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모델링 오차를 고려한 신경망 기법 기반 손상추정방법

Neural Networks-Based Damage Detection for Bridges Considering Errors in Baseline Finite Element Models

이종재* 윤정방** 이종원*** 정희영****
Lee, Jong-Jae , Yun, Chung-Bang Lee, Jong-Won Jung, Hie-Young

ABSTRACT

In this paper, a neural networks-based damage detection method using the modal properties is presented, which can effectively reduce the effect of the modeling errors in the baseline finite element model from which the training patterns for the networks are to be generated. The differences or the ratios of the mode shape components between before and after damage are used as the input to the neural networks in this method, since they are found to be less sensitive to the modeling errors than the mode shapes themselves. Results of laboratory test on a simply supported bridge model and field test on a bridge with multiple girders confirm the applicability of the present method.

1. Introduction

Structural health monitoring has become an important research topic in conjunction with damage assessment and safety evaluation of existing structures. The use of system identification approaches for damage detection has been expanded in recent years owing to the advancements in signal analysis and information processing techniques. Soft computing techniques such as neural networks and genetic algorithm have been utilized increasingly to this end due to their excellent pattern recognition capability[1-5].

In this study, a neural networks-based damage detection technique using the modal data is proposed. The differences or the ratios of the mode shape components between before and after damage are used as the input to the neural networks in this method, since they are found to be less sensitive to the errors in the baseline FE model than the mode shapes themselves. As a practical application, a procedure for damage estimation of bridge structures is presented using ambient vibration data caused by traffic loadings. It may generally consist of identification of the modal parameters, updating of the baseline FE model, and assessment of the damage locations and severities based on the changes of modal properties. However, in this study, updating of the baseline FE model is intentionally skipped to demonstrate the effectiveness of the present method. The information on the natural frequencies is excluded to reduce the environmental and operational effects such as temperature, humidity, traffic volume, etc, which are critical to the real structures. Laboratory test and field test were carried out on bridge structures to investigate the effectiveness of the proposed method.

* 한국과학기술원 건설 및 환경공학과 박사과정
** 한국과학기술원 건설 및 환경공학과 교수
*** 한국기계연구원 선임연구원
**** 서울시립대학교 교수

2. Modal Parameters Less-sensitive to Modeling Errors

For the effective neural networks-based damage detection using the modal parameters, it is very important to choose the input data which is less sensitive to the errors in the baseline FE model, since the training patterns for the networks are to be generated from the model. The effect of the modeling error on the mode shapes may exceed the modal sensitivity to the damage, then accuracy of the damage estimation may get severely degraded. In this study, the modal sensitivity is investigated based on the modal perturbation equations.

The first order modal perturbation equation for the stiffness change ΔK_d due to damages can be obtained as

$$[\Delta K_d]\{\phi_0\} + [K_0]\{\Delta\phi_d\} = \omega_0^2[M]\{\Delta\phi_d\} + \Delta\omega_d^2[M]\{\phi_0\} \tag{1}$$

where K is the stiffness matrix, M is the mass matrix , ω is the natural frequency, and ϕ is the mode shape. Subscripts o and d denote intact and damaged cases, respectively, and Δ denotes the perturbed value. In equation (1), it is assumed that the stiffness reduces due to damages, while the mass remains the same.

Similar modal perturbation equation for a case with modeling error can be obtained as

$$[\Delta K_d]\{\phi_0\} + [K_0]\{\Delta\tilde{\phi}_d\} = \omega_0^2[M]\{\Delta\tilde{\phi}_d\} + \Delta\tilde{\omega}_d^2[M]\{\phi_0\} \tag{2}$$

where the symbol ~ denotes the quantities with modeling errors.

Assuming $\Delta\omega_d^2 \approx \Delta\tilde{\omega}_d^2$, equation (3) can be obtained from equations (1) and (2) as

$$[K_0 - \omega_0^2 M]\{\Delta\phi_d - \Delta\tilde{\phi}_d\} = 0 \tag{3}$$

The solution for the above eigenvalue problem can be obtained as

$$\{\Delta\phi_d - \Delta\tilde{\phi}_d\} = \alpha\{\phi_0\} \tag{4}$$

where the proportional constant α reduces to zero in approximation, if the mode shapes are normalized as[5]

$$\{\phi_0\}^T\{\phi_0\} = 1, \quad \{\phi_d\}^T\{\phi_d\} = 1, \quad \{\tilde{\phi}_d\}^T\{\tilde{\phi}_d\} = 1 \tag{5}$$

