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Research Article

Characterization of Nonstationary Mode Interaction of Bridge by Considering Deterioration of Bearing

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As all bridges get deteriorated over time, structural health monitoring of these structures has become very important for the damage identification and maintenance work. Evaluating a bridge's health condition requires the testing of a variety of physical quantities including bridge dynamic responses and the evaluation of the functions of varied bridge subsystems. In this study, both the acceleration of the deck and the dynamic rotational angle of the bearings in a long-span steel girder bridge were measured when the bridge system was excited by passing-by vehicles. The nonstationary dynamical phenomena including vibration mode interactions and coupling are observed in response spectrogram. To elaborate the phenomena, the linear vibration mode properties of the bridge are characterized by finite element analysis and are correlated with the specific modes in test. A theoretical model is presented showing the mechanism of the mode coupling and instability originated from the friction effects in bearing. This study offers some insights into the correlation between complex bridge vibrations and the bearing effects, which lays a foundation for the in situ health monitoring of bridge bearing by using dynamical testing.

1. Introduction

Dynamic features identification is an important step for bridge health monitoring [1–4]. In the past, varied sensors have been widely used in bridge testing to obtain information on bridge performance, such as camera, fiber optic, electrochemical, accelerometer, strain gauge, tiltmeter, acoustic emission, temperature sensors, just to name a few. Bridge responses that are most often measured are acceleration, displacement, and strain, from which the bridge mode parameters are obtained and are used to conduct damage identification. Evaluating a bridge's overall condition requires the evaluation of the functions of varied bridge subsystems, which has been implemented by the testing of a variety of physical quantities in addition to bridge responses.

A typical bridge mainly consists of the superstructure and substructure, whereas the bearings provide an interface between the superstructure and the substructure. Bearings assume functionality of a bridge by allowing translation and rotation to occur while supporting varied loads. The bearings help in allowing certain permitted movements, limiting undesirable movements, and transferring the loads from the superstructure to the substructure. Many of bridges depend on steel bearings to transfer loads between the superstructure and substructure and to contribute to the lateral force resistance under varied loads such as vehicle braking and seismic loads. Steel rocker (expansion) bearings commonly used in highway bridges form interfaces with friction effect between super- and substructures of a bridge. Researches in [5–7] demonstrated that the friction coefficient of expansion bearings together with other factors should be considered during the fragility analysis of the bridge system. For aged bridge bearings, deterioration such as the corrosion of the bearing surfaces and debris build-up at the contact interfaces of steel bearings is unavoidable and could substantially change their originally designed/verified mechanical behavior. In the past, there are quite a number of failures of ill-conditioned steel rocker bearings affecting the proper functioning of the bridge, such as those documented in forensic investigations [8, 9]. However, only a few studies in the past have considered the dynamic behavior of steel bridge bearings [10–17]. Researches in [12, 13] presented computational models for evaluating quasi-isolated bridge systems, where certain bearing components are treated to slide and limit the forces transferred between the superstructure and substructure. In these researches, nonlinear elements were formulated to capture the local bidirectional stick-slip behaviors in the bridge bearings. The studies also used bridge prototype with the anticipated nonlinear behaviors in the structural components defined and implemented in the finite element model of the global structure.

The rocker bearings as vulnerable components due to longitudinal instability have been characterized by different response mechanisms. For example, the contact element of bearing is used to model the pounding between superstructure and abutments in [17], in which the material model is developed to explicitly account for the loss of hysteretic energy. The analytical models considered include the contact force-based linear spring, Kelvin and Hertz models, and the restitution-based stereo mechanical approach. Simple analytical approaches are used to determine the impact stiffness parameters of the various contact models. Parameter studies are performed using simple models such as two-degree-of-freedom linear oscillators to determine the effects of contact/impact modeling strategy, system period ratio, peak ground acceleration, and energy loss during contact/impact on the system responses.

Among the limited literature available on steel bridge bearings, issues concerning bearing friction and dynamic performance are often addressed separately instead of considering the correlation between the two. As a result, there is a significant need for in-depth research on the dynamical performance of bridges and bearings deterioration and friction changes, so as to quantitatively correlate bearings deterioration with bridge dynamic behavior.

