Neutral-Axis Position Based Damage Detection of Bridge Deck Using Strain Measurement: Formulation of a Kalman Filter Estimator

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ABSTRACT

In selecting monitoring-based damage indices for bridge deck condition assessment, their sensitivity to local damage and robustness with respect to random traffic load patterns are of great concern. In this study, a Kalman filter (KF) estimator is formulated to locate the neutral-axis position from measured strain responses under traffic loading. Its robustness with respect to different extents of noise corrupted in the sensor readings is first testified through numerical simulation of a beam-like bridge deck model. Then its capability for consistently locating the neutral-axis position under varying traffic load patterns is verified using the monitoring data of traffic-induced strain responses obtained from the suspension Tsing Ma Bridge (TMB) under different load scenarios (highway traffic, railway traffic, and their combination). The results indicate that the proposed KF estimator is much more robust than the direct estimation method in the case of noise contamination and gives rise to consistent neutral-axis position estimation results which are independent of load conditions and patterns.

INTRODUCTION

Bridge deck that directly carries traffic load is one of the most critical parts of a bridge system. Deterioration of bridge deck can cause public inconvenience, travel delay, economic impact, and even life lost, giving rise to the most severe problem for the highway industry today. For example, the deck trusses of the I-35W Bridge over the Mississippi River in Minneapolis, Minnesota, USA collapsed on August 1, 2007 without warning [1]. As a result of the catastrophic failure, 13 people died and 145 people were injured. This accident highlights again the importance of incorporating

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structural health monitoring (SHM) technologies into current bridge management programs to prevent similar tragedies in the future. In selecting monitoring-based indices for bridge deck condition assessment, their sensitivity to damage and robustness with respect to random traffic load patterns are two main factors of concern.

The neutral-axis position of bridge deck sections has been proposed as a damage indicator for bridge deck assessment because it reflects the local deck cross-section property and shifts when damage on the deck cross-section occurs [2-4]. Although the strain responses at different points of a deck cross-section under varying traffic loading evolve with time, their ratio would keep constant in the absence of damage and it can be used to derive the neutral-axis position. It has been demonstrated that the strain-derived neutral-axis position is considerably sensitive to local damage on the deck [4]. However, the accuracy of neutral-axis position estimation directly using the measured strain data may be significantly distorted in the presence of measurement noise and varying traffic load patterns. In this study, a Kalman filter (KF) estimator is formulated to reliably locate the neutral-axis position from measured strain responses under traffic loading. In succession comes the validation of its robustness to noise disturbance through numerical studies in consideration of different levels of noise corrupted in the sensor readings. Then its capability for consistently locating the neutral-axis position under varying traffic load patterns is verified using the field monitoring data of traffic-induced strain responses from the Instrumented Tsing Ma Bridge (TMB) which carries both highway and railway traffic.

NEUTRAL-AXIS POSITION BASED DAMAGE DETECTION

Beam-like bridge deck behaves like a flexural beam when traffic loads cause it to bend. According to the Euler-Bernoulli beam theory, the plane cross-sections of a bending beam remain plane after deformation and the strain distribution is linear over the depth of the cross-section. The strains at the bottom and top locations of the section are denoted by ε_b and ε_t, respectively, as shown in Figure 1.

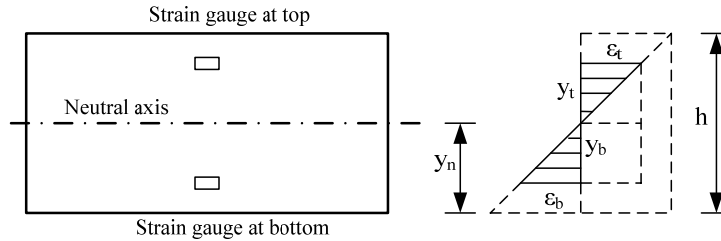*Figure 1. Flexural strain distribution on beam cross-section.*

Following the geometric relation, the ratio of ε_b to ε_t can be expressed as

$$\frac{\varepsilon_b}{\varepsilon_t} = \frac{y_b}{y_t} \tag{1}$$

where y_b is the distance between the bottom and the neutral axis; and y_t is the distance between the top and the neutral axis. From Equation (1), we can obtain

$$\frac{\varepsilon_b}{\varepsilon_b + \varepsilon_t} = \frac{y_b}{y_b + y_t} = \frac{y_n}{h} \tag{2}$$

where y_n denotes the neutral-axis location of the cross-section; and h is the depth of the cross-section.