Therefore, equation (4) reduces to

$$\{\Delta\phi_d\} \approx \{\Delta\tilde{\phi}_d\} \tag{6}$$

Equation (6) can be reduced further into the following approximate relationship

$$\frac{\phi_{dj}^i}{\phi_{0j}^i} \approx \frac{\tilde{\phi}_{dj}^i}{\tilde{\phi}_{0j}^i} \quad for\ \forall i, j \quad where\ \phi_{0j}^i, \tilde{\phi}_{0j}^i \neq 0 \tag{7}$$

In this study, the differences of the mode shapes before and after damages or the ratios of the mode shapes are proposed to be used as the input for the NN-based damage estimation, since they are less sensitive to the modeling error in the baseline FE model than the mode shape themselves as indicated in equations (6) and (7).

3. LABORATORY TEST ON A BRIDGE MODEL

A laboratory test was carried out for damage assessment of a bridge model subjected to vehicle loadings using a NN technique[4]. A schematic of the experimental setup is shown in Fig. 1a. and the FE model used in this study is shown in Fig. 1b. Damages were imposed by cutting out parts of the bottom flanges in the girder segments. The resonant frequencies and the mode shapes were obtained from the vertical accelerations at 7 equally spaced locations along the girders using the frequency domain decomposition technique[6, 7] (Fig. 2).

Damage estimation was carried out using three different types of modal quantities as the input to the NN. They are the mode shapes from the updated model, the mode shape differences and the mode shape ratios from the initial (un-updated) model. The information on the natural frequencies was not included to verify the effectiveness of the present methods using the mode shape information only.

Fig. 3 shows the estimated damage severities along with the inflicted values for various damage cases. Most locations of the inflicted damages are detected fairly successfully, if the mode shapes generated around the updated finite element model were utilized during the training of the NN. However there were a number of cases with false alarms. On the other hand, if the NN was trained using the mode shape differences or the ratios generated around the initial FE model, the estimated results are found to be much better than those using the NN trained by the mode shapes from the updated FE model. The above results confirm the effectiveness of using the differences or the ratios of the mode shapes for the NN-based damage estimation under the modeling errors in the initial FE model.

FIELD TEST ON HANNAM GRAND BRIDGE

Field tests on damage estimation were performed on the northern-most span of old Hannam Grand Bridge over Han River in Seoul, Korea (Fig. 4), which is to be replaced during bridge renovation. It is simply supported, and the length of the span is 22.7m. It consists of nine steel plate girders and a concrete slab. Originally it had ten girders, but the 10^{th} girder was removed during the construction of the new bridge next to it. Ambient vibration tests were carried out. The vibration was mainly induced by the traffic loads on the adjacent new bridge and the train loads under the test bridge. Eight sets of measurements were carried out on Girders 1 to 8 as shown in Fig. 4d. For each set, vertical accelerations were measured at 11 equally spaced points on the slab just above each girder. Reference signals to correlate each experimental set were obtained at 8 points (R1-R8).

Fig. 5 shows three inflicted damage scenarios imposed on the main girders of a bridge by torch for the present damage detection study. The damages were imposed locally, unlike in the bridge model for the laboratory test. An initial FE model for the bridge was constructed based on the drawings. Table 1 shows the modal properties obtained from the initial FE model and the experiments for each damage case. Changes in the first three natural frequencies for subsequent damage cases show no significant trend related to damages. This indicates difficulty in using resonant frequencies as a damage indicator for large civil engineering structures, where the environmental effects such as temperature, humidity, etc. may not be ignored. In Table 1, the modal assurance criteria (MAC) values are also shown, which represent the closeness between the calculated and the experimental mode shapes. The first three modes gave close results to the test results: i.e. above 97% in MAC value. Therefore the first three mode shapes were used as inputs for the damage estimation.

Damage estimation was performed on a substructure composed of 4 girders shown in Fig. 5. The differences and the ratios of the mode shapes between before and after damages were respectively used as the inputs to the neural networks. The damage detection was performed using selective information excluding the mode data near the node points. Fig. 6 shows that the damage locations are identified with good accuracy for all the cases, whereas the estimated results contained false alarms with small magnitudes at several locations. But it can be found that the estimated damage indices have dominant values at the locations of the actual damages.

CONCLUDING REMARKS

A neural networks-based technique is presented for element level damage assessments of structures using the modal properties. The mode shape differences or the mode shape ratios between before and after damage are used as the input to the NN to reduce the effect of the modeling errors in the baseline FE model, from which the training patterns are to be generated.

