Damage Detection of Bridge using Wireless Sensors

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Abstract: Bridges are essential links in any surface transportation network. A damage to an important bridge may result in enduring economic loss due to partial or complete closure of the route in addition to the cost of repair or replacement. Also, survival of bridges are of utmost importance in the aftermath of a devastating earthquake in order to facilitate rescue operations. Therefore, it has become customary to carry out a critical assessment of safety and integrity of bridges in regular intervals as well as immediately after disastrous events such as an earthquake. The prevalent practice of bridge inspection requires checking of each and every component, which is experience-based, highly time consuming and an expensive process, often enforcing disruption in traffic flow. As a result, the wireless sensor-based inspection methodology is gaining popularity in recent times. This paper a presents a study to show the efficiency of a multi-hopped wireless sensor network (WSN) for remote health monitoring of bridge. Various vibration-based and feature-based output-only damage detection techniques are applied to show their efficacy in terms of determining the location and severity of damages using the data collected from the bridge under damaged and undamaged conditions.

Keywords: bridge health monitoring, wireless sensor network, damage localization, output-only techniques, damage detection features.

1. INTRODUCTION

In any surface transportation network, bridges are the key elements. In an island nation like Japan, the bridges play major role in connecting various separated locations. Thus, the safety and integrity of bridges are of utmost importance for a healthy transportation network of a nation. In current practice, the safety evaluation is performed by means of visual inspection, which is experience-based, highly time consuming and may be an expensive process. It is, therefore, important to develop and implement in bridges a faster and reliable method of safety evaluation process, especially for the post-disaster situations.

Recent advances in wireless sensor technology and structural health monitoring (SHM) algorithms show tremendous potential to overcome the difficulties associated with visual inspection in terms of downtime and reliability of evaluation. Chae et al. [2012] implemented a wireless sensor network for health monitoring of a suspension bridge in order to demonstrate its feasibility. Guo et al. [2011] designed a real-time health assessment scheme to show its capability in terms of overall operation evaluation. Koeppe and Bartholmai [2011] used a temperature compensated measurement technology for long-term structural health monitoring of buildings and infrastructures, where WSN comprised of self-sustaining wireless sensor modules equipped sensors designed specifically for buildings and large-scale industrial facilities. Li et al. [2011] developed a WSN equipped with some useful features such as sleep mode and trigger value for bridge health monitoring and diagnosis.

Vibration-based structural damage detection has drawn considerable attention in recent years due to its non-destructive nature. Since the last few decades, several methodologies have been developed for this purpose. Sohn et al. [2001] applied statistical pattern recognition paradigm in structural health monitoring. Brincker et al. [2001] proposed a frequency domain method for structural modal identification of output-only systems. Caicedo et al. [2004] demonstrated the efficacy of natural excitation technique (NExT) and eigensystem realization algorithm (ERA) by applying on simulated data generated from the popular IASC-ASCE benchmark problem.

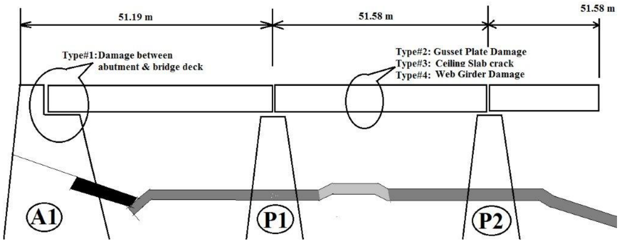

Fig. 1. Schematic Diagram of Kando Bridge (half portion)