On the other hand, traditional measurements of dynamic parameters of structures are based on accelerometers and other kinds of sensors such as strain gauges and displacement sensors. Tiltmeter has been used recently to supplement the bridge health monitoring [18–21], due to the high resolution of the commercial tiltmeter up to 0.001 degree. In this study, both accelerometer and fiber optic tiltmeters are used to monitor the bridge acceleration and bearing dynamic rotational angle. The goal of this research was to characterize complex dynamical vibrational behavior of the aged steel bridge and specifically to correlate the complex dynamical behavior with bearing effects, so as to get a more accurate evaluation of the dynamic performance of in situ bridge for structural health monitoring solutions. This is accomplished through experimental testing of steel bridge and bearings, finite element analysis, and theoretical modeling. The study provides previously nonexistent information about the complex response of the aged bridge excited by passing-by vehicles and the correlation with the aged steel rocker bearing friction. The results from testing, spectrum analysis, and the analyses of the theoretical model with bearing friction offer insights into the nonstationary response and mode interactions of the bridge, which can be used to evaluate the status of the aged bearings and its effect on the overall dynamical properties of the bridge.

2. Bridge Description and Testing Systems

The Chulitna River Bridge (Figure 1(a)) was built in 1970, and this bridge is located at Historic Mile Post 132.7 on the Parks Highway between Fairbanks and Anchorage, Alaska. The bridge is a 790-foot long, 42 feet 2 inches wide, 5 spans continuous bridge with two exterior steel plate girders and three substringers. Three longitudinal steel trusses were installed utilizing the stringers as top chords to reinforce the bridge. Figure 1(b) shows the bearing condition at the bridge end.

In order to monitor the overall response of the structure, accelerometers are placed on the surface of the bridge deck for the longitudinal vibration measurement. The expansion bearing is located at the bottom of the deck. The tiltmeter was installed on the expansion bearing as shown in Figure 2(a). Figure 2(b) shows the three-dimensional schematic drawing of the rocker bearing. In principle, the fiber optic tiltmeter operates using a beam of light, a shield, and a sensor. Depending on the angle of inclination, the amount of light passing through the shield changes, causing a change in intensity. Measuring this change in intensity allows for a calculation of the angle of inclination.

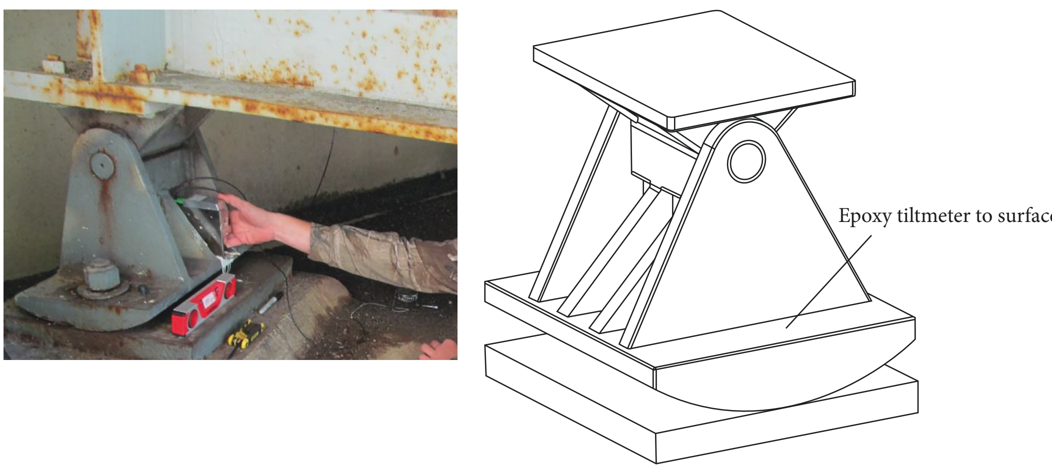
The expansion bearing is a rocker-type expansion bearing which consists of a pin at the top that facilitates rotations. The rotation of bearings can accommodate the bridge longitudinal movement. The tiltmeter can not only record rotation or deflection but also provide the dynamic feature based on signal process technology. The sensor with very high accuracy can provide nonstop and long-term angle monitoring. The tiltmeter has a measurement range of 8 degrees and has a resolution of ±0.05% FS. A built-in temperature compensated to adjust the temperature effect on the measurement. The sampling rate of the fiber optic tiltmeter is determined by the optical sensing interrogator. The optical sensing interrogator sends the wide-spectrum light to optical sensors and indicates the changing of reflected wavelength from the optical sensors. The Chulitna River Bridge health monitoring system selected the Optical Sensing Interrogator sm130, the scan frequency is 1000 Hz, and the sampling rate for the fiber optic tiltmeter is 250 Hz [22]. As such, the high accuracy tiltmeter sensors can monitor the structural dynamic movements.

