ENERGY-BASED DAMPING ESTIMATION OF STEEL BRIDGES AND ITS APPLICABILITY TO DAMAGE DETECTION

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ABSTRACT

Vibration-based Structural Health Monitoring (V-SHM) for bridges has been investigated worldwide to assist the widely used visual inspection which is not necessary a reliable method as many damaged bridges were not recognized during their periodic inspections. The main concern in the V-SHM is that the structural damages yield changes in their dynamic characteristics. Even though a change in modal damping ratio has been identified as a damage indicator, it is still hesitant as the accuracy of modal damping identification is uncertain. The present study is conducted focusing on the analytical estimation of modal damping ratios of a steel truss bridge using the energy-based damping estimation method. Experimental damping identification of the bridge is first done, and the eigenvalue analysis of the bridge is next conducted. The damping parameters of the bridge are estimated by using both the experimental and analytical results and hence, the modal damping ratios are analytically evaluated. The applicability of the proposed methodology for damage detection of steel bridges is also roughly discussed.

Keywords: Modal damping ratio, damping estimation, steel bridges, damage detection, structural health monitoring.

1. INTRODUCTION

In August 2007, the tragic collapse of the 40 years old I-35W steel truss bridge in Minneapolis, USA (Astaneh 2008) has emphasized the needs to develop more effective SHM for bridges to complement the current technique of periodic visual inspection which is used globally. This is because the reliability of visual inspection depends on not only the skills and experiences of the inspectors but also possibility of inspecting all the components of the bridges. Therefore, possible techniques that have been investigated worldwide to assist the visual inspection are V-SHM (Doebling et al. 1996; Carden and Fanning 2004). The literature revealed that the modal damping ratio is as a sensitive damage indicator in this field (Yoshioka et al. 2010). That is, the modal damping ratio of diagonal member coupled mode in a steel truss bridge is increased when cracks appear on diagonal members. Regardless of the modal damping ratio being identified as an effective

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damage indicator, there is still concern over the accuracy of modal damping identification. Analytical modal damping estimation is one of the possible approaches that can be used to justify the experimentally identified modal damping ratios of the structures. However, there are few studies on analytical modal damping estimation of structures in the literature. Energy-based damping estimation is the one of such analytical method that can be used (Yamaguchi et al. 1997; Yamaguchi and Matsumoto 2002).

A method of modal damping estimation for bridges is investigated in this study by using energy-based modal damping estimation approach. The experimental modal damping identification of a steel bridge was done by applying the Eigensystem Realization Algorithm (ERA). The eigenvalue analysis of the bridge was next conducted. The results of both analyses was used to estimate the damping parameters of the bridge such as equivalent loss factors of truss bridge's upper chord, diagonal and girders, and dynamic friction coefficient at moveable support. Then modal damping ratios of the bridge were analytically estimated using those parameters and the applicability of the proposed methodology for damage detection of bridges was discussed.

2. STUDIED BRIDGE AND ITS FIELD VIBRATION MEASUREMENT

The studied steel bridge constructed in 1965, is a simple Warren through-type truss bridge with a span length of 70.77m and width of 7m as shown in Figure 1. The bridge has five spans over the river, supported by pin and roller bearings on either side of the span. The tension diagonal members and compression diagonal members have H-sections and box sections respectively, while the chord members have box sections. The bridge deck is a composite deck of steel plate girders and reinforced concrete slab. In July 2007, after 42 years of service, crack damages were found in both the top and bottom ends of D5 diagonal members in all spans. The cracks occurred at a flange of the diagonal members in the neighborhood of gusset plates and propagated to the webbing in some cases. Reinforcing plates were attached to those parts by high strength bolts as a repair.

The field vibration measurement at the 1^{st} span of the bridge was performed during service (Yoshioka et al. 2010). The accelerations were picked up under two schemes: that is, sensors along the curb to catch truss modes and sensors on the diagonals to catch diagonal modes. The placement of piezoelectric accelerometers and servo velocimeters is also shown in Figure 1. Ambient vibrations were recorded for 10 minutes with a sampling rate of 100Hz under the service condition being relatively low traffic. 7 sets of free vibration (FV) records were extracted from the ambient vibration records and utilized in estimating the natural frequencies, mode shapes, and modal damping ratios by applying the ERA. Mean value of natural frequency and modal damping ratio of the identified modes used in this damping parameter estimation are shown in Table 1 including coefficient of variation (CV) of modal damping ratios. It is noted that the modes with the modal damping ratio less than 0.05 and the modal amplitude coherence greater than 0.9 was selected by quantitatively distinguishing the system and noise modes.

