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Impedance-based Structural Health Monitoring for Insulated Rail Joints

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Summary

Virginia Tech, an AAR Affiliated Laboratory, investigated the feasibility of utilizing impedance-based structural health monitoring (SHM) for insulated rail joints (IJs). Laboratory and in-field experiments were conducted and results showed that some joint-related defects can be successfully detected using the proposed SHM techniques.

Impedance-based SHM utilizes piezoelectric materials as collocated sensors and actuators. The coupled electromechanical characteristics of this class of materials provide insights about the mechanical characteristics of the structure through the easily measured electrical impedance. The capabilities of impedance-based SHM to detect several joint-related defects, including rail wear, torque loss, and joint bar breakage, were demonstrated on laboratory-scale and full-scale IJs. Several aspects pertaining to the practical implementation of these techniques, including optimal excitation frequency, sensor placement, sensor protection, damping effects, and environmental conditions, were thoroughly investigated. Laboratory experiments showed that all of the previously mentioned joint-related defects can be successfully detected using the proposed SHM technique. In-field experiments were conducted at the Facility for Accelerated Service Testing at the Transportation Technology Center track to assess the performance of this technique under railroad operating conditions. Torque loss in the bolted joint was successfully detected in the field. Degradation-sensitive features were identified to distinguish torque loss effects from those induced by temperature variations. Other types of defects were not able to be detected in track due to effects of ties and other conditions.

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INTRODUCTION

This digest provides a detailed discussion of the experimental work Virginia Tech conducted to evaluate the feasibility of impedance-based structural health monitoring (SHM) for insulated rail joints (IJs). Laboratory and in-field experiments were conducted and showed that some joint-related defects can be successfully detected using the proposed SHM techniques, which include optimal excitation frequency, sensor placement, sensor protection, damping effects, and excitation level.

BACKGROUND

Track defects, in the form of mechanical failure of track components or thermally induced buckling of rail sections, are considered a major safety concern for the railroad industry. Current rail inspection techniques rely mainly on ultrasonic measurements, which have proven successful for detecting anomalies in rails, but they are not suited for testing rail in joints and switches.

On railroad tracks, IJs are used for signaling, where adjacent rail sections are held together by these joints while remaining electrically insulated.[1] A bolted IJ consists of two joint bars bolted to rail sections with six or eight bolts. All joint components are electrically insulated and glued together with a high-stiffness adhesive. The lower vertical stiffness at joint locations renders them more susceptible to failure under load.

Impedance-based SHM has emerged as a promising non-destructive tool for real-time structural damage assessment. It utilizes piezoceramics as collocated sensors and actuators.[2] The electrical impedance of the piezoelectric transducer is directly related to the mechanical impedance of the host structure.[3,4] Therefore, variations in the host structure, as a result of structural defects, are reflected on the electrical impedance of the piezoelectric transducers, and thus, can be detected and identified.[5,6] This technique has been successfully applied to monitor changes in the structural integrity of numerous components and structures.[7]

Impedance-based SHM

Impedance-based SHM relies on changes in the dynamic response of the structure to detect and identify structural defects. This technique utilizes piezoelectric transducers to simultaneously excite the structure and measure its response. Making use of the coupled electromechanical characteristics of piezoelectric materials, the mechanical impedance of the host structure is directly related to the electrical impedance of the piezoelectric transducer (Figure 1).

Variations in the dynamic response of the host structure, due to structural defects, material degradation, or changes in connectivity, are reflected on the electrical impedance of the piezoelectric transducer. Degradation can then be detected by comparing the impedance signature of the structure to a baseline signature. In this work, two metrics most commonly used for impedance-based SHM are utilized; these are the root mean square deviation (RMSD) and correlation coefficient defined in reference.[8]

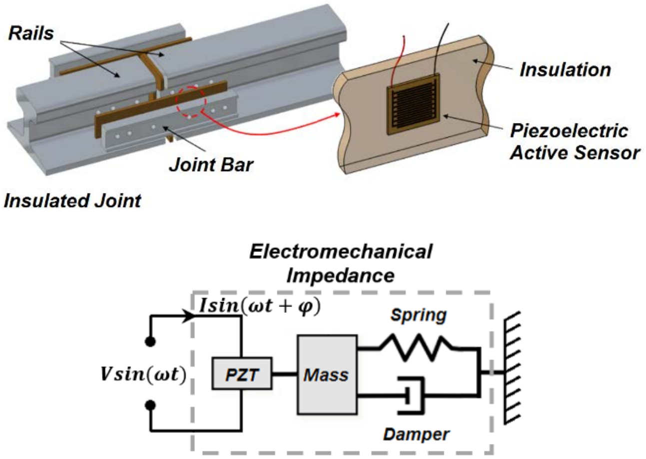

Figure 1. (top) Piezoelectric-augmented IJ for impedance-based SHM and (bottom) concept of electromechanical impedance

Laboratory-scale IJ Experiments

A laboratory-scale IJ was designed and tested to conduct an initial assessment of the performance of impedance-based SHM. To facilitate impedance measurements, the IJ was instrumented with Macro Fiber Composite (MFC) piezoelectric active sensors.