3. Dynamic Test and Dynamic Properties Characterization

A dynamic load test was conducted on the bridge by using a truck. The truck was heading to the south direction with the speed of 45 mph. Figure 3(a) shows the acceleration response of the bridge when the truck left. The bridge is in a free-decay response when the truck left the bridge, and this study uses free-decay response to identify the bridge dynamic features.

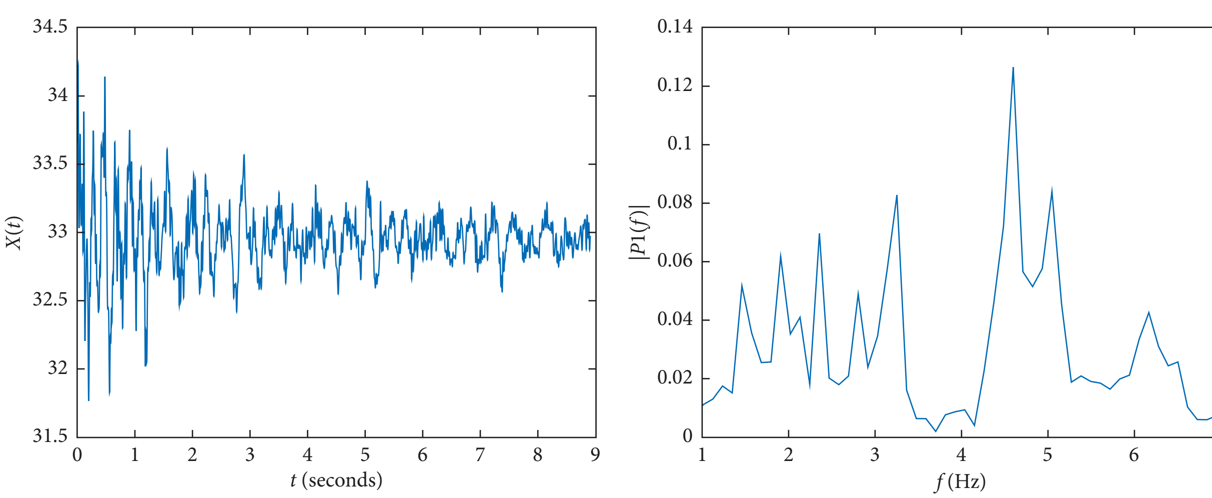
(a) (b)

Figure 1: Photographs of the bridge system: (a) Chulitna River Bridge and (b) expansion bearing condition.



(a) (b)

Figure 2: Picture of the tiltmeter: (a) installed tiltmeter on bearing and (b) three-dimensional drawing of bearing.



(a) (b)

Figure 3: Measured acceleration and FFT when the vehicle left: (a) time history and (b) FFT of the accelerometer signal.

The dynamic characteristics of the structure were extracted by converting the time domain data to frequency domain data. Figure 3(b) is the FFT of the vibration signal after trucks left the bridge. Figure 3(b) shows the merging of two modes (4.6 Hz and 5.0 Hz) and forms a narrow band. A second dynamic load test was conducted by using two trucks.

