Monitoring of Bridges Damage Based on the System Transfer Function Maps from Sensors Datasets

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Abstract. To ensure the normal service of the bridge, it is necessary to detect and evaluate the health status of the bridge structure. This work provides a novel framework for damage detection in trusses bridges through analyzing of displacement sensors datasets and plotting the frequency maps of bridge system transfer function (TF). First, the bridge finite element model under random load is analysis, and the cumulative damages are considered and introduced to bridge model. The datasets of the sensors installed in bridge are compiled in both static and transient types. Finally, the bridge structure TF is determined by applying the principles of open loop control system on bridge structure and then plotting the frequency maps. The results show that the system becomes unstable in frequency maps when damage evolves in bridge structure.

Keywords: Bridges Structure Systems · Damage Detection · Displacement · Open Loop System · Transfer Function · Frequency Analysis

1 Introduction

In recent years, the construction of bridge structures has developed rapidly, and the health monitoring of bridge structures has become a research hotspot at home and abroad. Reasonable configuration of sensors is the premise to ensure the quality of bridge structure health monitoring, and it is very important to obtain accurate and real-time information on the health status of bridge structures and realize the monitoring and evaluation of bridge structures [1–12].

Bridges have been under the heavy pressure of vehicles for many years, and the judgment of whether it is "healthy" is mainly based on manual inspections. It is difficult to achieve real-time, continuous and uninterrupted monitoring, and the efficiency is low and there are visual blind spots. Nowadays, more and more traffic managers use intelligent and digital means to automatically capture various structural safety-related data such as environmental temperature and humidity, expansion joint displacement, etc.

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through the bridge and tunnel structural health monitoring system, identify and record the development of existing diseases in real time, Discover new diseases and report to the police, assist in decision-making and judgment, reduce maintenance costs, and improve monitoring efficiency and quality [13–25].

The bridge structure of the time-frequency domain characteristics is detected, but the number of frequency domain features in the original time is large, which adversely affects the efficiency of the health state detection of the bridge structure. In the process of the health state of the bridge structure, the selection of the detection algorithm is also very important [10–12].

A frequency response function (FRF) of the system using a signal of conventional valve closing is proposed to study the different faults effects, the viscoelasticity, and friction of pipe wall on that function and then compare it with corresponding influences the time domain [26]. The appropriately of FRF in transient mode method for complex pipelines leakage detection is investigated [27]. A FRF method that require measuring pressure and fluctuations of discharge at single location was used to detect the possibility of leaks in real piping systems carrying various types of fluids [28]. The simplification method of FRF system's analytically based approach was performed to determine the key blocking parameters that controlling on the frequency shift. It was shown that the of blockage severity follows that the increases of frequency shift magnitude related to wave propagation, and impedance of the pipe coefficients such as pipe diameter, thickness and/or wave velocity [29].

This paper discusses a new strategy of damage detection of bridges structure in static and transient sensing methods using displacement sensors, the displacement as system inputs and outputs of TF system is proposed, and the "open loop" bridge system is applied. As far as the author knows, no work has been done on new damage indicators based on "systems control theory" for bridge structures. By applying static and dynamic load to the displacement sensor distributed on bridge, damage area of the bridge.

2 Bridge Modeling

2.1 Bridge Description

Figure 1 shows a graphical representation of the truss bridge. The bridge is a combination of I-shaped, U-shaped, box-shaped and other cross-sections. The bridge's height is 4.25 m, its total length is 33.5 m, and its wide is 5.5 m. The truss high is 4.4 m. The average daily traffic is about 19066 vehicles northbound and 231748 southbound. The random excitation (−300–300 kN) is shown in Fig. 2, The corresponding elastic modulus value was, $E = 210\,\text{GPa}$, and the Shear modulus value was $G = 10.64$ GPa, Poisson coefficient was υ QUOTE ν_3 $\nu_3 = 0.3$, and the density was $7,860\ \text{kg/m}^3$. Various sensors were installed on the trusses and longitudinal deck of bridge as shown in Fig. 3 the sensors positions in red boxes. An appropriate finite element is selected, i.e. the LINK1 element is used to model the structural behavior with material model EX 210000.