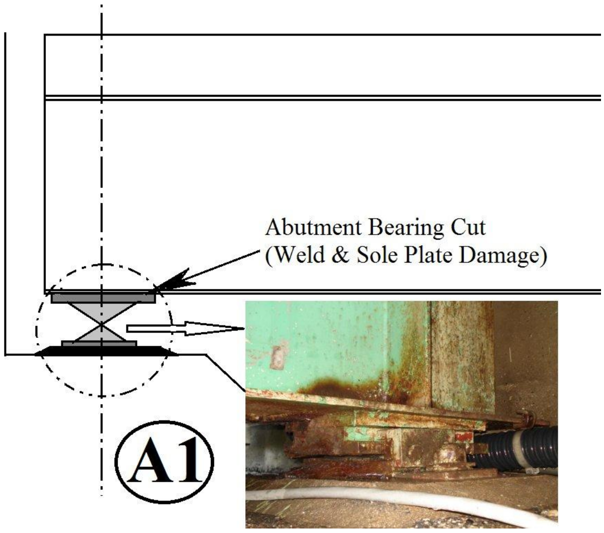

Fig. 2. Abutment Bearing Damage

1.1 Scope of this Paper

This paper deals with the damage detection of an abandoned bridge in Japan using a multi-hopped wireless sensor network (WSN). Various vibration-based and feature-based output-only damage detection techniques are applied to show their efficacy in terms of determining the location and severity of damages using the data collected from the bridge under damaged and undamaged conditions.

2. EXPERIMENTAL STUDY

2.1 Bridge Description

An abandoned bridge in Japan has been instrumented for experimental analysis. The bridge is a steel girder bridge with concrete deck slab having five equal spans of length 50.8 m each with an expansion joint of length 0.78m between each intermediate joints with pier-to-pier distance of 51.58 m. An end clearance of 0.44m with abutments is also present. Figure 1 provides schematic diagram showing half of the symmetrical bridge. The total length of concrete bridge deck is 258m and is rested on braced steel girders of 2.1 m high placed at 2 m centerline distance. The girders are large I-section with vertical stiffeners at a centerline distance of 1.25 m.

2.2 Damage Description

Several damage scenarios were created to study the efficiency of damage detection methods. Damages were inflicted at four different places with various levels of severities. These damage types are as follows.