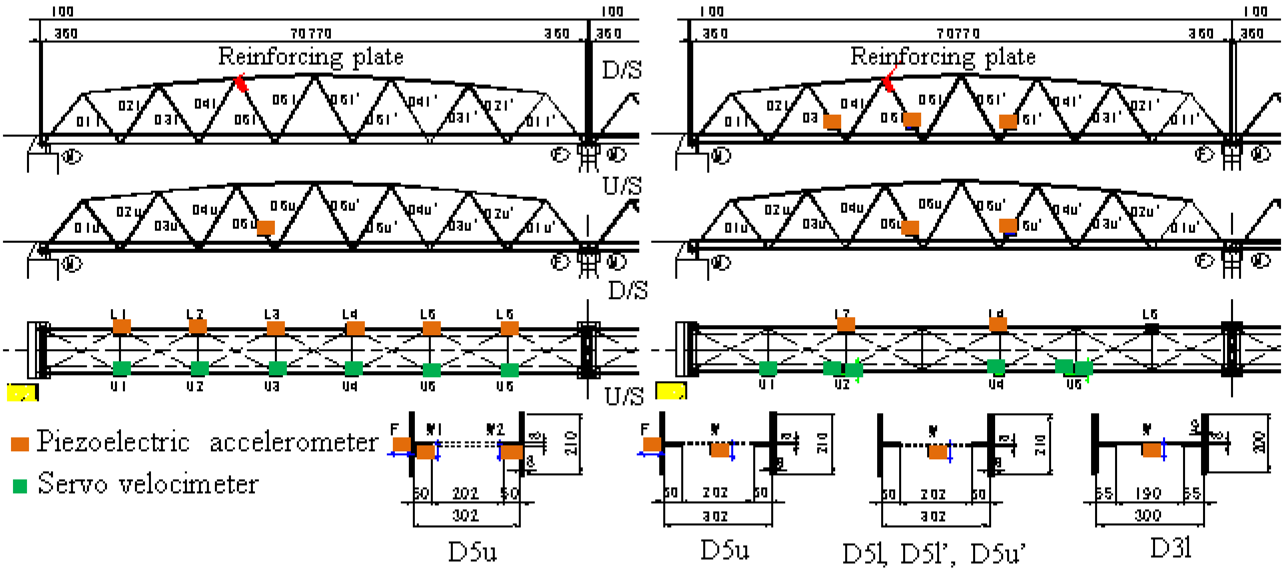

Figure 1: Elevation/plan views of bridge and position of sensors.

3. NATURAL FREQUENCY/MODE SHAPE ANALYSIS

The finite element model was created for eigenvalue analysis of the studied bridge followed by nonlinear static analysis. All the structural members were modeled by general sectioned bar element with assigned mass and geometric properties. The gusset plate was modeled by adding its stiffness and mass to the truss nodes. The equivalent section concept was utilized in modeling the concrete deck slab. In order to model the dynamic friction at bridge moveable supports, the spring elements were introduced and their constants were assumed as 1.0×10^4 kN/m and 5.0×10^5 kNm/rad, respectively. The natural frequencies obtained by the eigenvalue analysis are also listed in Table 1.

Table 1: Experimentally identified and analytically estimated modal parameters of the bridge

Mode shape	Experimental identification			Analytical estimation		
	Mean frequency/(Hz)	Damping ratio Mean	Damping ratio CV	Mode No	Frequency / (Hz)	% error
1st Vertical symmetric	2.559	0.0085	0.285	2	2.567	0.32
1st Vertical Asymmetric	5.295	0.0039	0.484	6	5.371	1.43
2nd Vertical symmetric	7.307	0.0049	0.329	9	7.676	5.05
D5 in plane 1st (all 4 in-phase)	9.011	0.0007	0.149	12	9.092	0.89
D5 in plane 1st (d/s or u/s 2 anti-phase)	9.215	0.0030	0.364	13	9.186	-0.32
D5 in plane 1st (start or end 2 anti-phase)	9.233	0.0029	0.489	15	9.264	0.33

4. ENERGY-BASED DAMPING ESTIMATION OF THE BRIDGE

The sources of damping in the steel truss bridge are assumed to be the material viscous damping of bridge's upper chords, diagonal members and girders, and the frictional damping at the moveable supports. That is, the energy dissipation at the members' connection was assumed to be included in the energy dissipation of each member and the energy dissipation in the girder implicitly accounts for that of deck slab. Using the energy-based damping definition, the n-th modal damping ratio, ξ_n , can then be expressed in the following form (Yamaguchi et al. 1997).