From laboratory tests on a bridge model, it has been found that the present neural networks technique can be effectively used for damage detection of the bridges under traffic loadings considering the modeling errors. Most of the inflicted damages have been detected very successfully for various damage cases. For an experimental study on a real bridge with multiple girders, the damage estimation was performed on a substructure using selective information excluding the mode shape data near the nodal points. The damage locations were identified with good accuracy for all the damage cases, whereas the estimated damage severities contained minor false alarms at several locations.

ACKNOWLEDGEMENTS

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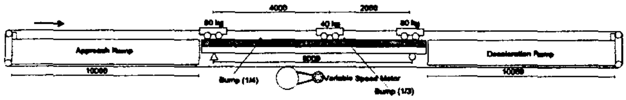
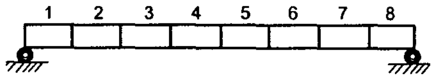
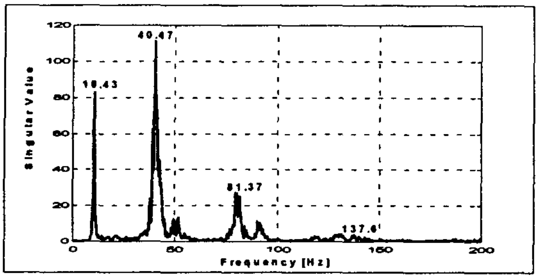


(a) Schematic of experimental setup (mm)

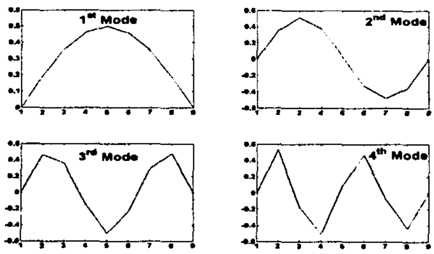


(b) FE model and element number

Fig. 1 Experimental setup for a bridge model



(a) Singular value in FDD : $S_1(\omega)$



(b) Mode shapes

Fig. 2 Identified modal parameters of a bridge model using FDD

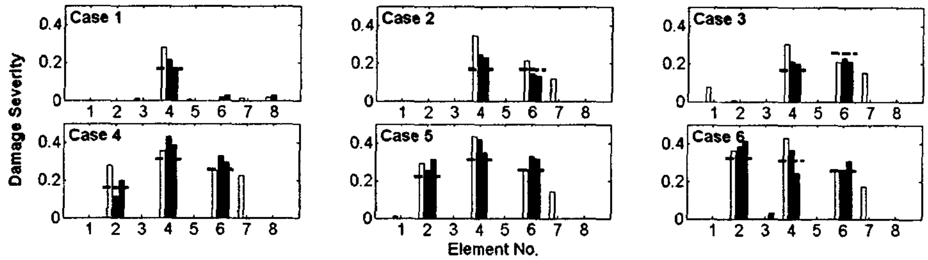
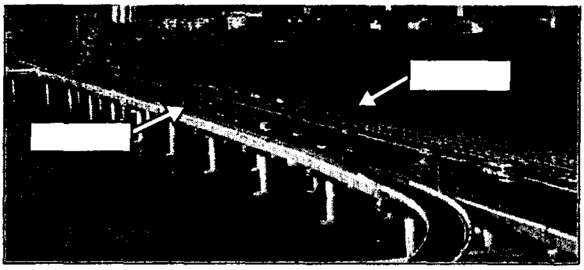
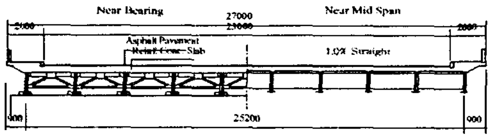


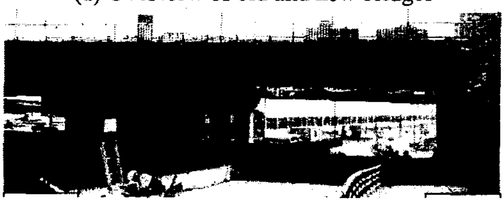
Fig. 3 Estimated damages of a bridge model using various input data for six damage cases
(----: Inflicted, ▭: Using mode shapes (trained using updated model), ■: Using mode shape differences (trained using initial model), ■: Using mode shape ratios (trained using initial model))