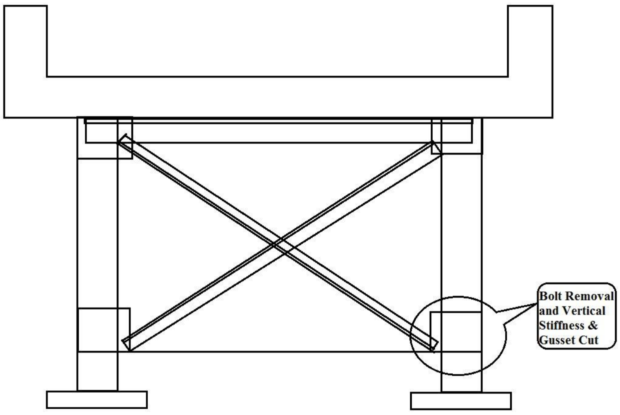

Fig. 3. Gusset Plate Damage

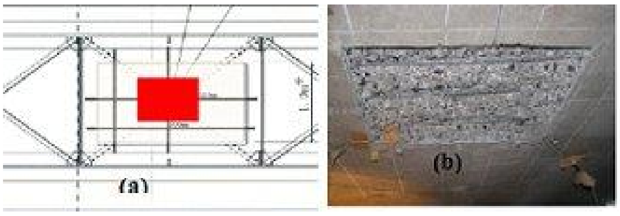

Fig. 4. Deck Ceiling Damage:(a)schematic and (b)real image

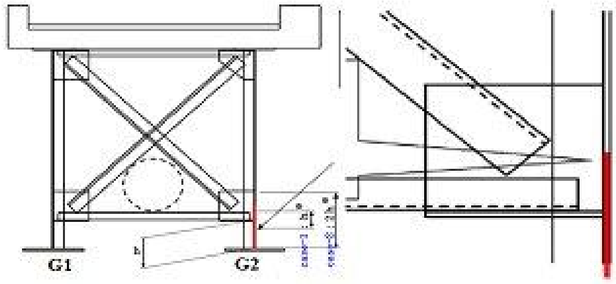

Fig. 5. Web Girder Damage

(a) **Type I:** The bearing between the abutment and bridge deck was damaged with 6 levels of severities (see figure 2 for the location of damage).
(b) **Type II:** The gusset plate of the bridge deck located between the piers *P1* and *P2* was damaged with 6 levels of severities (see figure 3 for the location of damage).
(c) **Type III:** The concrete ceiling from the bottom along with reinforcement was scratched out to damage the deck of the bridge as shown in figure 4.
(d) **Type IV:** The web girder of the bridge deck located at the same place is damaged with 7 cases of severities as shown in figure 5.

Here, damage is induced as degradation of structural elements to reduce the stiffness. Degree of degradation in stiffness is meant here to be the level of severity of damage.

2.3 Instrumentation and Data Acquisition

The bridge is instrumented with various sensor at different locations. Typically sensors for all damage cases are placed near the damage location in order to identify

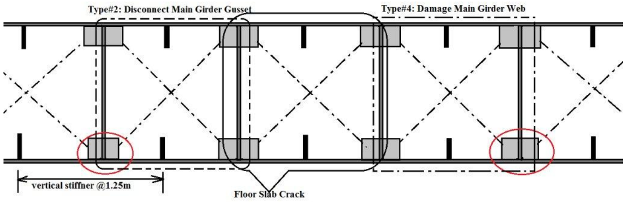

Fig. 6. Sensor Location

local changes. For damage type I, there are 8 sensors, 4 each on either side of the bridge near the bearing as shown in figure 2. For other damage cases the sensor locations are as per shown in figure 6. A multi-hopped network is used for remote data collection.

2.4 External Excitation

Apart from ambient excitation, two types of external excitations were also used. The first one involves excitation using loaded moving car and the second one is a impact hammer of 20 kg hitting from 1 m on a pier top.

3. SYSTEM ID METHODS

To find out the modal properties of a system, transfer function based approach is the most typical approach where both input excitation and output response are needed to be known. But in this bridge diagnosis,the system is excited with moving car or hammer. So for this diagnosis purpose, two types of methods are being used here; one is frequency based method and the another is feature based method. Prior to apply any vibration based output-only damage detection technique mentioned, a mandatory step to follow is to denoise the data. Here 4^{th} order butter worth filter is used for denoising.

In this paper, various vibration-based output-only damage detection techniques such as frequency domain decomposition (FDD), natural excitation technique(NExT) coupled with Eigen realization algorithm (ERA) and, statistical pattern recognition (SPT) paradigm, are used for structural damage detection. For this purpose, the input motions are assumed to be white noise. The methods used can be classified in two categories.

3.1 Frequency based Method

Frequency domain decomposition (FDD) and natural excitation technique (NExT) coupled with eigensystem realization algorithm (ERA) are the two techniques to calculate the corresponding frequencies of damage states as well as the reference state, where any drop down in frequency directs to structural stiffness degradation *i.e.*, structural damage.

FDD: FDD is a modal parameter identification method for linear output-only system, based on singular value decomposition of power spectral density (PSD) matrix of the responses. This method can perform well in no or low damping situations. In addition, unlike classical transfer function based approach, the higher modes are difficult to identify in this method as they are not excited well with ambient vibration data.

$$P_{yy}(jw) = \overline{H}(jw)P_{xx}(jw)H(jw)^T \qquad (1)$$

where $H_{m\times r}$= frequency response function (FRF) with the overbar and superscript T designate the complex conjugate and transpose respectively. P_{xx} $(r\times r)$ and P_{yy} $(m\times m)$=power spectral density (PSD) of the input excitation and output response respectively where P_{xx} $(r \times r)$ is constant as input excitation is assumed to be white noise.

