was selected for laboratory testing. This connection, consisting of more than one bolt, is essential to the proper operation of a turnout.

Using piezoelectric materials as sensors and actuators, an impedance-based structural health monitoring method system was tested on the full-scale railroad switch built at the Center for Intelligent Material Systems and Structures at Virginia Tech University. This method was shown to be able to detect the loosening of switch bolts for as low as 25 ft-lbs of loosening, which corresponds to merely 1/10th of a bolt turn.[1] With the ability of detecting the loosening of the bolted joints in railroad switches, the concept of self-healing bolted joints was proposed to automatically retighten loosened bolts to their prescribed functional conditions.[1] At the end, in order to enable a self-powered system, the two aspects of (1) reducing the required computational energy of the method and (2) examining ambient energy harvesting were implemented.

INTRODUCTION

Impedance-based structural health monitoring (SHM) is possible through monitoring changes in the measured, high-frequency electrical impedance of small, self-sensing piezoceramic (PZT) patches. This method works through coupling between the electrical impedance of the PZT patches bonded to the host structure and the mechanical impedances of the PZT and the host structure itself.[2]

The measured impedance of the PZT patches provides useful data regarding the health of the host structure. However, the data in its unprocessed, original state does not provide quantifiable information regarding the presence and the state of the damage within the structure. Therefore, by processing the measured signal, an index needs to be extracted that is sensitive to the damage and insensitive to the other parameters, such as temperature variations and humidity.

RESEARCH APPROACH

Figure 1 shows the full-scale prototype of a railroad switch that was made for investigating the impedance-based SHM method in monitoring the bolted joints in railroad switches. This prototype was machined from A36 steel with a Young's modulus of 29,000 kpsi (200 GPa); close to that of the R260 steel. The two parts of the switch rods were insulated using fiberglass insulation paper, 1/8 inch thick, 16 inches wide and 10 inches long. The self-sensing parts of the impedance-based SHM are the PZT patches. Wired, circular wafers of these PZTs were used in the impedance measurements in the experimental setup.

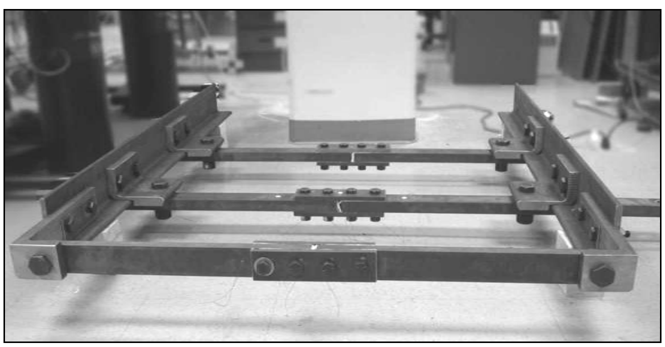

Figure 1. Prototype Railroad Switch with Bolted Joints

Being able to detect the loosening of the switch bolts, the self-healing method was applied in order to complete the health monitoring process by offering a healing solution. The self-healing concept combines health monitoring techniques and smart actuators to restore tension in a loose bolt. The concept of self-healing bolted joints was initially examined by Muntges et al.[3] and further investigated by Peairs et al.,[4] successfully demonstrating that a shape memory alloy (SMA) washer could be used to restore preload in a bolted joint.

A set of experiments was performed on the lock rod of the railroad switch prototype in order to investigate the applicability of a self-healing bolted joint method. The rod consisted of two long-beam segments connected at the center by two symmetric plates and four bolts. One of the bolts was reassembled with the self-repairing bolt, as Figure 2 shows.[1]

