Global and Local Health Monitoring of Plate-Girder Bridges under Uncertain Temperature Conditions

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Abstract

Even significant damage may cause very small changes in structural characteristics, particularly for large structures. Furthermore, these changes may go undetected due to changes in environmental and operational conditions. In this paper, the temperature-driven variability on a combined structural health monitoring (SHM) system is examined in a model plate-girder bridge. The combined SHM system consists of a global vibration-based technique and local electro-mechanical impedance (EMI) based technique. First, dynamic modal parameters of the test structure are measured before and after the occurrence of flexural cracks at various temperatures. Also, EMI signatures are sensed before and after the changes in support systems at various temperatures. Next, the risk of damage-occurrence in the structure is alarmed by statistical pattern recognition of the signals. Damage-induced changes in the signals are distinguished from temperature-driven uncertainty. The effect of temperature variability is also assessed to estimate the accuracy of damage detection.

Keywords: Global and local health monitoring, modal parameters, electro-mechanical impedance (EMI), temperature effect, plate-girder bridges

1. Introduction

During the past two decades, researchers have attempted to develop many structural health monitoring (SHM) techniques. A suitable SHM system is required to acquire structural response signals, to extract useful feature information from the signals, and to discriminate the feature information of identifying damage locations and severities in the structure. Global vibration-based techniques aim for detecting damage and estimating structural safety using changes in vibration characteristics (Kim and Stubbs, 2003). The most appealing feature associated with using modal parameters is that they are relatively simple to measure and to utilize for a prompt diagnosis. However, the feasibility of using them for damage detection is limited for at least two reasons. First, significant damage may cause very small changes in modal parameters, particularly for large structures. Furthermore, these changes may go undetected due to changes in environmental and operational conditions. Cornwell et al. (1999), Farrar et al. (2000), Peeters and De Roeck (2000), and Kim et al. (2004) reported extensive field experiments on the variability of dynamic properties of bridges caused by the changing environmental conditions. Based on their works, temperature differences are about 50°C during a year in a real-life situation of a bridge, and these changes can completely mask damage-induced changes in modal parameters of the structure.

The global vibration-based techniques rely very much on modal parameters of the first few modes. These modes are global but not sensitive enough to detect localized damage, such as incipient cracks or minor changes in support systems. Recently, local SHM techniques using smart materials such as piezoelectric ceramic (PZT) materials, shape-memory alloys, and optical fibers have been developed to detect the incipient-type local damage (Ayres et al., 1998; Kessler, 2002). The electro-mechanical impedance (EMI) technique which uses smart PZT has emerged as a valuable local SHM tool and implemented on several complex structures to detect incipient-type damage such as small cracks or loose connections at local points (Bhalla and Soh, 2003; Park et al., 2004). In this technique, a PZT patch is attached to the structure and a series of EMI signatures are sensed to make a diagnosis of the structure. However, there are also some problems to be solved before implementing this technique into real structures is possible. One of these problems is the temperature dependency of PZT materials which make difficult to distinguish from the damage-induced variation in EMI signatures (Park et al., 1998). Another problem is that a large number of PZT sensors are required in practical use since the sensing area of a single PZT sensor is very small.

A promising SHM system, to date, is a combination of

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global vibration-based techniques and local EMI-based techniques. Despite the aforementioned research efforts, however, two key issues are existed and must be solved before the combined SHM system is implemented into real structures (Ayres et al., 1998; Peeters, 2000; Farrar et al., 2000; Bhatia and Soh, 2003; Kim and Stubbs, 2003). The first challenge is “Does the change come from damage, temperature, or others?” The temperature-driven variability of structural response data should be quantified in the determination of features such as modal parameters or impedance signatures. For instance, boundary conditions and material constants of both sensor materials and structures are temperature-dependent. Therefore, an issue arises on how to distinguish the temperature-induced variability on feature extraction. The second challenge is “Does the detection reproduce correct results?” The detected output may be true, false-positive, or false-negative. Even in the true case, moreover, damage-localization error and severity-estimation error are inevitable due to the temperature effect. The effect of temperature on the accuracy of damage detection should be quantified in the determination of damage-occurrence, the localization and the severity estimation of damage. As a matter of course, another issue arises on how to discriminate the correct damage alarms from the temperature-driven false alarms in damage prediction results.