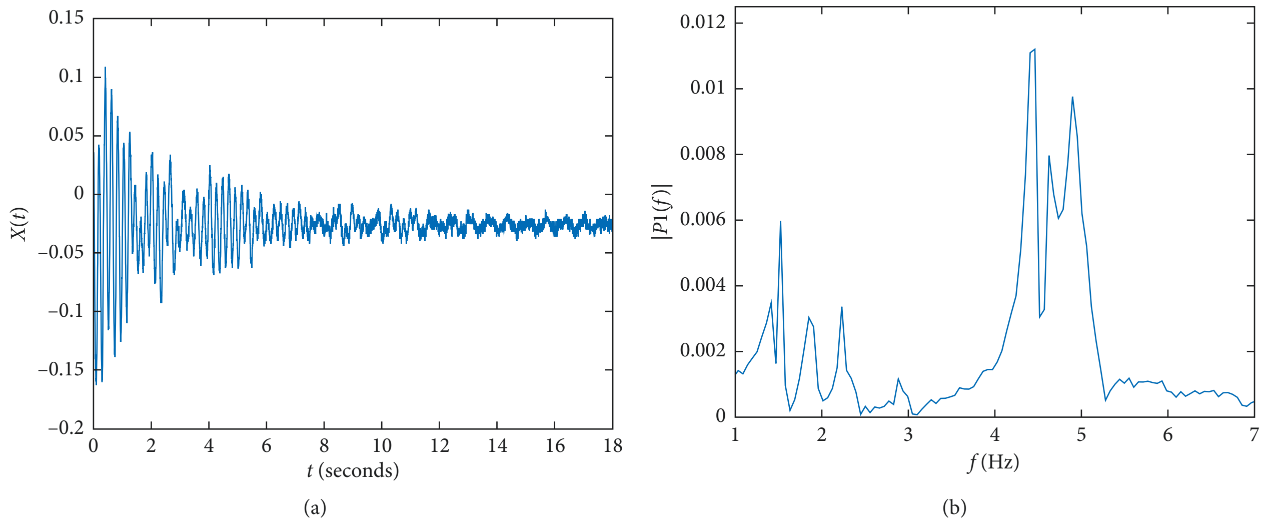


Figure 4: Measured tiltmeter signal and FFT when the vehicles left: (a) time history and (b) FFT of the tiltmeter signal.

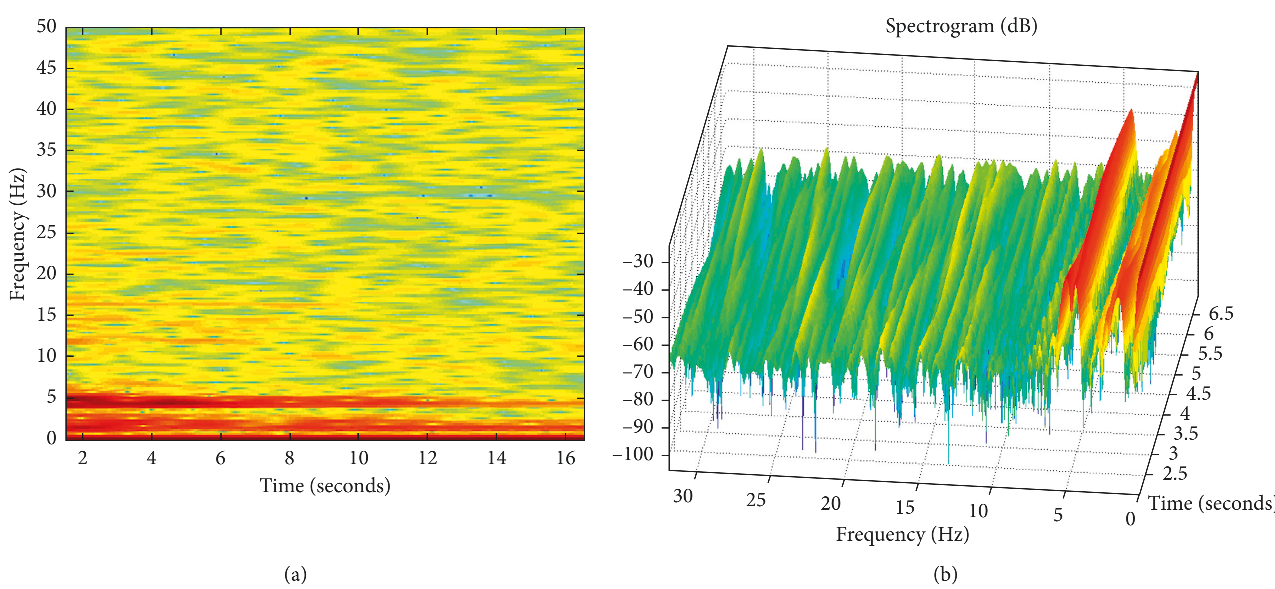


Figure 5: Spectrum of the tiltmeter signal of bearing: (a) spectrogram and (b) 3D spectrogram.

The two trucks were side by side heading to the north direction with the same speed. Figure 4(a) shows the tiltmeter signal of bearing when the trucks left. Figure 4(b) shows the results of FFT spectrum of the tiltmeter signal. It shows the dominant specific frequency at 1.50 Hz, and a narrow band between 4.4 Hz and 5 Hz, which are consistent with the spectrum of acceleration shown in Figure 3(b).