$$\xi_n = \frac{2\pi\eta_{uc}V_{uc,n}}{4\pi U_n} + \frac{2\pi\eta_d V_{d,n}}{4\pi U_n} + \frac{2\pi\eta_g V_{g,n}}{4\pi U_n} + \frac{8A_{s,n}\mu_s R}{4\pi U_n} \quad (1)$$

where η_{uc}, η_d, η_g and $V_{uc,n}$, $V_{d,n}$, $V_{g,n}$ are the equivalent loss factors and the n-th modal strain energies of the upper chords, diagonal members and girders, respectively. $A_{s,n}$, μ_s and R are the moving amplitude, dynamic friction coefficient and vertical reaction at the moveable support and U_n is the n-th total potential energy. Furthermore it is assumed that the equivalent loss factors are independent of the vibration mode shapes. The equations for several modes are then solved by applying the least square method using experimentally identified modal damping ratios and the energy quantities calculated from the relevant experimental and numerical results. Once these damping parameters are estimated, the modal damping ratio of respective mode can be evaluated analytically by substituting back the estimated parameters to Eq. (1).

5. DAMPING PARAMETER ESTIMATION RESULTS AND DISCUSSION

The damping parameter estimation is done by categorizing the vibration modes based on their strain energy dominancy of the structural components. The first category of vibration modes consist of the 1st vertical symmetric mode (Mode 2), 1st vertical asymmetric mode (Mode 6) and 2nd vertical symmetric mode (Mode 9) as the modes with significant level of girder vibration and support movement. The second is a group of the diagonal member D5 modes coupled with the upper chord members. . The third is the in plane anti-phase D5 mode (Mode-15) as the diagonal dominant mode. These mode shapes and their strain energy ratio distributions are shown in Figure 2 in which UC, D and G denote the upper chord, diagonal and girder, respectively.

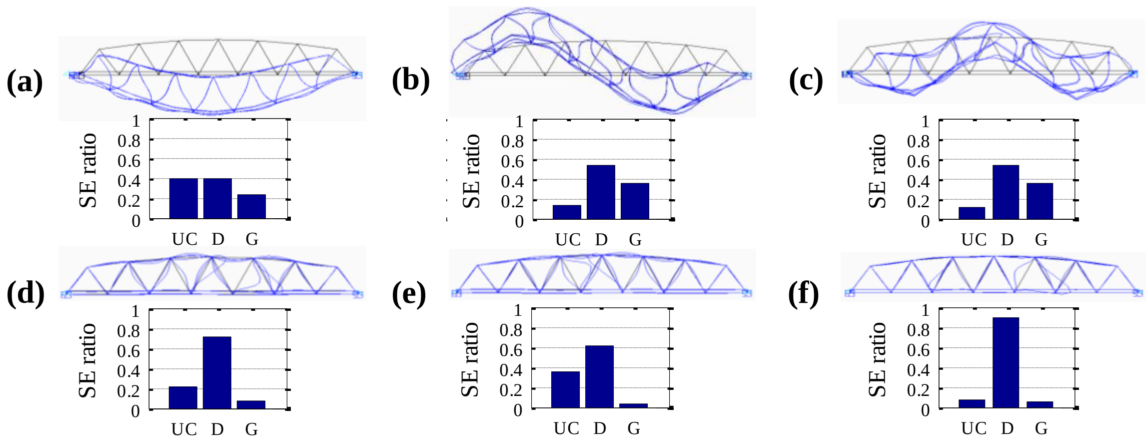

Figure 2: Mode shapes and strain energy ratio distributions: (a) Mode 2; (b) Mode 6; (c) Mode 9; (d) Mode 12; (e) Mode 13; and (f) Mode15.

The equivalent loss factor of diagonal member is first estimated by considering the Mode 15 with the assumption of energy dissipated only from material viscous damping of diagonals. This particular mode is analyzed to identify the loss factor of diagonal only by using three FV records.

The estimation results are shown in Table 2 including the mean value and coefficient of variation (CV). Even though the higher variation exists, the mean value of estimated diagonal loss factors is taken as the equivalent loss factor of diagonal in the next step of the damping parameter estimation. The estimation of equivalent loss factor of upper chord is next done by considering Modes 12 and 13. The energy dissipations in these particular modes are assumed as the ones only from material viscous damping of diagonal and upper chord members, while the energy dissipation in girders and frictional energy dissipation are neglected because of the characteristics of these local vibration modes. It is noted that the mean value of diagonal loss factor estimated in the previous step is considered as a known parameter in this step. The parameter estimation was done by applying the non-negative least square method and the positive non-zero estimation is successful only for FV6 as shown in Table 2. Getting zero estimation for other FV records might be due to the assumed value of diagonal loss factor, which could be erroneous. Finally the equivalent loss factor of girder and the dynamic friction coefficient are estimated by considering the first category of modes with previously estimated equivalent loss factors of diagonal and upper chord members. The mean value and CV of girder loss factor and dynamic friction coefficient are also shown in Table 2.