Equation (2) relates the neutral-axis position in ratio (y_n/h) with the strains at the bottom and top of a cross-section. Under traffic loads, bending behavior dominates the response of beam-like bridge deck. When the strain responses at the top and bottom points are measured, the neutral-axis position can be estimated by

$$\hat{r} = \frac{\varepsilon_b}{\varepsilon_b + \varepsilon_t} \tag{3}$$

The KF has been formulated to use measurements observed over time (containing noise and other inaccuracies) to produce values that tend to be closer to the true values of the measurements [5, 6]. In this study, the neutral-axis position in ratio ($r = y_n/h$) is taken as the state variable to be estimated.

NUMERICAL SIMULATION

A finite element model (FEM) of a beam-like bridge deck model is formulated using 3D solid elements in the commercial software ANSYS and used to carry out the numerical simulation on estimating the neutral-axis position from strain responses (noise-free and noise-corrupted) under moving loads. The simulated deck model is 6 m in length and the material grade is BS4360-43A. Its elastic modulus and yielding strength are 205 GPa and 275 MPa, respectively, and the Poisson's ratio is 0.3. In the simulation, two kinds of boundary conditions (simply-supported and fix-ended) are considered, and strain responses at the top and bottom of the mid-span section are acquired for neutral-axis position estimation.
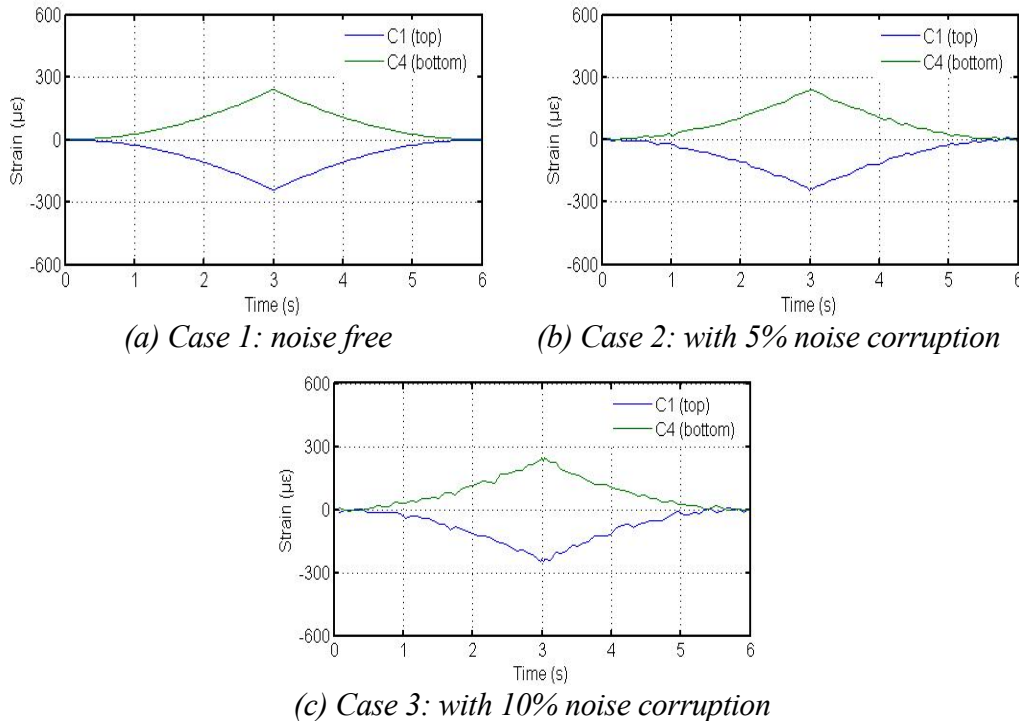

(a) Case 1: noise free   *(b) Case 2: with 5% noise corruption*

(c) Case 3: with 10% noise corruption

Figure 2. Simulated strain responses at top and bottom of mid-span section.