To further characterize the nonstationary response and narrow band in spectrum, time-frequency analysis is conducted. Figure 5 is the corresponding spectrograms of the tiltmeter signal, which shows the specific vibration mode exhibiting nonstationary features. It is noted that the 3D spectrum shows that the specific mode of 5 Hz and 4.5 Hz merged to be an identical one after several seconds from the starting point. The merged mode peak in between 4.5 and 5 Hz can also be found in Figure 4(b).

4. Linear Mode Characterization by Using Finite Element Analysis

To clarify the dynamic characteristics obtained from the acceleration and tiltmeter testing, a bridge finite element model was built by using SAP2000 according to the as-built plans. Based on the modal participating mass ratios, the first three longitudinal modes have been identified successfully through the numerical mode analysis. Figure 6(a) is the first mode of longitudinal vibration, Figure 6(b) is the second mode of longitudinal vibration, and Figure 6(c) is the third mode of longitudinal vibration. The derived natural frequencies are, respectively, 1.58, 4.35, and 5.06 Hz. According to identified mode shapes, there exists a large longitudinal displacement at the end bearings for each mode, and it will directly cause the dynamic rotation at the rocker bearings.

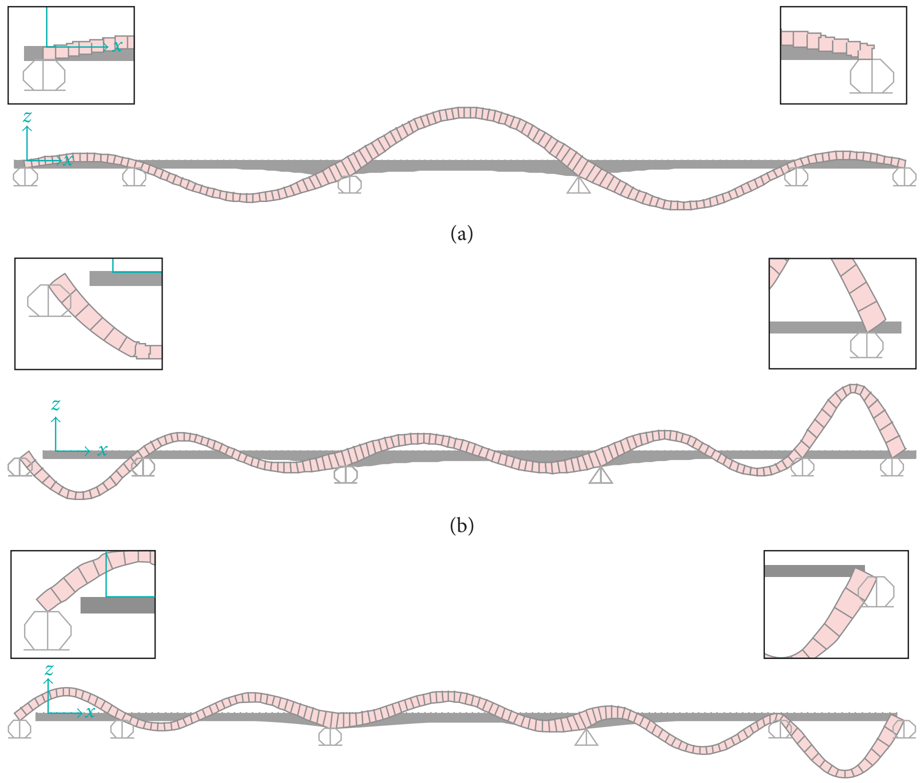


Figure 6: Longitudinal mode shapes from FEM analysis: (a) mode 1 (1.58 Hz; modal participating mass ratio 0.1), (b) mode 2 (4.35 Hz; modal participating mass ratio 0.17), and (c) mode 3 (5.06 Hz; modal participating mass ratio 0.18).

The results from the bridge finite element model illustrate that there exists a strong correlation between longitudinal motions and bearing rotation motions, as such the monitoring of the rotation motion of expansion bearings can be used to evaluate or extrapolate the bridge longitudinal dynamic features. This suggests that the longitudinal motion features could be affected by the bearing motion status. The further analysis of this correlation will be given in the following section.