In this paper, the temperature-driven variability on a combined structural health monitoring (SHM) system is examined in a model plate-girder bridge. The combined SHM system consists of global vibration-based technique and local EMI-based technique. First, dynamic modal parameters of the test structure are measured before and after the occurrences of flexural cracks at various temperatures. Also, EMI signatures are sensed before and after the changes in support systems at various temperatures. Next, the risk of damage-occurrence in the structure is alarmed by statistical pattern recognition of the signals. Damage-induced changes in the signals are distinguished from temperature-driven uncertainty. The effect of temperature variability is also assessed to estimate the accuracy of damage detection.

2. Experiment on Model Plate-girder Bridge

2.1. Description of test structure

The test structure is a single-span, stainless steel, plate-girder bridge model, as shown in Fig. 1. The bridge spans 2.0-m and is simply supported with a set of pin supports at the left edge and a set of roller supports at the other edge. The superstructure of the bridge consists of the deck, the deck supporting systems and piers. The deck consists of a 5-mm thick, 50-cm wide stainless steel plate. The deck supporting system consists of two, 13-cm deep stainless steel plate-girders and a set of rectangular stringer. The stringers are supported by a system of 3-mm thick, 30-mm deep floor beams. The girders are supported by piers. Each pier consists of a steel column and four steel rods to stabilize the column by piling onto a 12 cm × 22 cm × 72 cm steel block. The substructure consists of the four steel blocks and a system of steel frame basis.
2.2 Vibration test and modal parameters

Controlled vibration tests were set up on the structure to measure changes in dynamic responses caused by temperature and structural degradation. Figure 2 shows the locations and arrangements of the accelerometers for vibration tests. Eighteen accelerometers (i.e., Stations 1-9 along South Girder and Stations 10-18 along North Girder were selected to measure the modes. An accelerometer (Dytran 3101BG) was mounted to the girder at the mid-height of the web to measure the structure’s response accelerations at each sensor location. Forced vibration tests were conducted using a random input excited by a VTS-100 electromagnetic shaker. The shaker was located over the south girder directly above Station 6 in Fig. 2. An accelerometer mounted on the shaker tip was used to measure the force into the model bridge. One accelerometer was always positioned on Station 6 as the reference channel. After all, 8-channel signal analyzer SA-390 and a PC were set to compute power spectra and frequency response functions. As the third party software, the STAR-Modal by the Spectral Dynamics was employed to extract the modal parameters.

A series of forced vibration tests were performed on the model bridge as temperature varied between low −3°C and high 23°C. As shown in Fig. 3, baseline mode shapes of the first four modes were measured from the undamaged bridge model at the temperature of 23°C. Figures 3(a) and 3(c) are the first and the second bending modes and Figs. 3(b) and 3(d) are the first and the second torsional modes. Next, the undamaged structure was tested under twelve different temperature conditions. For each temperature case (e.g., −3°C), natural frequencies were repeatedly monitored by 10 times as shown in Fig. 4. The results of Fig. 4 demonstrate the relationship between temperatures and natural frequencies of the undamaged structure. As it goes to lower modes, the temperature has relatively higher effects on the change in natural frequency. In all modes, natural frequencies go down as the temperature goes up. Bending modes (i.e., modes 1 and 3) are more sensitive than torsional modes (i.e., modes 2 and 4). For each mode, an average frequency was calculated at each temperature step. Natural frequencies of the undamaged model bridge measured at 6 different temperatures (i.e., 0, 10, 20, 23, 25, and 30°C) are summarized in Table 1.

![Figure 3. Mode shapes of model plate-girder bridge.](image)

![Figure 4. Pre-damage temperature-frequency history at temperatures −2~26°C.](image)
Two levels of damage were inflicted to the front girder at 0.99-m location \((x/L = 0.495)\) near the center of the structure (0.99-m from the left edge) (see Fig. 5): (a) the bottom flange was cut halfway in from outside and (b) the bottom flange was cut completely in from either side. The cuts were introduced to the girder by sawing it about 2-mm width (see Fig. 5(b)). Then we identified and extracted modes, resonance frequencies, and mode shapes of the test structure. For each dam aging episode, a series of forced vibration tests were performed at the temperature of 23\(^\circ\)C. Accelerometer readings were taken at the eighteen stations shown in Fig. 2 and modal analyses were performed to extract the modal parameters. Natural frequencies of the two damage cases measured at 23\(^\circ\)C cases are summarized in Table 1. Mode shapes of the damaged structures are identical as shown in Fig. 3.