Figure 4 shows the acceleration responses of random excitation measured from the various sensors installed on the trusses and longitudinal deck of bridge.

Changes in acceleration response due to damage effect on structural. Therefore, the response of the acceleration in time-history is sensitive to structural damage and can be considered as a damage indicator.

Fig. 1. General View of truss bridge.

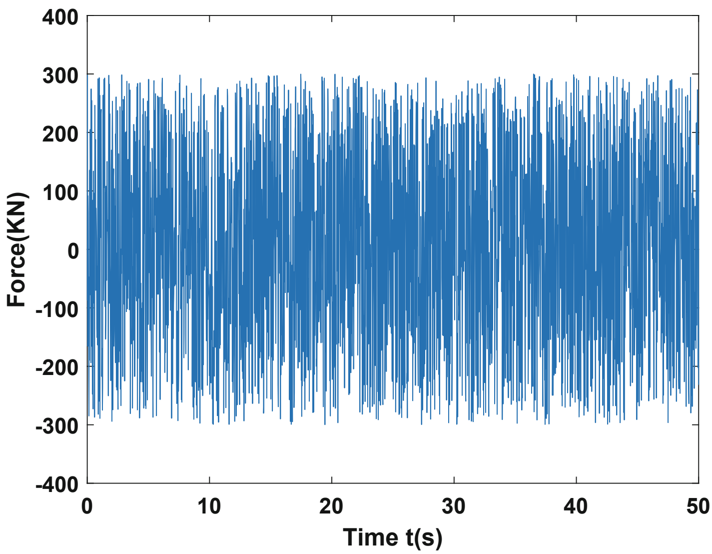


Fig. 2. Random Excitation.

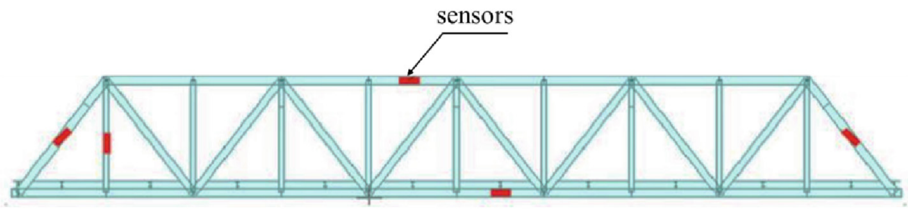


Fig. 3. Finite Element Bridge Modeling.