The CVs of estimated damping parameters in Table 2 are comparatively higher than those of experimentally identified modal damping ratios in Table 1. The errors in the estimated damping parameters are accumulated. In this sense, the fluctuations in experimentally identified modal damping ratios significantly affect on the accuracy of estimated damping parameters. Furthermore, because the field measured support movement data is not available; the support movement analyzed by FE model was used in frictional energy dissipation calculations. Thus estimated dynamic friction coefficients can be erroneous, which could be another source of higher variation in estimated loss factors. Figure 3 shows the comparison of experimental and analytical modal damping ratios of the first category of vibration modes while Mode No. denotes the modes according to their appearing order. It is noted that well matching in both damping estimations from most of the FV even though higher variation exist in estimated damping parameters.

Most importantly, the proposed method is capable of identifying the damping parameters of bridge members with the assumed damping sources of the bridge. Therefore, it is possible to use this analytical approach to identify the changes in those damping parameters for two different stages of the life span of subjective bridge, which could show some amount of change in modal damping ratios. Then, it is possible to recognize the components of the bridge which may have a damage considering the significant changes in identified damping parameters.

Table 2: Estimated damping parameters

Parameter	FV1	FV2	FV3	FV4	FV5	FV6	FV7	Mean	CV
Diagonal loss factor	0.0031	-	0.0087	-	-	0.0129	-	0.0082	0.488
Upper chord loss factor	-	0	0	-	0	0.0046	-	-	-
Girder loss factor	0.0166	0.0057	0	0.0148	0.0107	0.0001	0.0193	0.0112	0.588
Dyn. friction coefficient	0	$7.8\text{x}10^{-5}$	$3.5\ \text{x}10^{-5}$	$2.0\ \text{x}10^{-6}$	$6.2\ \text{x}10^{-5}$	$5.3\ \text{x}10^{-5}$	$1.5\ \text{x}10^{-5}$	$4.0\ \text{x}10^{-5}$	0.642

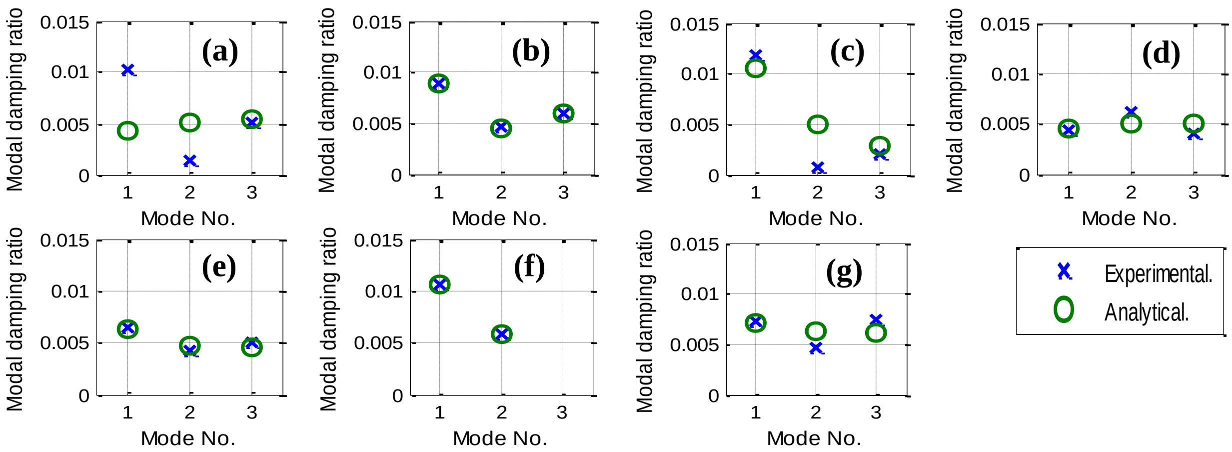

Figure 3: Comparison of experimental and analytical modal damping ratios of the first category of vibration modes: (a) FV1; (b) FV2; (c) FV3; (d) FV4; (e) FV5; (f) FV6; and (g) FV7.

6. CONCLUSION

The method of modal damping estimation for bridges is investigated in this study and its applicability to the damage detection is roughly discussed.

- The most important finding of this study is that the proposed analytical method of modal damping estimation is capable of identifying damping parameters of different damping sources of the bridge which contribute to its vibration energy dissipation.
- Therefore, it is possible to use this approach for damage detection of bridges by applying the concept to a particular bridge at two different stages of its life span.

Fluctuations in experimentally identified modal damping ratios affect significantly on the accuracy of damping parameter estimation. Thus, further studies are required by considering possible errors in both experimental and analytical modal damping estimation.

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