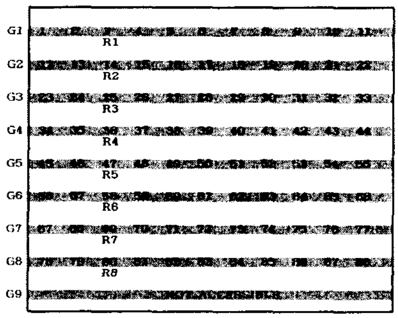
(a) Overview of old and new bridges



(c) Section view of old bridge

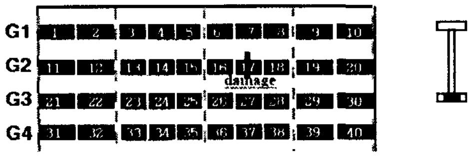


(b) Northern-most span of old bridge (L=22.7m)

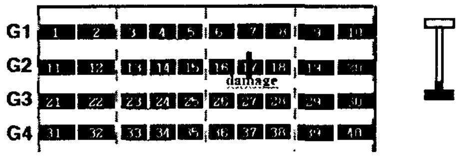


(d) Measurement locations
(1-88 : Roving sensors, R1-R8 : Reference sensors)

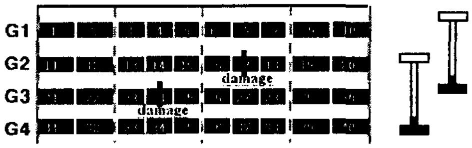
Fig. 4 View of Hannam Grand Bridge in Seoul, Korea



(a) Damage Case I



(b) Damage Case II

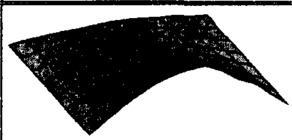
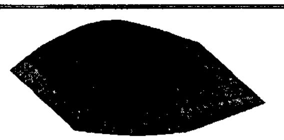


(c) Damage Case III

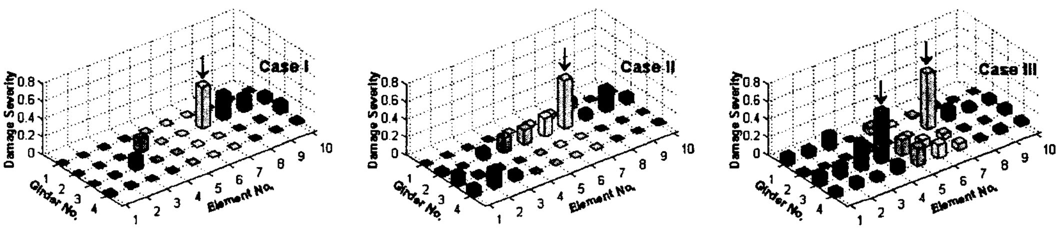
(d) Inflicted Damage by Torch

Fig. 5 Damage scenarios for Hannam Grand Bridge

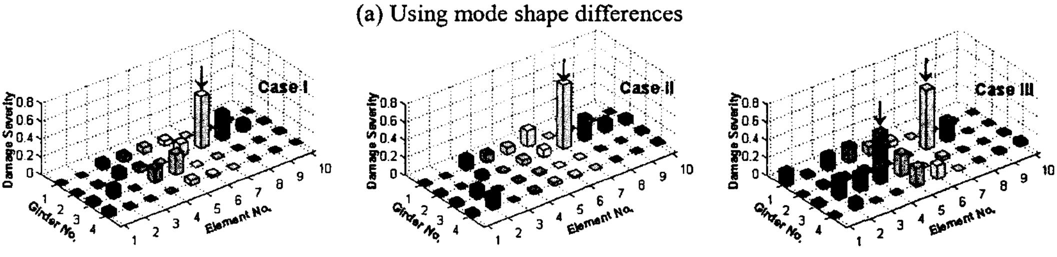
Table 1 Natural frequencies and modes of Hannam Grand Bridge for various damage cases

Modes		1st mode	2nd mode	3rd mode
Calculated (Intact)		4.071 Hz	4.452 Hz	5.626 Hz
Measured	Intact	4.247 Hz (99.79)	4.876 Hz (97.86)	5.771 Hz (99.71)
	Damage I	4.188 Hz (99.38)	4.903 Hz (99.45)	5.823 Hz (99.64)
	Damage II	4.196 Hz (99.90)	4.780 Hz (99.35)	5.778 Hz (99.57)
	Damage III	4.218 Hz (99.51)	4.757 Hz (99.56)	5.799 Hz (99.73)
Measured mode shapes (Intact case)				

Note: Values in parentheses are the MAC values (%)



(a) Using mode shape differences



(b) Using mode shape ratios

Fig. 6 Estimated damages for Hannam Grand Bridge

(The exact locations of damages are marked with arrows(↓))