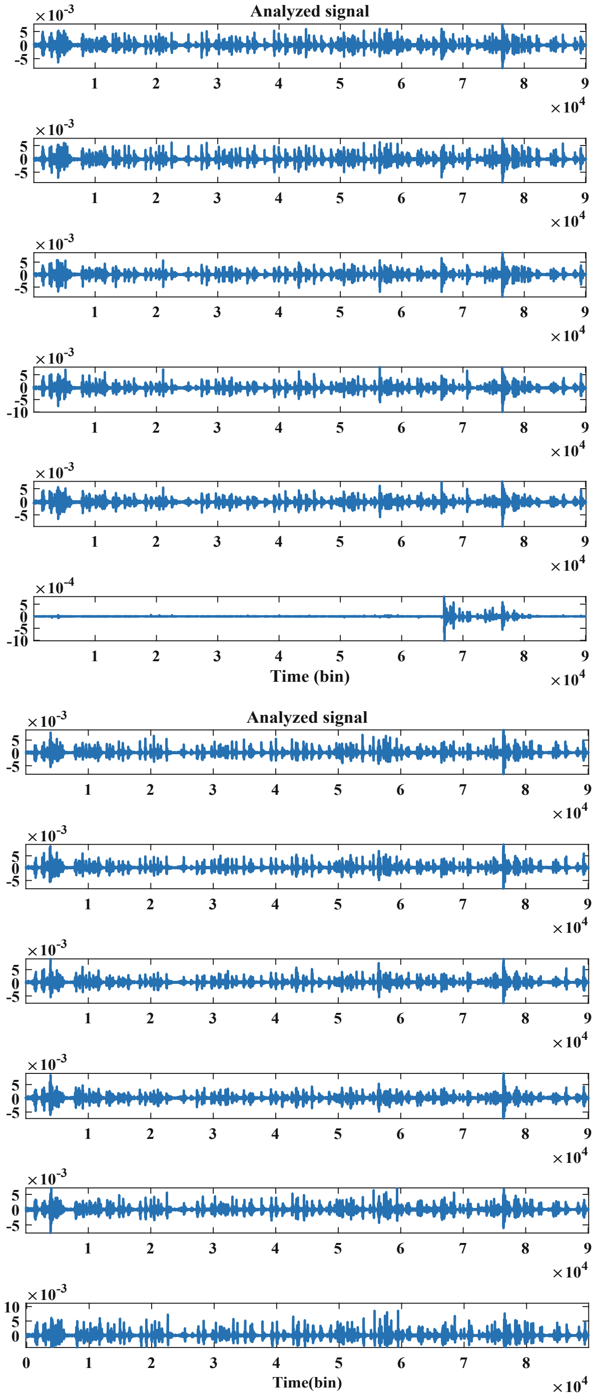


Fig. 4. The acceleration of random excitation.

Table 1. Structural frequency.

Frequency Order	D0 (Hz)	D1 (Hz)
1st order (Lateral Bending)	233.55	232.85
2nd order (Vertical Bending)	315.62	312.67
3rd order (shear)	824.38	822.90

Figure 5 shows the energy variations strength or shows at which frequencies variations are strong and at which frequencies variations are weak. Any changes in the PSD can be used as indicator of damage. Also, it can be used to reduce the effect of noise in the signal and also can be used to trace the damage through the curvature of the power spectrum energy. If tracking the ridge though time-frequency energy distribution and show any change due to damage. The energy variations strength or shows at which frequencies variations are strong and at which frequencies variations are weak. Any changes in the PSD can be used as indicator of damage. Also, it can be used to reduce the effect of noise in the signal and also can be used to trace the damage through the curvature of the power spectrum energy.

Table 1 lists all the values of frequency orders for different damage case (D0 & D1).

3 Results and Dissections

3.1 Acceleration Responses Analysis in the Frequency Domain

Accounting for modeling uncertainty, typical fitting curve (Mean) of acceleration select change response (Eq. 2) for output description of the structure system field excitation by random input, where the Cubic, Quadratic, Linear, and Constant terms of the fitting equation are 0.0287, −0.0016, 0.0063, 0.0005, respectively.

$$X(t) = 0.0287t^3 - 0.0016t^2 + 0.0063\text{t} + 0.0005 \tag{1}$$

The differential equation can represent herein:

$$\begin{aligned} a_0x_o^{(n)}(t) + a_1x_o^{(n-1)}(t) + \cdots + a_{n-1}x_o^{(1)}(t) + a_nx_o(t) \\ = b_0x_i^{(m)}(t) + b_1x_i^{(m-1)}(t) + \cdots + b_{m-1}x_i^{(1)}(t) + b_mx_i(t), n \\ \geq m \end{aligned} \tag{2}$$

where x_o is the system output, x_i is the system input.

$$G(s) = \frac{X_o(s)}{X_i(s)} = \frac{b_0s^m + b_1s^{m-1} + \cdots + b_{m-1}s + b_m}{a_0s^n + a_1s^{n-1} + \cdots + a_{n-1}s + a_n} \tag{3}$$