Using this laboratory-scale IJ, experiments were conducted to assess the capabilities of impedance-based SHM in detecting several types of joint related damages and determine optimal transducer configurations. Four damage types were identified: rail damage, joint bar damage, torque loss, and insulation failure. Sensors attached to the inner surface of the joint bar were found to be sensitive to joint bar damage and torque loss in the IJ, and sensors attached to the rail web were found to be sensitive to rail damage.

Full-scale IJ Instrumentation and Assembly

At Norfolk Southern Railway testing facilities in Virginia, a full-scale IJ and its corresponding rail sections were assembled and instrumented for in-field testing. The IJ consisted of 4 feet 11 inches and 10 feet 5 inches long 136RE rail sections connected together with a Koppers IJ kit. The IJ kit consisted of two joint bars, 3 feet long, with a pre-attached insulating mesh (Figure 2). The IJ bars were attached to the rail with six bolts and ES39-6 industrial grade epoxy. The kit also included plastic inserts for the insulation of rail sections and bolts.

Figure 2. Koppers IJ kit compatible with 136RE rail section

Individual joint components were first instrumented with MFC and monolithic piezoelectric active sensors. Rail sensors were placed at the area that was later covered by joint bars upon the joint assembly (Figure 3). Although this placed significant pressure on the MFC transducers, it provided permanent protection and supported the bonding between the MFCs and the rail. All sensors that were attached to free surfaces, as in the case for the joint bar and the instrumented bolts, were coated with ES39-6 industrial grade epoxy.

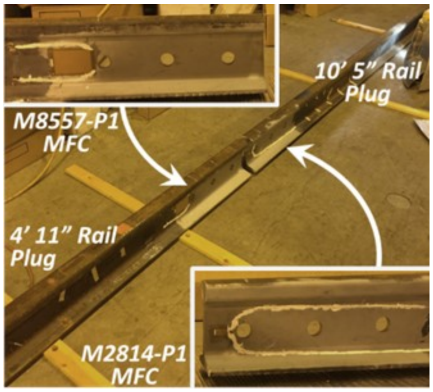

Figure 3. Instrumented rail sections for in-field testing

Frequency Range Selection

The frequency range significantly affects the sensitivity of impedance-based SHM. In order to identify the optimal frequency range for each damage type, impedance signatures of the components were measured over the frequency range of 10-100 kHz, with 10 Hz resolution. Damage was then introduced to each component in a reversible manner, and impedance signatures were measured again. This frequency range was then subdivided into 5 kHz intervals and damage metrics were calculated for each interval (Figure 4).

Rail impedance signature was found to be highly sensitive to railhead damage over the frequency range of 20-30 kHz. On the other hand, multiple frequency ranges were found to be sensitive to torque loss damage type. The frequency range of 50-55 kHz yielded the largest RMSD value, whereas the frequency range of 65-75 kHz yielded the largest correlation coefficient value.

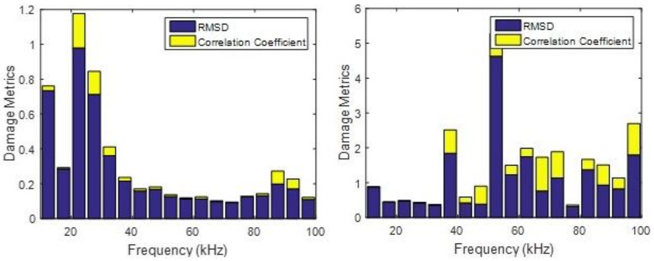

Figure 4. Damage metrics calculated for (left) rail damage, and (right) torque loss

Figure 5 (left) depicts the impedance signature measured using the piezoelectric disk attached to the bolt's head. All measurements were conducted at room temperature; thus, changes in impedance signature are merely due to torque loss. The effects of torque loss on impedance signatures are clearly detectable (Figure 5 right).