(a) Case 1: noise free 　 *(b) Case 2: with 5% noise corruption*
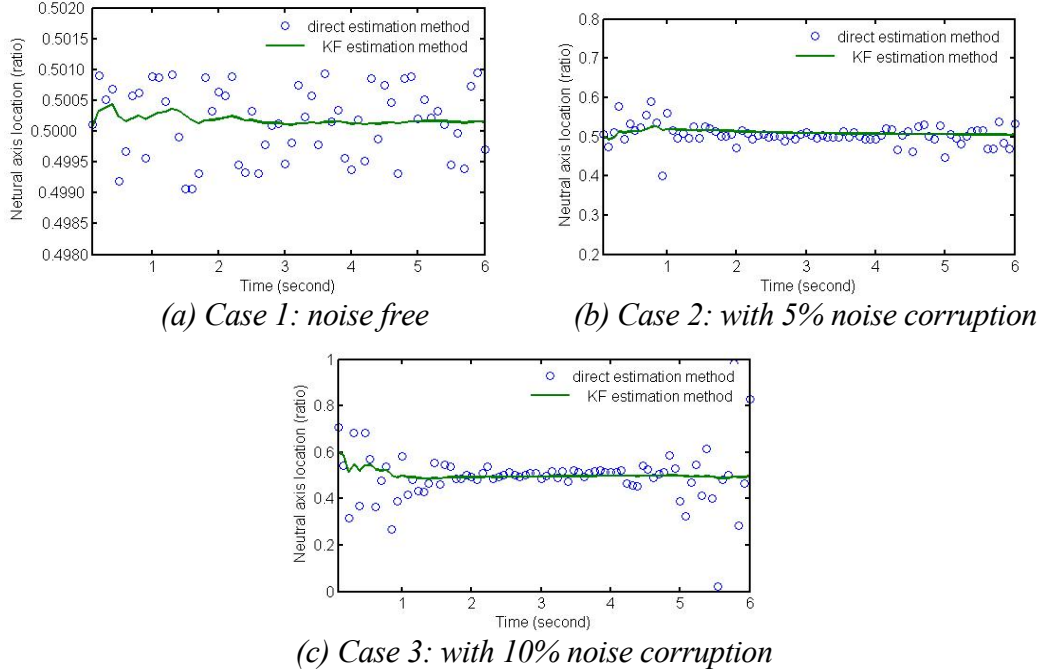

(c) Case 3: with 10% noise corruption

Figure 3. Comparison between direct and KF methods.

Figure 2 shows the calculated strain responses at the top and bottom of the mid-span section under different noise levels with simply supported ends under a moving load with a velocity of 1 m/s. A comparison of the estimation results of the neutral-axis position by the direct and KF methods under different noise levels is illustrated in Figure 3. In Case 1 (noise-free), both the direct method and KF estimator can provide a reliable estimation of the neutral-axis position. With the increase of noise extent, however, the performance of the direct method deteriorates seriously. Contrarily, the KF estimator achieves greatly improved estimation results. The relative errors of the estimated values of the neutral-axis position in the three cases are 0.030%, 0.044%, and -0.092%, respectively, demonstrating the robustness of the KF estimator in estimating the neutral-axis position in the presence of measurement noise.

VERIFICATION USING FIELD MONITORING DATA

Tsing Ma Bridge (TMB)

The TMB with a main span of 1,377 m, as shown in Figure 4, is a suspension bridge in Hong Kong carrying both highway and railway traffic. The deck of TMB is a double-deck box with truss stiffening and non-structural edge fairing as illustrated in Figure 5. The longitudinal diagonally braced trusses on north and south sides of the cross-section consist of top chords, diagonal struts and bottom chords. As part of a long-term SHM system instrumented on TMB [7], 110 strain gauges were installed to measure dynamic strain response at three bridge deck sections denoted by CH23488, CH23623 and CH24662.5 (chain mileages of the deck sections of TMB) as shown in Figure 5. The strain data were continuously acquired at sampling rates of 25.6 Hz and 51.2 Hz, respectively.
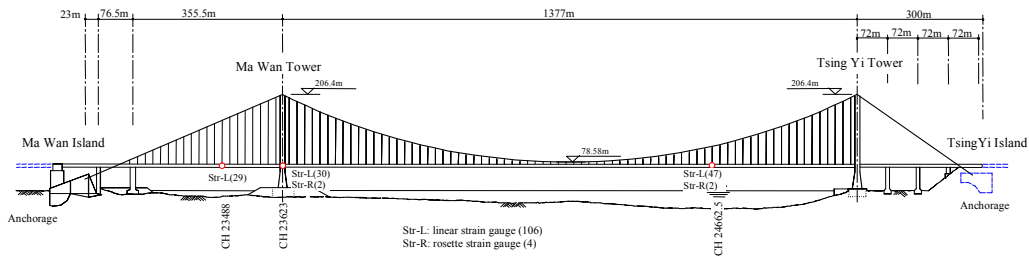
Figure 4. *Tsing Ma Bridge*