NExT: NExT is a method to find out the free vibration response of a linear system from ambient vibration responses by assuming the excitation to be white noise. Hence, the cross-correlation of excitation vector results to a Dirac delta function vanishing at any time, which leads the system governing differential equation to a free vibration keeping all system parameters unchanged. Now the responses turn to be compatible for ERA.

Considering a multi-degree-of-freedom simple structure, the system equation can be expressed as,

$$M\ddot{y}(t) + C\dot{y}(t) + Ky(t) = F(t) \qquad (2)$$

Taking cross-correlation function of both side of Eq. 2 results,

$$M\ddot{R}_{y,y_i}(\tau) + C\dot{R}_{y,y_i}(\tau) + KR_{y,y_i}(\tau) = 0 \qquad (3)$$

The above second order homogeneous differential equation of motion is well comparable with the free vibration response of a MDOF system where the cross-correlation function $R_{\ddot{y},\ddot{y}_i}(\tau)$ is analogically comparable with free vibration response of the structure with identical system properties as the original structure.

ERA: ERA was first proposed by Juang and Pappa [1985] for modal parameter identification and model reduction of linear dynamical systems. It was later refined and ERA with data correlations (ERA/DC) was formulated by Juang et al. [1987] to handle the effects of noise and nonlinearities.

3.2 Feature based Technique

Statistical Pattern recognition technique (PRT) is one of the popular feature based technique, where Euclidean distance (ED) plays the role of damage sensitive feature which helps to determine the severity as well as location of damage. for a signal $x(t)$, auto-regressive model of p order can be written as,

$$x(t) = \sum_{i=1}^{p} \phi_{ix}x(t-i) + e_{(x)}(t) = \Phi_X^T X + e_{(x)}(t) \qquad (4)$$

where $e_{(x)}(t)$ is the residual error, $\phi_i^{(x)}$ is AR coefficients' to be determined by Yule-Walker or Burg method. Here the order of the signal refers to the number of past time steps to be considered for a future data prediction.

Let $y(t)$ be the response of unknown structural condition, so following the same model in Eqn. 5. can be written as,

$$y(t) = \sum_{i=1}^{p} \phi_{iy}y(t-i) + e_{(y)}(t) = \Phi_Y^T Y + e_{(y)}(t) \qquad (5)$$

where the notations carry their usual meaning as earlier. Now to judge whether two cases (reference and unknown)

Table 1. Frequency Change for Type I

Severity	f_1 (Hz)	Δf_1 (%)	f_2 freq. (Hz)	Δf_2 (%)
0	2.411	-	7.355	-
1	2.411	0.000	7.324	-0.415
2	2.380	-1.265	7.294	-0.829
3	2.350	-2.530	7.202	-2.075
4	2.350	-2.530	7.202	-2.075
5	2.289	-5.064	7.172	-2.490
6	2.258	-6.330	7.111	-3.319

Table 2. Frequency Change for Type II

Severity	f_1 (Hz)	Δf_1 (%)	f_2 freq. (Hz)	Δf_2 (%)
0	2.350	-	7.446	-
1	2.350	0.000	7.446	0.000
2	2.319	-1.302	7.385	-0.008
3	2.319	-1.302	7.324	-0.016
4	2.289	-2.600	7.263	-0.025
5	2.289	-2.600	7.507	0.008
6	2.289	-2.600	7.263	-0.025

Table 3. Freq. Change for Type III and IV

Severity	f_1 (Hz)	Δf_1 (%)	f_1 freq. (Hz)	Δf_1 (%)
	Type III		Type IV	
0	2.335	-	2.319	-
1	2.327	-0.343	2.319	0
2	2.327	-0.343	2.319	0
3	2.312	-0.985	-	-
4	2.304	-1.328	2.258	-2.630
5	2.281	-2.313	2.258	-2.630
6	2.274	-2.612	-	-

are comparable to an extent, the Euclidean distance is to find out, reflecting the difference between those two signals.

$$\Delta = \sum_{i=1}^{p} \left(\phi_{ix} - \phi_{iy}\right)^2 = \left(\Phi_{ix} - \Phi_{iy}\right)^T \left(\Phi_{ix} - \Phi_{iy}\right) \qquad (6)$$

The minimum is the *Delta*, the anonymous signal is close to the reference model; hence a way to detect as well as quantify damage.