### Table 1. Pre-damage and post-damage natural frequencies of test structure at 0-30\(^\circ\)C

<table>
<thead>
<tr>
<th>Mode No</th>
<th>Pre-damage Natural Frequency (Hz)</th>
<th>Post-Damage Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0(^\circ)C</td>
<td>10(^\circ)C</td>
</tr>
<tr>
<td>1</td>
<td>76.150</td>
<td>71.822</td>
</tr>
<tr>
<td>2</td>
<td>101.455</td>
<td>98.320</td>
</tr>
<tr>
<td>3</td>
<td>212.223</td>
<td>203.694</td>
</tr>
<tr>
<td>4</td>
<td>295.347</td>
<td>289.123</td>
</tr>
</tbody>
</table>

![Damage inflicted in test structure.](image)

(a) Inflicted Damage 1 & Damage 2  
(b) Saw Cut of Flange

2.3. Electro-mechanical impedance signatures

The experimental setup for the EMI tests consists of the test structure, PZT transducers, an impedance analyzer, and a PC equipped with data acquisition software. The target member is the supporting “roller” device that carries loads from the upper girder to the lower pier. Two PZT patches of 1cm diameter are bonded on the target support member: one on vertical face and another on horizontal face nearby (about 1 cm apart) bolts as shown in Fig. 6(a) and 6(b). The vibrating PZT patch is assumed infinitesimally small as compared to the target structure and has negligible mass and stiffness. Also, the bonded area of the target structure is assumed to have uniform material properties so that the PZT patch can measure uniform impedance over the bonded surface. The distance from sensor to sensor is about 3 cm. They are connected...
The impedance signatures that consist of real and imaginary parts are extracted as functions of the exciting frequency. The complex admittance $Y$ (unit ohm$^{-1}$) consists of real and imaginary parts, the conductance ($G$) and the susceptance ($B$), respectively (Bhalla and Soh, 2003). These $G$ and $B$ are measured by the impedance analyzer. We imposed an alternating signal of 1 Volt rms to the bonded PZT sensor and recorded the magnitude and the phase of the steady state current in the form of $G$ and $B$.

A series of EMI tests were performed on the model bridge as temperature varied between low 3°C and high 23°C. As shown in Fig. 7, pre-damage EMI signatures $G$ and $B$ were tested from the undamaged structure when temperatures were 3, 10, 13, and 23°C. The results of Fig. 7(a) show that the conductance magnitude (identical to...
the admittance magnitude) increases as the temperature goes up. Note that the admittance is the inverse of the impedance. The results of Fig. 7(b) demonstrate that the resonant frequency of the vibrating PZT patch increases as the temperature goes up.

Damage was locally simulated to the south roller support which carries loads from the south girder to the pier. Two levels of damage were inflicted by constraining the roller’s longitudinal motions so that the roller was transformed into a hinge: (a) one out of four bolts was loosened and (b) two bolts were loosened. As shown in Fig. 8 and Fig. 9, post-damage EMI signatures G and B were measured at temperatures 10°C and 23°C, respectively, from the two damaged states. Both Fig. 8 and Fig. 9 show that the conductance magnitude and the resonance frequency change as damage occurs and no temperature changes.

3. Risk-alarming of Damage Occurrence

3.1. Temperature-natural frequency history

In the previous section, the modal parameters were extracted from the signals acquired from the test structure. In this section, the risk of damage-occurrence is alarmed by using signal-based pattern recognition techniques. The patterns of the signals are analyzed to distinguish damage-induced changes from temperature-induced changes in modal parameters.