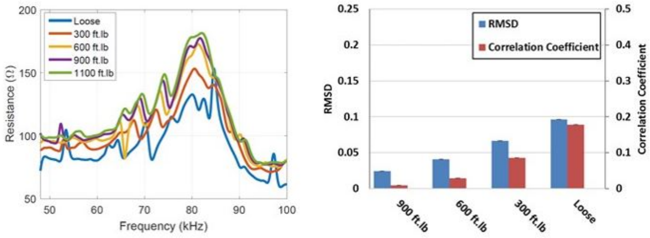

Figure 5. (left) The electromechanical impedance of a bolt measured at several torque levels, and (right) the corresponding damage metrics

Impedance-based SHM Performance at FAST

The instrumented IJ was installed on track at FAST to investigate impedance-based SHM under railroad operating conditions. A total of 12 sets of baseline measurements were carried out. Eight baseline sets were measured. An 111,000-pound on-track welder was then rolled over the joint, as shown in Figure 6, and four other sets of baselines were measured. Table 1 shows the time at which each baseline set was measured, along with the rail temperature and longitudinal stress at the time of measurement. Since the IJ is fully constrained by the surrounding track, baselines measured at different times during the day were not only affected by temperature variations, but also by the variations in rail longitudinal stress.

Figure 6. In-field loading experiment showing (left) the welder used to load the IJ, and (right) the wheels loading the IJ

Impedance signatures measured at the rail section were found to be strongly dominated by the dielectric characteristics of the MFC active sensor without any clear impedance peaks. This drastic change compared to the response measured prior to joint installation can be ascribed to the added damping as the rail is connected to the ties underneath. Therefore, impedance signatures measured at the rail section cannot be used for SHM practices, as they do not carry clear information about the dynamic response of the structure. This limitation is expected to be common among all steady-state vibration-based damage identification techniques.

Table 1. Rail temperature and longitudinal stress at the time of baseline measurements

Baseline No.	Measurement Time	Temperature (°C)	Longitudinal Stress (MPa)
Baseline 1	7:45	18 ± 0.5	760
Baseline 2	8:45	21.5 ± 0.5	685
Baseline 3	9:40	28.5 ± 1	535
Baseline 4	10:35	36.5 ± 0.5	385
Baseline 5	11:30	39.5 ± 0.5	300
Baseline 6	12:25	44 ± 0.5	205
Baseline 7	13:10	48.5 ± 0.5	115
Baseline 8	13:45	51	35
Loaded 1	14:35	44.5	70
Unloaded 1	15:05	43 ± 1	130
Loaded 2	15:25	41	165
Unloaded 2	15:50	42 ± 1	185

Torque loss, on the other hand, was successfully detected for the fully assembled joint, as discussed in the previous section. Figure 7 shows the effects of temperature variations on the impedance signature of the instrumented bolts (for a subset of the baselines given by Table 1). As the rail temperature increases, the rail approaches the neutral state. The combined effect of temperature-stress variations appears as changes in the magnitude and slope of the measured impedance signatures. This, in turn, is reflected on the calculated damage metrics, as shown in Figure 7 (right). Similar trends have been observed for the other instrumented-bolts.

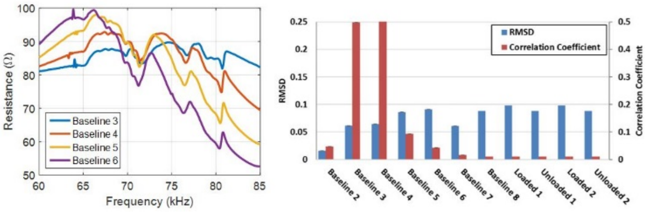

Figure 7. (left) Impedance signatures (right) damage metrics

In spite of the significant change in baseline signatures due to temperature variations, only minimal changes in impedance peaks frequency have been observed. Torque loss, on the other hand, resulted in a clear shift in impedance peaks. Tracking a single peak in the impedance signature, the one at 70 kHz for example, reveals that as the torque is increased, impedance peaks frequency increases monotonically. This indicates an increase in the bolt's stiffness with tensile loading. Thus, tracking impedance peaks, rather than relying on conventional damage metric definitions, allows the distinction between the effects of operating and environmental conditions and those induced by structural damage.

CONCLUSION

Virginia Tech, an AAR Affiliated Laboratory, investigated the feasibility of using impedance-based SHM for IJs. Laboratory and in-field experiments were conducted and showed that bolt torque defects can be successfully detected using the proposed SHM technique.

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