5. Complex Mode Interactions and Mode-Coupling Mechanisms

It is noted that the free-decay response of the bridge recorded in bearing tiltmeter signal exhibits nonstationary pattern as shown in Figures 4 and 5 and also exhibits complex mode variations and interactions, specifically the mode-merging as shown in Figure 5(b). Bearings provide the connection between the superstructure and substructure of a bridge system. Under service conditions, bearings transmit the dead load and traffic load from the superstructure to the substructure while also accommodating relative movements between the superstructure and substructure caused by the thermal action and vehicular loading. Bearings also provide lateral resistance in both the longitudinal and the transverse directions under extreme loads such as collisions, winds, and earthquakes. Conventionally, bridge bearings have been designed and selected in terms of standard procedures and guidelines [23, 24]. The behavior of steel bearings at the contact interface is dictated by hard contact in the normal direction allowing transfer of vertical load from the superstructure to the substructure and by Coulomb friction (with coefficient of friction in the level of 0.01), rolling resistance, and bearing in the tangential direction providing lateral resistance to horizontal actions such as thermal action, wind, vehicular forces, and so on. Steel bearings with cylindrical contact surfaces have a line of contact that will yield to a rectangular contact plane. For sliding bearings, horizontal force resistance can be determined ideally as the product of the friction coefficient and normal force. As a result of deterioration, the contact surfaces of a steel bearing can undergo corrosion and are build-up of debris, which affects the tangential behavior at the contact interfaces due to the increase of the friction coefficients resulting from the condition of the contact surfaces and changes to the contact area. The aged bearing could have a much higher coefficient of friction compared with newly clean bearing [10, 25, 26]. Mazroi et al. [25] studied a class of steel bearings including pinned rocker bearings to determine their effective friction coefficients under as-built, corroded, and in situ conditions. The conducted tests were restricted to monotonic displacement-controlled loading under constant vertical loads. It was found that the effective coefficient of friction increased to 0.02 for corroded pinned rocker bearings and 0.09 for in situ pinned rocker bearings compared to 0.01 for clean pinned rocker bearings. In addition, results of the sensitivity study showed a significant dependence of the behavior of pintle rocker bearings on the variation in the radius of the sole plate socket. This study comprehensively demonstrated the effects of corrosion on the monotonic behavior of steel bridge bearings. Mander et al. [26] carried out one of the most comprehensive experimental studies of steel bearings by considering the cyclic behavior of salvaged steel bearings. In the longitudinal direction, quasi-rectangular hysteresis loops were observed from the test results indicating that the rocker specimens obeyed a Coulomb friction law. These rocker specimens were grouped by corrosion levels (i.e., heavy and mild), and the test results revealed that heavily corroded bearings had equivalent friction coefficients in the range of 0.07 to 0.1, while for mildly corroded bearings equivalent friction coefficients varied between 0.02 and 0.04.

On the other hand, it is noted that if system friction coefficient increases to a relatively high level, the vibration system has the likelihood to have two close natural modes be coupled to form an identical one in-between the original two leading to instability vibrations [27]. In terms of the friction dynamics principle, the mode-coupling phenomenon could occur if bearing friction is large enough at a certain phase, as shown in the 3D spectrogram in Figure 5(b), in which the two modes (4.47, 4.90 Hz) coupled at about 3.5 second to form an identical mode peak. Since the response decay process is associated with the relative speed variation of bearing, whereas the friction is typically speed-dependent, the bearing motion at 3.5 second may experience relatively larger friction. As such, to obtain a deep understanding of the mode interactions, the effect of friction should be incorporated. The above proposed mechanism can be further elaborated by using the following friction involved complex eigenvalue analysis.

Larger friction effects between the roller and base plate could lead to a self-excitation mechanism which may change the bridge system's linear dynamic natural mode properties quantified by finite element analysis in Section 4. The natural mode properties are characterized by linear eigenvalue problem which yields the natural frequencies and mode shapes as given in Section 4. However, larger friction in a system could transfer the real eigenvalue problem to be a complex eigenvalue problem which consists of eigenvalues with positive real part and accordingly leads to mode coupling or instability of the system. In a dynamic governing equation of mass and structural stiffness, existence of friction leads to the nonsymmetric stiffness matrix. A complex eigenvalue problem is usually attained for a system containing contact friction interface. Consider a multi-degree-of-freedom system consisting of a contact sliding interface with the coefficient of friction μ. The equation of motion of the system can be expressed as