System input can be expressed as:

$$X_i(s) = \frac{2232\pi}{s^2 + 35642\pi^2} \tag{4}$$

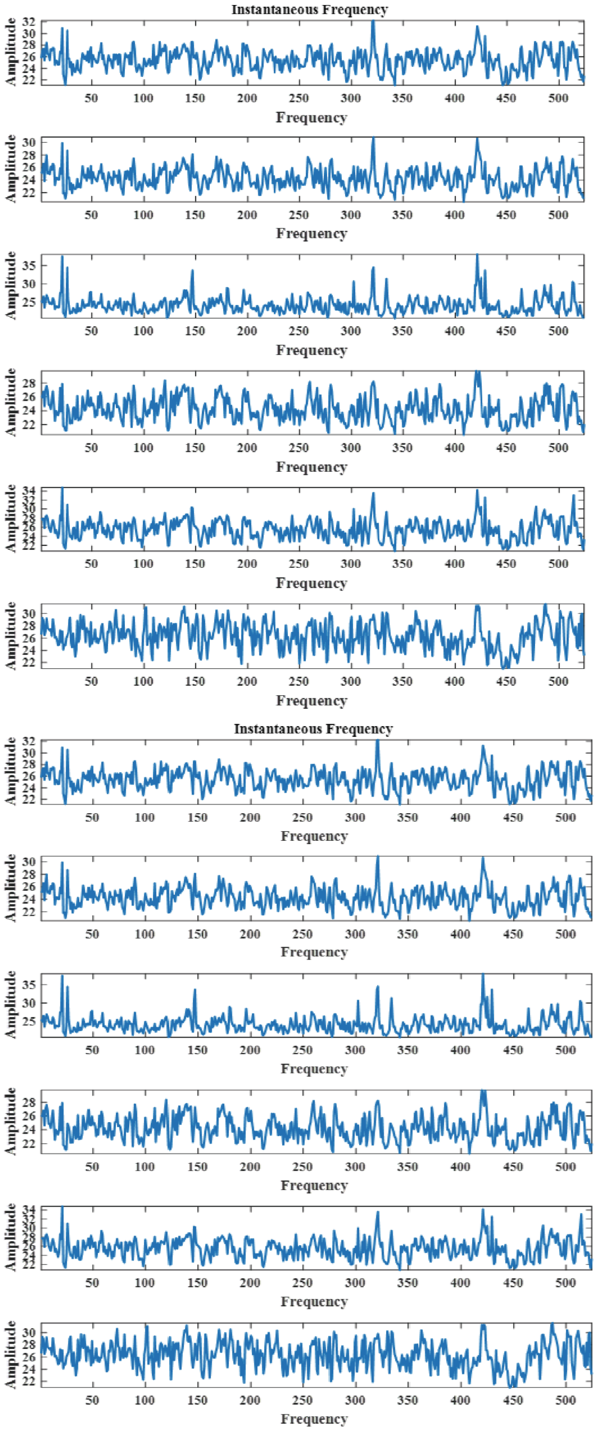
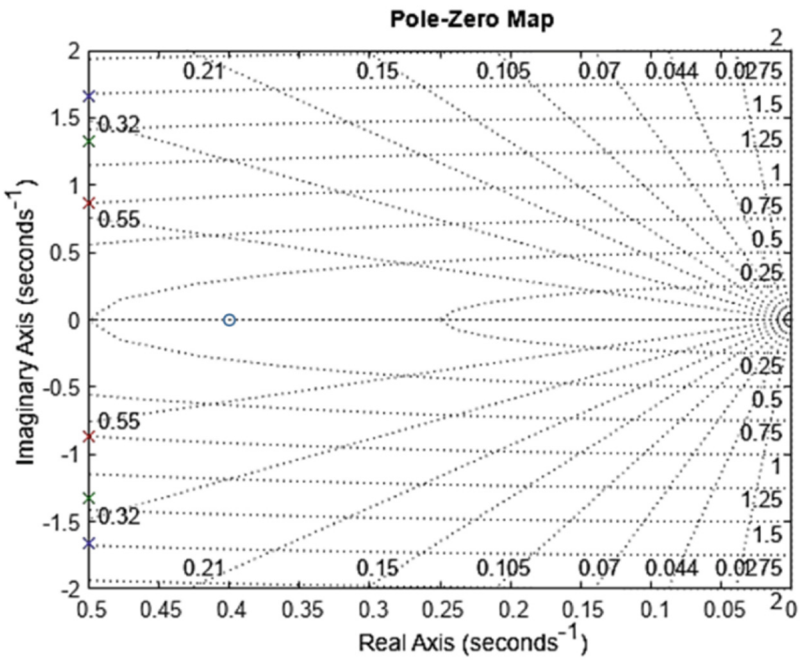
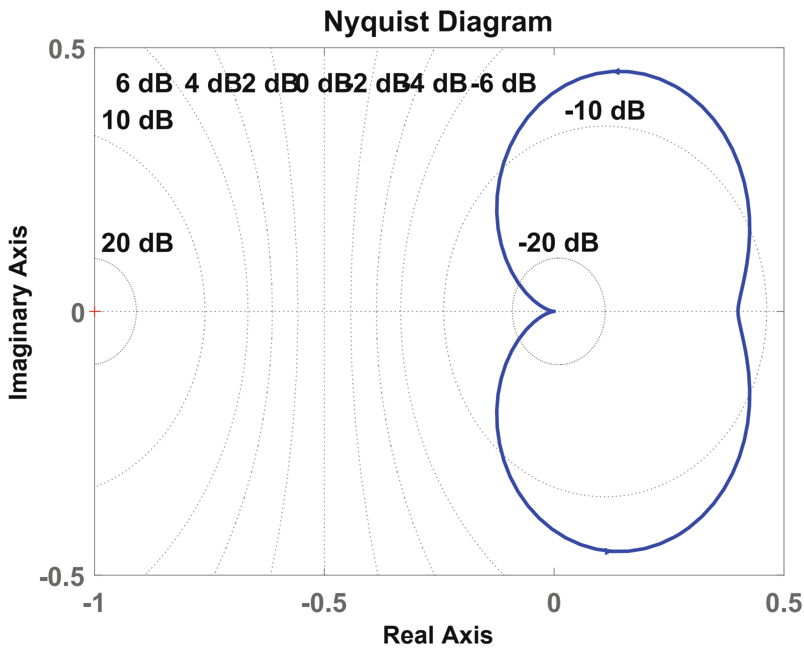