As a signal-based feature, frequency-temperature history is assessed and the risk of damage-occurrence in the test structure is alarmed by distinguishing the damage-driven variation in natural frequency from the temperature-induced uncertainty. As described in Fig. 3, four vibration modes were measured for the test structure. For each mode, pre-damage natural frequencies were measured at 13 different temperature points between −2°C and 26°C. At each temperature point, natural frequencies were repeatedly monitored by 10 times, as depicted in Fig. 4. Assuming normal distribution, a probability density of natural frequencies was computed at each temperature point. For instance in mode 1, the 13 probability density curves corresponding to the 13 temperature points between −2°C and 26°C were plotted in Fig. 10. Each curve represents the variability of natural frequencies at the temperature point. All of probability density curves were standardized and averaged into a standard normal probability density curve. Figure 11(a)-11(d) are the standard normal probability density curves of the four modes. For example, Fig. 11(a) represents a statistical pattern recognition (PR) model with setting the lower and upper rejection-trigger values to −2.456 and 2.263 each other. The probable occurrence of the first natural frequency is within the rejection-trigger values. That is, beyond the rejection trigger is alarmed as the occurrence of damage risk.

Figure 10. Probability density curves of natural frequencies at 13 temperature points (Mode 1).

Figure 11. Standard normal probability density: statistical pattern recognition (PR) models of four modes.
On implementing the rejection-trigger values into the natural frequency histories, which are shown in Fig. 4, the statistical PR-models were obtained as shown in Fig. 12. In mode 1, the occurrence of both Damage 1 and Damage 2 could be alarmed as the post-damage natural frequencies measured at 23°C were mapped onto the PR-model, as illustrated in Fig. 12. In modes 2-4, however, only the occurrence of Damage 2 could be alarmed, since those modes’ PR-models fail to distinguish Damage 1 from the temperature-induced uncertainty.

3.2 Temperature-EMI signature history

The EMI signatures were acquired at various temperatures before and after damage, as described in the previous section. In this section, those signatures are analyzed statistically to extract features that can be utilized to alarm the risk of damage-occurrence. Resonance frequencies of EMI signatures extracted from the susceptance (B) signals, as shown in Figs. 7-9, are listed in Table 2. Any features other than the resonance frequencies could not be feasibly quantified due to the complicity of the susceptance (B) and conductance (G) signals. Note from Table 2 that the damage-induced variation is smaller than temperature-induced one.

In order to quantify the temperature-driven uncertainty and furthermore to adjust the damage-induced change in the EMI signatures, we estimated the linear relationship between EMI frequency and temperature, $\text{Freq}(\text{MHz}) = 0.0009T + 4.5554$, as shown in Fig. 13. The linear regression line represents a statistical PR model and it works to alarm the risk of damage-occurrence in the roller support by distinguishing the damage-driven variation in EMI signatures from the temperature-effect.

![Figure 12. Alarming damage on temperature-frequency history by statistical PR-model.](image1)

![Figure 13. Statistical PR-Model for temperature-EMI signature frequency.](image2)

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>Pristine</th>
<th>1 Bolt loosened</th>
<th>2 Bolts loosened</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>4.557</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>10</td>
<td>4.565</td>
<td>4.563</td>
<td>4.560</td>
</tr>
<tr>
<td>13</td>
<td>4.568</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>23</td>
<td>4.575</td>
<td>4.577</td>
<td>4.565</td>
</tr>
</tbody>
</table>
4. Summary and Conclusion

In this paper, the temperature-driven variability on a combined structural health monitoring (SHM) system was examined in a model plate-girder bridge. The combined SHM system consists of global vibration-based technique and local electro-mechanical impedance (EMI) based technique. First, dynamic modal parameters of the test structure were measured before and after the occurrences of flexural cracks at various temperatures. Also, EMI signatures were sensed before and after the changes in support systems at various temperatures. Next, the risk of damage-occurrence in the structure was alarmed by statistical pattern recognition of the signals. As the global SHM technique, temperature-natural frequency was assessed for the test structure under various temperatures before and after flexural cuts. Then the risk of damage-occurrence was alarmed by distinguishing the damage-induced variation in natural frequency from the temperature-driven uncertainty. As the local SHM technique, temperature-EMI signature frequency was assessed for the test structure under various temperatures before and after loosening bolts on a support system. The risk of damage-occurrence was alarmed by discriminating the temperature effect by a statistical regression model of temperature-EMI signature frequency.

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References