4. RESULTS AND DISCUSSION

The bridge was excited with running car and impact hammer. As the excitation due to the running car and hammer impact may not excite the higher modes, only a few lower modes are considered in this study for damage detection purpose. These frequencies are calculated using the FDD and NExT methods. These results are tabulated in table 1, table 2 and table 3. ($f_1 = 1^{st}$ freq., $f_2 = 2^{nd}$ freq., Δf=freq. change)

It is observed from table 1 that with an increase in damage severity (DS), the modal frequencies are decreasing, depicting the stiffness degradation of the structure. It can also be observed from from table 1 that the drop in the 2^{nd} frequency is less than that of the 1^{st} frequency implying that the damage type I is more sensitive to the 1^{st} frequency than that of the 2^{nd} frequency. A similar trend of frequency drop is also observed from table 2. However, it may be noted that the percentage drop in the first two frequencies is less in this case when compared with type I damage cases. It can also be noted from table 2 that a slight increase in damage severities may not result in noticeable change in frequencies. This may be due to various reasons including change in damping and noise levels.

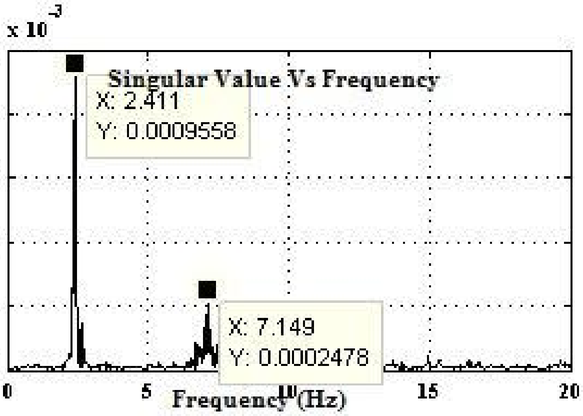

Fig. 7. Singular Value with Frequency (Hz)

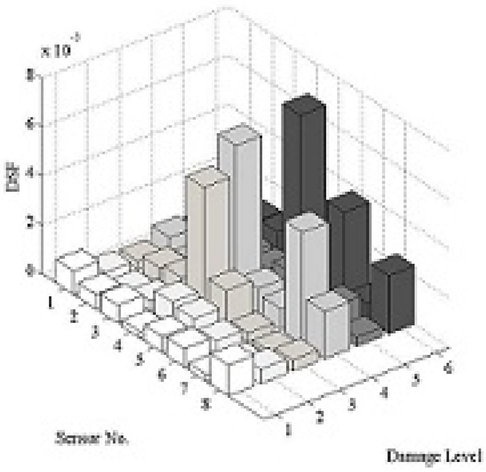

Fig. 8. ED for Damage Type I

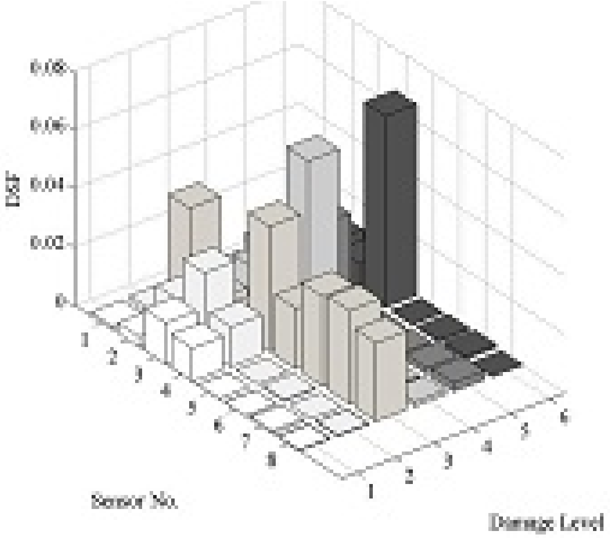

Fig. 9. ED for Damage Type II

Table 3 shows change in the 1^{st} frequency for damage type III and IV. The type III damage shows degradation in modal frequency with an increase in damage severities,

