VIBRATION BASED TECHNIQUE FOR ON-LINE BRIDGE DIAGNOSTICS

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1. INTRODUCTION

On-line monitoring has become an attractive approach to detecting damage in a structure during its service time. Once damage is detected, necessary measures can be employed to ensure satisfactory system performance and to prevent drastic economic loss that may be caused by the damage. The present paper offers structural damage detection method based on changes in Transfer Function Estimate (TFE) for detecting damage, predicting its location and monitoring the growth in damage. This method assumes that the displacement or the acceleration response time histories at various locations along the structure both before and after damage are available for damage assessment. These responses are used to estimate TFE. The change of TFE between the baseline state and the current state is then used to identify the location of possible damage in the structure.

2. EXPERIMENTAL SETUP

The experimental work in this research was performed on a railway steel bridge that is no longer in service. The bridge is removed from its service location several years ago and is supported now on two wooden blocks. The owner of the bridge has granted us a permission to introduce some damage to the bridge such as releasing some bolts and tightening them again. However, introducing torch cuts to the bridge was not permitted. The bridge consists of two steel plate girders and two steel stringers support the train rails. Loads from the stringers are transferred to the plate girders by floor beams located at various intervals. The bridge dimensions and layout are shown in Fig. 1. The multi-layer piezoelectric actuator[1], [2] is used for local excitation. The actuator force amplitude is 200 N. Although this force amplitude is very small compared to the shaker force or ambient vibration, it was enough to excite the web of the main girder at the position of the farthest accelerometer. Two actuators are used for exciting the web of the main girder in the horizontal direction. The actuators are located at the upper part on the web of the main girder (Fig. 1). The excitation forces used for the undamaged and damaged structure are random, equal in amplitude and have the same vibration waveform but the excitation force does not need to be measured.

3. PROPOSED ALGORITHM

Let $T_{xr}(f)$ denote the TFE which relates a response $x(t)$ to a reference response $r(t)$. Since every channel will be used as a reference for other channels, $T_{rx}(f)$ will represent the TFE which relates a response $r(t)$ to a reference response $x(t)$. The relative TFE between x and r is defined as

$$R_{xr}(f) = T_{xr}(f) - T_{rx}(f)\,. \qquad (1)$$

$R_{xr}(f)$ represents the relative movement (response) between x and r in the frequency domain. If equal forces are used to excite the undamaged structure a number of times, then it is assumed that the same relative response, $R_{xr}(f)$, will be obtained each time. On the other hand, if damage occurs at (or near to) the location of x or r (or both), then the value of $R_{xr}(f)$ will in turn change. The absolute difference in absolute value of $R_{xr}(f)$ before and after damage can then be defined as

$$D_{xr}(f) = \left\| R_{xr}(f) \right| - \left| R^{*}_{xr}(f) \right\| \qquad (2)$$

where the asterisk denotes the damaged structure. When the change in relative TFE, $D_{xr}(f)$, is measured at different frequencies on the measurement range from f_1 to f_m, a matrix [$\mathbf{D_r}$] can be formulated as

$$\mathbf{D_r} = \begin{bmatrix} D_{1r}(f_1) & D_{1r}(f_2) & \cdots\cdots & D_{1r}(f_m) \\ D_{2r}(f_1) & D_{2r}(f_2) & \cdots\cdots & D_{2r}(f_m) \\ . & . & \cdots\cdots & . \\ . & . & \cdots\cdots & . \\ . & . & \cdots\cdots & . \\ D_{nr}(f_1) & D_{nr}(f_2) & \cdots\cdots & D_{nr}(f_m) \end{bmatrix}_r \qquad (3)$$