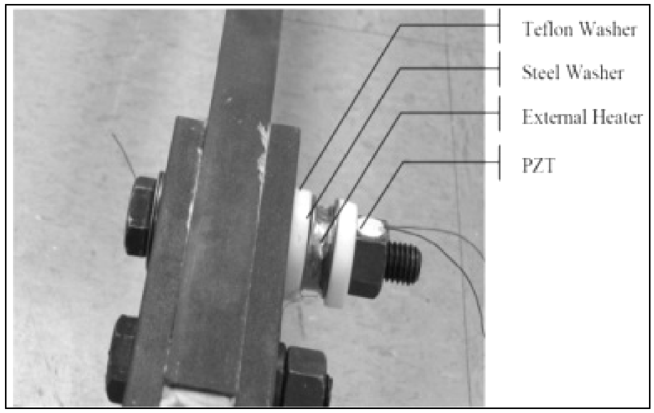

Figure 2. SMA Self-repairing Bolted Joint

First, the computational power consumption of the system had to be reduced to provide the power required for the proposed monitoring and healing method. This was done by eliminating digital-to-analog converter (DAC) and analog-to-digital converter (ADC) by using digital excitation signal and phase detection. Based on this concept, a SHM system with self-healing function was assembled, as Figure 3 shows. This system can automatically detect damage and heal until the initial condition is recovered. Also, it is fully monitored and controlled with software and results in a 30-percent reduction in required energy (as compared to systems with DACs and ADCs). This system requires 5-volt (V) input, 1.5 watt (W) for SHM operation, 10V-12.5W power input for self-healing process, and is powered by lithium-ion (Li-ion) battery with power converters.

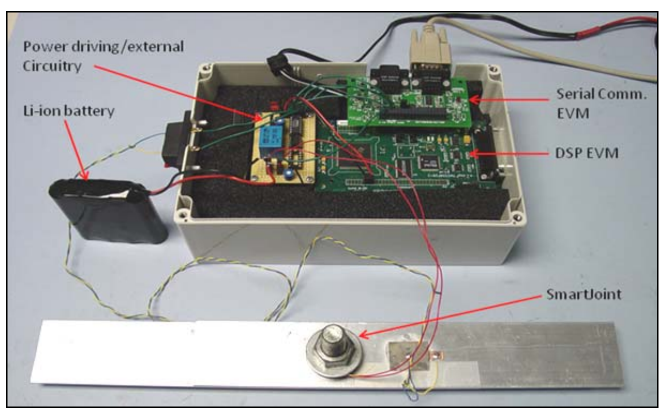

Figure 3. First Prototype SHM System with Self-healing Function

Energy Harvesting

As for the last part of the self-contained health monitoring setup, the energy is harvested from the ambient. The two sources of energy feasible to be harvested for the SHM setup were photovoltaic and thermal electric.

The first part of the energy harvesting setup uses solar panels to harvest solar energy for charging the Li-ion battery, as Figure 4 shows. The energy harvested using this method was sufficient for monitoring the loosening of bolted joints.

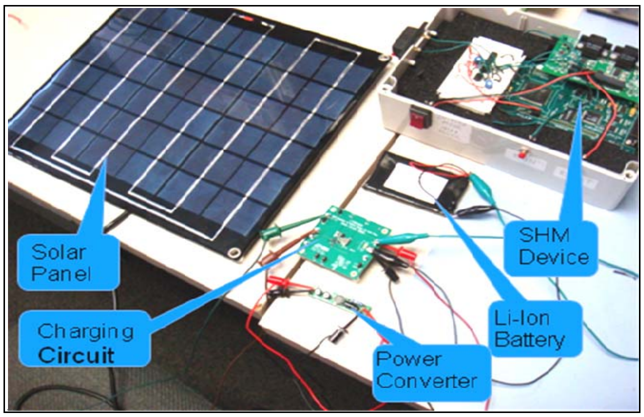

Figure 4. Schematic of the Solar Energy Harvester used for Charging a Li-ion Battery

Also, line side power at mainline switches is often available and can be used to power the monitoring system.

Detecting the Loosening of Bolts using the Electrical Impedance Method

In order to detect the loosening of the switch bolts, the electrical impedance of the PZT's bonded to the nuts were measured using the HP 4194A impedance analyzer. Switch bolts are loosened to different torques and the damage index of each state was calculated based on a comparison of the two impedance signatures of the intact bolt (before loosening) and the loosened bolt. The damage metric used here was the root mean square deviation (RMSD),[5] as Figure 5 shows.