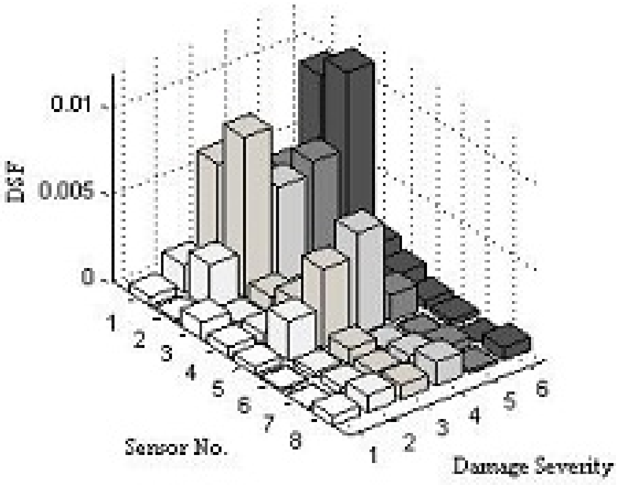

Fig. 10. ED for Damage Type III

illustrating the contribution of web girder stiffness in structural frequencies. The damage type IV, which implies damage of the concrete slab shows interesting trend. It is observed that the damage can not be detected until the damage severity is high. For type III and IV, the higher modes could not be captured with the methods used here.

Figure 8, figure 9 and figure 10 show the Euclidean distance (ED) of the autoregressive model coefficients between the reference states and the damaged state of type I, II and III. From these figures, it can be observed that the damage detection feature (DSF) i.e., ED is a measure of damage severity. In other words, all the figures show that the ED is increasing with the increase of severity of damage. Besides, from figure 8, it can be observed that the ED value is more at sensor no. 4, depicting the damage to be close to that sensor. From figure 2 a similar trend is also observed, where the sensor no. 4 is placed almost on the location of the bearing cut. A similar observation can also be made from figure 9 and figure 10, where damage occurred near sensor no.3 for type II damage and at sensor no. 2 & 5 for type III damage.

5. CONCLUSION

Bridges are essential links in any surface transportation network. A damage to an important bridge is always undesirable. The prevalent practice of bridge inspection requires checking of each and every component, which is experience-based, highly time consuming and an expensive process, often enforcing disruption in traffic flow. As a result, the wireless sensor-based inspection methodology is gaining popularity in recent times. This paper a presents a study to show the efficiency of a multi-hopped wireless sensor network (WSN) for remote health monitoring of bridge. For this purpose, the abandoned Kando bridge in Japan was instrumented using WSN. Damage at different locations were inflicted to achieve various levels of damage severities. A vibration-based and a feature-based output-only damage detection techniques are applied to show their efficacy in terms of determining the location and severity of damages using the data collected from the bridge under damaged and undamaged conditions. External excitation was used by means of loaded running car and hammer impact at a pier top. In this study, a frequency based and a feature based methods are used to identify and localize damage. The results obtained from this study demonstrate that the location and severity of damage can be identified using these two methods. However, placement of sensors is an important consideration for damage localization.

ACKNOWLEDGEMENTS

One of the authors (Koushik Roy) would like to thank Mr. Harikrishnan P. and Mr. Tansheng Li for valuable discussion on sensor network system and system identification techniques respectively. The work is jointly funded by Kitakyushu Foundation for the Advancement of Industry Science and Technology,Japan and Ministry of Human Resources Development (MHRD), India.

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