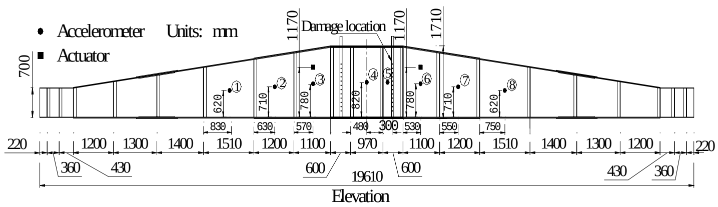

Fig. 1 Bridge layout and main dimensions

where n represents the number of measuring points and r represents the number of reference channel. In matrix [$\mathbf{D_r}$], every column represents the changes in $D_{xr}(f)$ at different measuring channels but at the same frequency value. Each measuring channel will be used as a reference for the other channels ($r = 1 : n$). Therefore, the matrix [$\mathbf{D_r}$] will be formulated n different times (3D matrix). The total change in the relative TFE in frequency range of f_1 to f_m can be estimated from the sum of rows of matrix [$\mathbf{D_r}$]. The sum of the changes in the relative TFE over different frequencies using different references can be used as the indicator of damage occurrence;

$$\mathbf{SST} = \sum_r \sum_f D_r\,. \qquad (4)$$

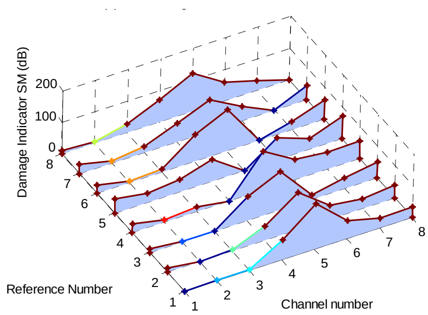

Fig. 2 Damage localization results using damage indicator SM

This indicator is used to detect the occurrence of damage and monitor the growth in damage; however it was found to be a weak indicator of damage localization. A number of statistical decision making approaches will be employed to determine the location of damage.

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The first step in this procedure is the selection of the maximum change in relative TFE at each frequency line (the maximum value in each column of matrix [$\mathbf{D_r}$]) and discarding all other changes in relative TFE measured at other nodes. For example in matrix [$\mathbf{D_r}$] (Eq. (3)), if $D_{3r}(f_1)$ is the maximum value in the first column then this value will be used as $M_{3r}(f_1)$ and other values in this column will be discarded. The same process is applied to the different columns in matrix [$\mathbf{D_r}$] to formulate the matrix of maximum changes of relative TFE at different frequencies, [$\mathbf{M_r}$]. It should be noted that [$\mathbf{M_r}$] is a 3D matrix where each value of r ($r = 1 : n$) formulates one matrix

$$\mathbf{M_r} = \begin{bmatrix} 0 & 0 & 0 & ..... & 0 \\ 0 & M_{2r}(f_2) & 0 & ..... & 0 \\ M_{3r}(f_1) & 0 & 0 & ..... & M_{3r}(f_m) \\ 0 & 0 & M_{4r}(f_3) & ..... & 0 \\ . & . & . & ..... & . \\ . & . & . & ..... & . \\ 0 & 0 & 0 & ..... & 0 \end{bmatrix}_r . \qquad (5)$$

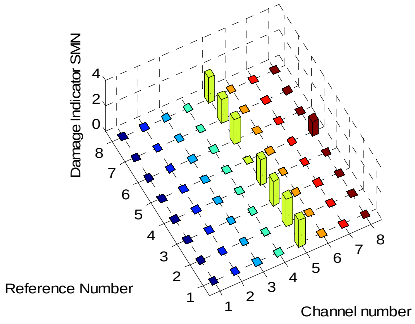

Fig. 3 Damage localization results using damage indicator SMN

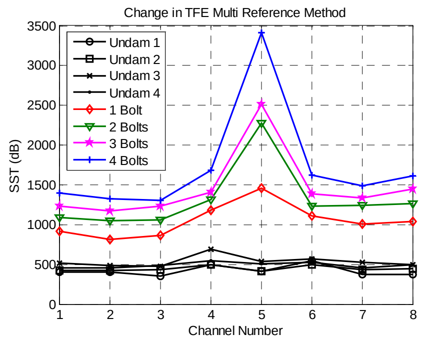

Fig. 4 Monitoring the growth in damage near to channel 5

The total of maximum changes in relative TFE is calculated from the sum of the rows of matrix [$\mathbf{M_r}$] using different references. At each value of r, the sum of rows of matrix [$\mathbf{M_r}$] will result in one vector. Therefore, n different vectors can be obtained;