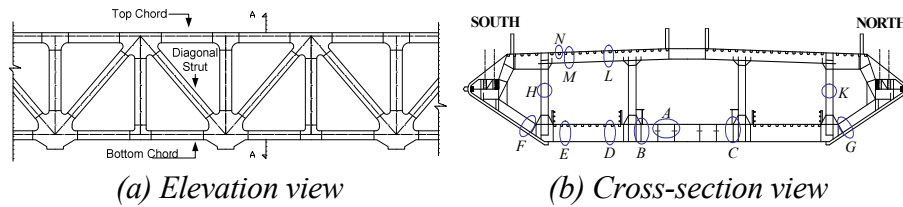*(a) Elevation view*   *(b) Cross-section view*

Figure 5. Deck trusses of TMB.

Estimation of Neutral-Axis Position

Figure 6 illustrates the traffic-induced strain responses experienced by the longitudinal top and bottom chords on deck section CH24662.5 for a typical day (24 hours) under weak wind condition, which are extracted from raw measurement data after eliminating temperature effect [8]. As afore-mentioned, the strain responses acquired during about 2:00 to 5:00 are relatively small because of no railway traffic. It evidences that the strain responses are sensitive to traffic load patterns. Figures 7 to 11 show the estimated neutral-axis position when using the whole-day (24-hour) data and different segments of strain monitoring data. The estimated neutral-axis position ranges from 0.5408047 to 0.5476296 (-0.49% to 0.77% of the mean value) under different traffic load patterns (highway traffic, railway traffic, and their combination). It is concluded that the proposed KF estimator can achieve consistent and robust estimation of the neutral-axis position using strain monitoring data obtained under different traffic load patterns.
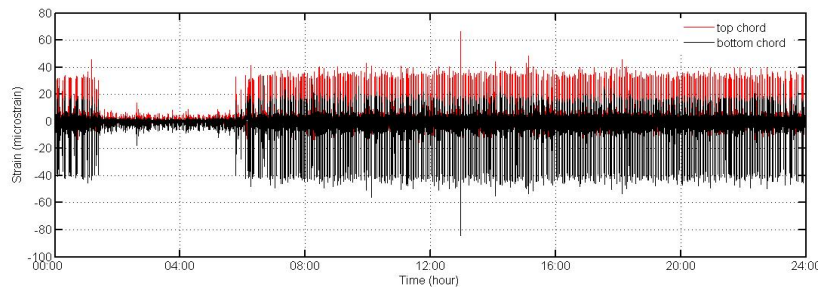

Figure 6. Traffic-induced strain responses experienced by top and bottom chords on deck section CH24662.5 for a typical day.
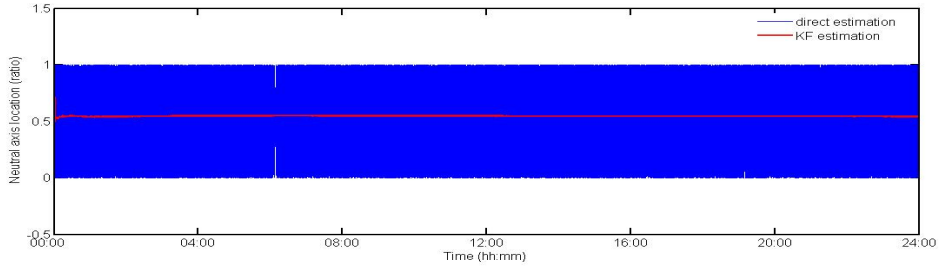
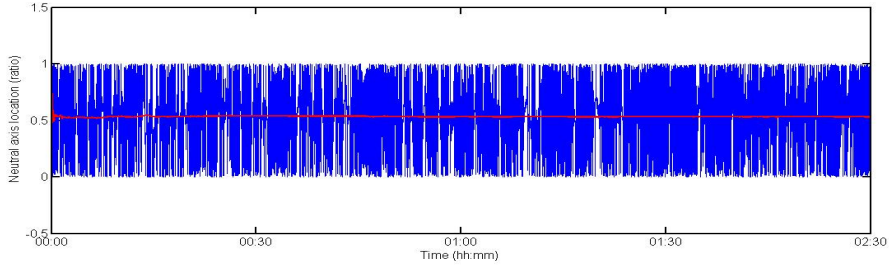*Figure 7. Estimated neutral-axis position from strain data acquired during 00:00 to 24:00.*