$$[M]\{\ddot{u}\} + [K]\{u\} = \left\{F_f\right\}, \tag{1}$$

where $[M]$ and $[K]$ are the mass and stiffness matrices for the nonfriction system, respectively, $\{u\}$ is the displacement vector, and $\left\{F_f\right\}$ is the friction force vector of the systems. The friction system consists of an interface with contact and is connected in the normal direction, but not in the tangential direction. The tangential friction can be modeled as follows:

$$\left\{F_f\right\} = \mu\left(\left\{N_{\text{static}}\right\} + \left\{N_{\text{dynamic}}\right\}\right), \tag{2}$$

where $\left\{N_{\text{static}}\right\}$ and $\left\{N_{\text{dynamic}}\right\}$ are the static and dynamic normal forces, respectively. For the solution of the eigenvalue problem, the static force is removed from the equation of motion. The dynamic normal force is caused by the vibration of the subsystem 1 and subsystem 2 and is represented by

$$\left\{N_{\text{dynamic}}\right\} = K_s\left(\{u_{N1}\} + \{u_{N2}\}\right), \tag{3}$$

where $\{u_{N1}\}$ and $\{u_{N2}\}$ denote the displacements of the interface in the normal direction, and K_s is the local contact stiffness. Hence, the system equation of motion becomes

$$[M]\{\ddot{u}\} + [K]\{u\} = -\mu K_s\left[K_f\right]\{u\}. \tag{4}$$

The matrix K_f is the effective stiffness due to friction in the interface. It is a nonsymmetric matrix that couples the relative normal displacement with the tangential force. If the system has no friction, it can be expressed as

$$[M]\{\ddot{u}\} + [K]\{u\} = \{0\}. \tag{5}$$

The solution of (5) for the bridge system is given in the above finite element analysis in Section 4. The modal domain transformation can be obtained from the equation as

$$\{u\} = [\psi]\{\gamma\}, \tag{6}$$

where $[\psi]$ is the modal matrix of system equation. $\{\gamma\}$ is the modal coordinate vector. With the modal transformation, the following relationship can be established:

$$[\psi]^T[M][\psi] = [I], \tag{7}$$

$$[\psi]^T[K][\psi] = \begin{bmatrix} \omega_1^2 & 0 & \cdots & 0 \\ 0 & \omega_2^2 & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & \omega_n^2 \end{bmatrix}, \tag{8}$$

where ω_i is the ith natural frequency of system equation (5). From (7), (8), and (4), if the system has friction involved, then the complex eigenvalue equation is attained as follows:

$$\left\{ s^2 \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & 1 \end{bmatrix} + \begin{bmatrix} \omega_1^2 & 0 & \cdots & 0 \\ 0 & \omega_2^2 & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & \omega_n^2 \end{bmatrix} + \mu K_s\left[\Lambda_f\right] \right\}\{\gamma\} = \{0\}. \tag{9}$$

It is noted that the above equation represents a complex eigenvalue problem for which the eigenvalue could have positive real part leading to an instable solution. Specifically, sufficient friction increase could lead to two close modes to be coupled to be an identical mode associated with the instability [27]. There are limit-cycle oscillation solutions in a multi-degree-of-freedom system with friction. The linear complex mode analysis can be used to predict the onset of the mode coupling and limit cycle. Although it cannot predict the magnitude of limit cycle and the characteristics of the limit cycle, it helps to gives stability margin or threshold.

6. Conclusions

In this study, both the acceleration of the deck and the dynamic rotational angle of the bearings in a long-span steel girder bridge are measured when the bridge system was excited by passing-by vehicles. The measured acceleration of the deck exhibits very rich information of system vibrations of the bridge, whereas the tiltmeter signal of dynamic rotational angle from bearing gives more information of bridge vibrations associated with bearing. In addition to the primary natural modes, spectrum analysis of the response also shows that the tiltmeter signal exhibits nonstationary mode interactions. The specific modes are quantified by the numerical finite element analysis. The theoretical modeling elaborated that the observed mode interactions could be due to the bearing friction-induced mode coupling. This study offers some insights into the correlation between complex bridge vibrations and the bearing deterioration effects. The identified bridge dynamic features can be used as an index for model updating and damage detection, which lays a foundation for the in situ health monitoring of bridge bearing by using dynamical testing.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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