$$\mathbf{SM}_r = \sum_f M_r \,. \qquad (6)$$

Assuming that the collection of the damage index {$\mathbf{SM}_r$} represents a sample population of a normally distributed random variable, a normalized damage localization indicator is obtained as follows

$$\mathbf{SMN_r} = \frac{\{SM_r\} - \overline{\beta}_r}{\sigma_r} \,. \qquad (7)$$

where β_r and σ_r represent the mean and standard deviation of the vector {$\mathbf{SM}_r$}. It should be noted that for each value of r , new values of β_r and σ_r are estimated. In order to reduce the effect of noise or measurement errors, a threshold level of one will be used. In vector {$\mathbf{SMN}_r$} values smaller than the threshold level will be discarded.

4. DAMAGE IDENTIFICATION RESULTS

The first level of damage is introduced to the bridge by removing the first bolt from the top of the right stiffener (near to channel 5). Fig. 2 shows the resulting values of {$\mathbf{SM_r}$}. At each reference number, the estimated values in each vector are drawn using waterfall curves. Although the values at the measuring channels are discrete, it was decided to use continuous line to connect them instead of using bars for better view of the results. In Fig. 2, the maximum reading is indicated accurately at channel 5 using various reference channels (except channel 5). However, the accuracy of detecting the damage at channel 5 depends slightly on the used reference. It should be noted that when one channel is used as a reference, it cannot be used to detect the damage at its location at the same time. For example, the reading at channel 7 at the reference number 7 equal 0. This is simply because $R_{xx} = R^*_{xx} = 0$ (Eq. (1)) and hence $D_{xx} = 0$ (Eq. (2)). In Fig. 2, although the maximum reading exists at channel 5 using various references, the readings at the undamaged locations sometimes degrade the accuracy of locating damage. It was, therefore, decided to create new damage localization indicator that can locate the damage more accurately. In the proposed damage localization indicator presented in Eq. (7), a threshold level of one is defined to eliminate the readings at the undamaged locations that usually results from the presence of noise or measurement errors. The values of {$\mathbf{SMN}_r$} below the threshold level are related to undamaged cases and the values above (or equal to) the threshold level identify a potentially damaged element. The resulting values of {$\mathbf{SMN}_r$} for this case of damage are shown in Fig. 3. Damage is located very accurately at channel 5 without any false positive readings at every reference channel except the reference number 5.
Four different combinations of TFE data obtained from the undamaged structure are used to estimate the values of **SST** as shown in Fig. 4 by the legend Undam1 – Undam4. The values of **SST** was determined using TFE data in the frequency range of 1–800 Hz. The total change in TFE ranged from about 400 to 600 dB. The estimated changes in TFE are obviously due to the presence of noise and measurement errors. The upper limit of this range can be used as a threshold for the damage indicator **SST**. It is then assumed that if **SST** exceeds the threshold limit, this will indicate the occurrence of damage. When the first level of damage is introduced to the bridge, the values of **SST** increased at most of channels to around 1000 dB and increased at the damage location to around 1500 dB, exceeding the threshold limit at all channels. The resulting damage indicator values of the damage indicator **SST** for four levels of actual damage – removing one to four bolts are shown Fig. 4 and indicated by the legends 1 Bolt through 4 Bolts, respectively. It is clearly indicated in this figure how the values of **SST** increase with increasing the damage level.

5. CONCLUSIONS

This paper presents the novelty detection technique for structural damage diagnosis, using TFE data. TFE is calculated from the acceleration response at every channel relative to a reference channel and every channel is used as a reference to other channels to create a large number of information. The technique presented here will allow the some progress in in-service monitoring of steel bridges where the acceleration data can be transferred via wireless methods and the piezoelectric actuators can be used for local excitation. The high detection performance, combined with the simple computation structure and the easy implementation could lead to a promising real-time damage detection system.

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