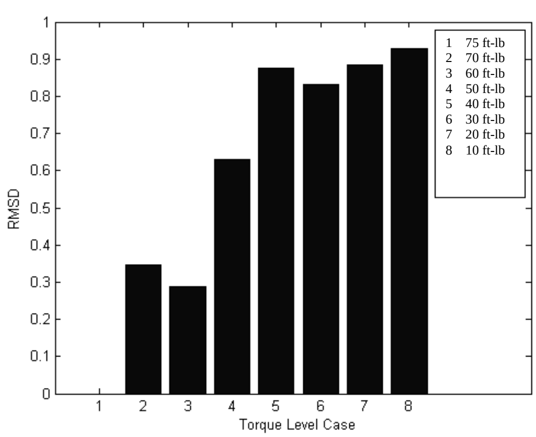

Figure 5. RMSD Damage Metric for Different Torque Levels

Self-healing Switch Bolt Experiment

The bolted joint was initially tightened to 75 ft-lbs and the on-nut PZT's electrical impedance was measured. Then, the joint was loosened to 10 ft-lbs (a quarter of a turn), and the electrical impedance was measured again. The resistive wire was connected to a direct current power supply (Agilient E3648A 0-8V 5A / 0-20V 2.5A). The voltage and current were set to 16 V and 2 A, respectively. The wire instantly turned red and using a noncontact infrared thermometer (Craftsman 82327), the washer temperature was measured at 328.73°F (438 K). Heating was maintained at this temperature for about 5 minutes to ensure the SMA washer completed actuation.

The RMSD values show that the SMA washer actuation was able to bring the loosened bolt close to its original tightened status, as Figure 6 shows. Thus, the actuation was partially successful in restoring the lost preload in the joint. A joint torque of 50 ft-lbs was measured after the actuation.

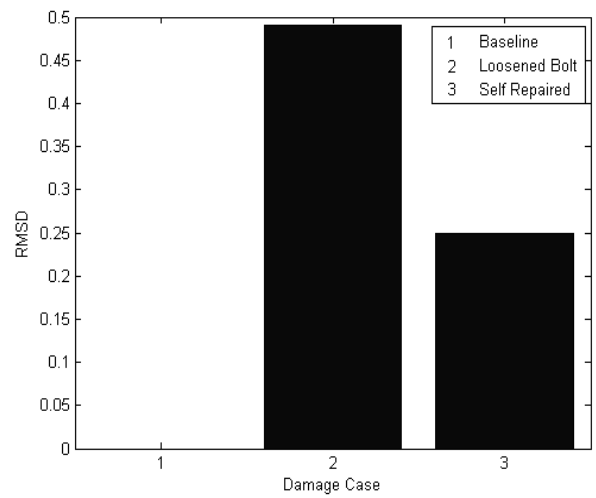

Figure 6. Self-healing Bolted Joint RMSD Metric

Voltage output from the solar panels was measured to be up to 21 V. Less than 2 hours is required to charge a 1,800-mAh two-cell Li-ion battery from 6.5 V to 7.8 V during a sunny day, using the solar panel setup shown in Figure 4. Testing this energy harvester setup with bolted joints on rail structures confirmed its capability to detect loose bolts.

CONCLUSIONS

The impedance-based SHM technique was applied for monitoring the loosening of bolted joints in a full-scale railroad switch. It was shown that a quarter of a turn of a bolt could be clearly detected by measuring the electrical impedance of a PZT patch at the bolted connection. Also, the experimental results showed that the proposed damage detection method could unmistakably detect the damage when the bolt assembly was loosened by 25 ft-lbs, which corresponds to merely 1/10th of a bolt turn, with the damage index value way above the damage detection threshold assigned experimentally.

Once the loosening of the bolted joint was detected, the self-healing concept was applied. It was shown that, by using a SMA washer as the actuator, a loosened bolt could be tightened back to the preload. Integrating the self-repairing concept with the impedance-based SHM, the inspection and a portion of the required maintenance for the switch can be fully automated.

The required computational energy of the SHM technique was reduced by eliminating DACs and ADCs and using digital excitation signal and phase detection. Moreover, solar energy was harvested using solar panels. The harvested energy charged the battery required for the SHM system. Thus, a self-contained SHM system for detecting and repairing the loosening of bolted joints in railroad switches has been demonstrated. A field test of the SHM system is the next step in this research.

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