Fig. 5. The Power spectral density.

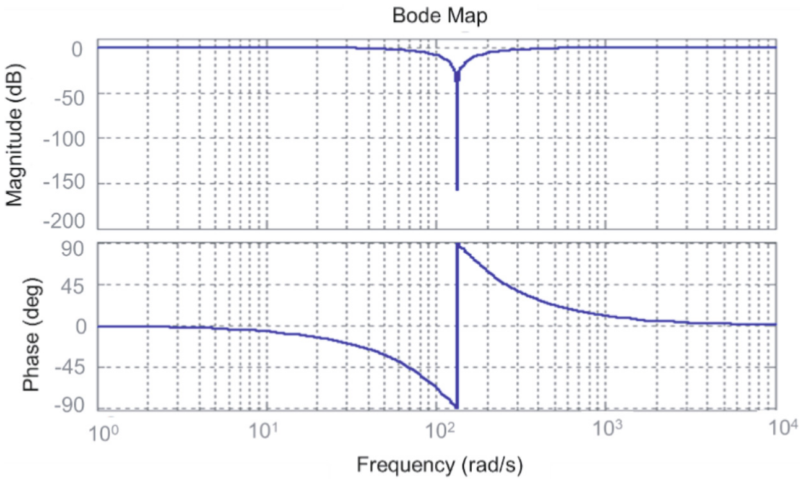


(a) Pole-Zero Map

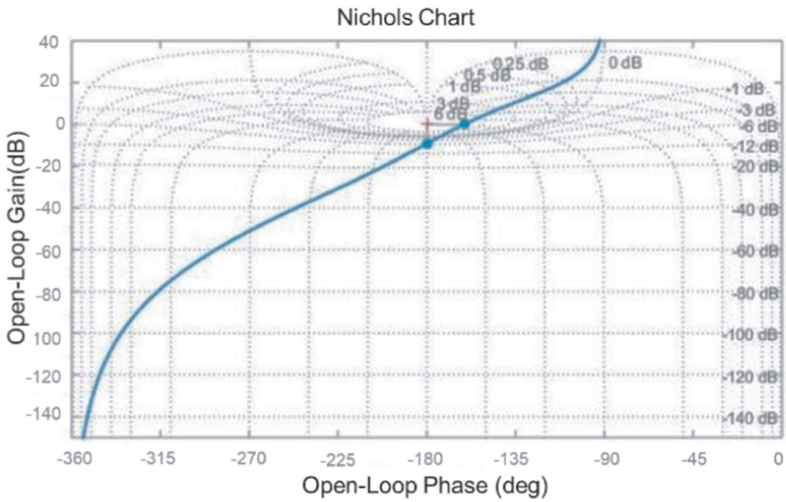


(b) Nyquist Map

Fig. 6. The frequency domain analysis methods for steel truss bridge.



(c) Bode Map



(d) Nichols Map

Fig. 6. (*continued*)

System output can be expressed as:

$$X_o(s) = \frac{213}{854s^4} - \frac{1}{2232s^3} \tag{5}$$

System TF can be expressed as follows according to the presented damage case (D1).

$$G_1(s) = \frac{\left(s^2 + 35642\pi^2\right)(854s - 11160)}{2.5E9\pi s^4} \tag{6}$$

3.2 Bridge System Analysis in Frequency Domain

The bridge system subjected to different conditions of damage features when excited by a random signal input. Let us regard it as a "control system" with an input excitation and an output measurement sensors. When considering the system as an open loop control system, this means that no feedback from output to the system, the main control on the system is from input only. The frequency domain analysis methods (Zero-Pole, Nyquist, Bode, Nichols) are applied to measure the dynamic response characteristics of the system regarding damage using Simulink software.

The Zero-Pole Point Map analysis for the presented damage case is plotted in Fig. 6(a). For the presented damage we can see that the Zero point of system TF (0.4) moves towards zero when the damage range increases. The Nyquist map analysis for the presented damage case is plotted in Fig. 6(b). As shown in the Figure, for the presented damage we can see the variation of the endpoint trajectory of the vector $G(j\omega) = A(\omega)e^{j\varphi(\omega)}$ (Where shows $A(\omega_i)$ appears the vector magnitude $G(j\omega_i)$ when the frequency equals ω_i, and The case of polar coordinates is $\varphi(\omega)$) when frequency ω changes from $0 \rightarrow \infty$. The Nyquist diagram shows in the non-overlapped part the system frequency of G is -11.4. The system frequency decreases as the damage range increases. The Bode map analysis for the presented damage case is plotted in Fig. 6(c). As shown in the Figure, for the presented damage we can see the frequency of the excitation signal is 100π. In detail, when damage occurs the absolute value of magnitude increases over 153 dB, and the corresponding phase changes more than 180°. The Nichols map for the presented damage case is plotted in Fig. 6(d). As shown in the Figure, for the presented damage phase reaches about -180, accordingly G change at the inflection point with Gain -10 at the frequency is 100π.

4 Conclusions

This paper established a FEM of steel truss bridge damage system from the traffic effect, by extracting the measurements of sensors and loaded with random signal. Results show that the signal magnitude will suddenly and sensitively change when the damage starts. The bridge system TF and the frequency domain are established and applied to reflect damage evolution through plotting the zero-pole points map, Nyquist Map, Bode Map, and Nichols Map. The most motivating conclusion in this work is that, instead of using the vibration signals of the responses of the structural system, the variation of the frequency is used to observe the time and displacement characteristics variation of the system due to structural damage.

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