Figure 8. Estimated neutral-axis position from strain data acquired during 00:00 to 02:00.
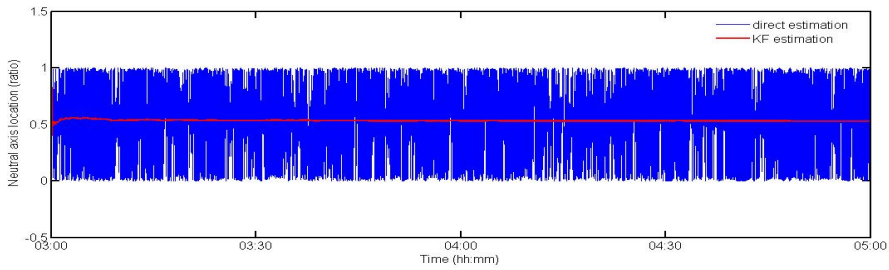

Figure 9. Estimated neutral-axis position from strain data acquired during 03:00 to 05:00.
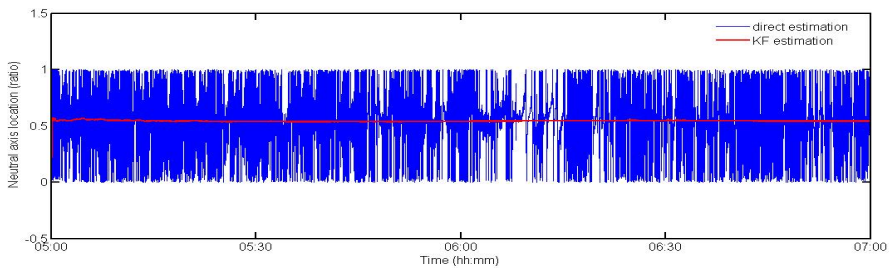

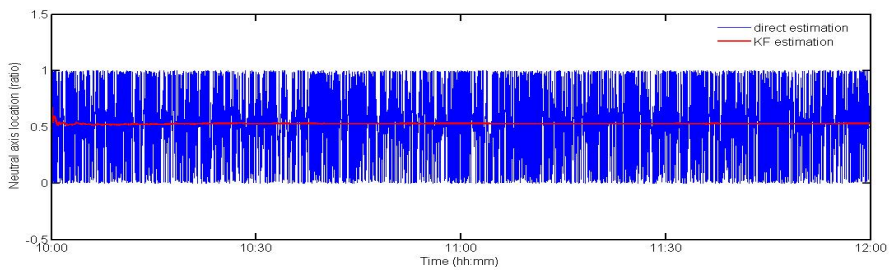*Figure 10. Estimated neutral-axis position from strain data acquired during 05:00 to 07:00.*

Figure 11. Estimated neutral-axis position from strain data acquired during 10:00 to 12:00.

CONCLUSIONS

In this study, a KF estimator was formulated to locate the neutral-axis position of bridge deck from measured strain responses under traffic loading. Its robustness with respect to different levels of measurement noise was testified through numerical simulation and comparing with a direct estimation method. Then its capability for consistently locating the neutral-axis position under varying traffic load patterns was verified using the field monitoring data from the instrumented TMB. From this study, the following conclusions are drawn: (i) the proposed KF estimator greatly improves the estimation accuracy in the presence of measurement noise, and exhibits similar convergence rate under difference noise levels; (ii) the field monitoring data from the suspension TMB evidences the flexural bending behavior of the bridge deck under traffic loading; and (iii) the estimated neutral-axis position from the traffic-induced strain response data of TMB remains almost unchanged under different traffic environments (highway traffic, railway traffic, and their combination), verifying the robustness of the proposed KF estimator to varying traffic loading and the independence of the neutral-axis position on traffic load patterns.

ACKNOWLEDGMENTS

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