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Drive-by bridge modal identification under multi-source excitations

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ABSTRACT: The drive-by bridge modal identification (BMI) method, which employs a sensory system mounted on a moving vehicle, offers an efficient and cost-effective alternative for monitoring the health of bridge structures, particularly for short- to mid-span bridges. This technique allows for real-time, large-scale bridge assessments without the need for stationary sensors or traffic disruptions. However, extracting accurate modal parameters, such as frequencies and damping ratios, from vehicle responses is challenging due to the influence of multi-source excitations, including road surface roughness, random traffic loads, and dynamic vehicle-bridge interactions. These factors introduce noise and complexity that can compromise the reliability of the BMI method.
To address these challenges, this study integrates an adaptive signal decomposition technique, Successive Variational Mode Decomposition (SVMD), with Operational Modal Analysis to accurately identify the modal frequencies and damping ratios from drive-by measurements. The impact of multi-source excitations on the vehicle-bridge interaction process is systematically investigated, and key factors affecting the accuracy and reliability of BMI under such conditions are analyzed. Based on these findings, recommendations are made to improve the robustness and precision of the drive-by BMI method. This work might contribute to advancing the practical implementation of BMI in real-world bridge health monitoring applications.

KEY WORDS: Drive-by Modal Identification; Vehicle-Bridge Interaction; Successive Variational Mode Decomposition; Operational Modal Analysis; Multi-source Excitations.

1 INTRODUCTION

Vehicular onboard sensing technology dynamically collects bridge response data through moving vehicles, offering advantages such as wide coverage and low cost (Yang et al. 2020). . However, its application in bridge monitoring still faces multi-faceted challenges. On one hand, multi-source random excitations (e.g., road roughness, the simultaneous operation of multiple vehicles, and environmental loads) induce time-varying non-stationarity and strong uncertainty in the dynamic responses of the vehicle-bridge coupled system. On the other hand, the coupled interference from system transfer characteristics, speed fluctuations, and environmental noise results in multi-component mixing and quality heterogeneity in the collected data, significantly compromising the reliability of bridge vibration characteristic identification and condition assessment (Zhu and Law, 2015). The extraction of bridge related dynamic information from the multi-component vehicle responses for bridge condition assessment is the key task of drive-by bridge monitoring (Tan et al. 2019).

Successive variational mode decomposition (SVMD) (Nazari and Sakhaei 2020) has been used to accurately extract the mono-component from the multi-component dynamic signal without much manual parameter setting or adjustment. Li et al. (2022) investigated its feasibility and effectiveness for the extraction of bridge related dynamic components from vehicle response considering a random Class A road surface roughness. This paper studies the feasibility of SVMD for the drive-by bridge modal identification considering the multi-source excitation.

2 VBI MODELING CONSIDERING RANDOM OPERATIONAL EXCITATIONS

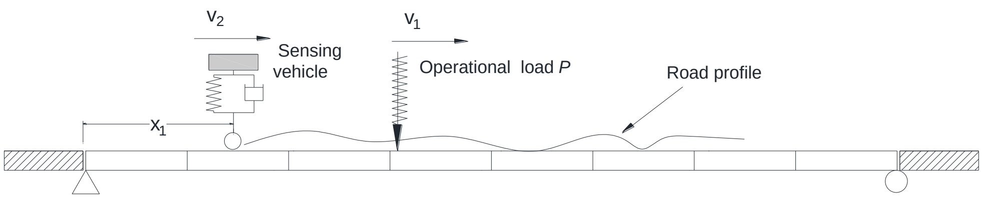

Figure 1 The model of drive-by bridge inspection in operational condition

The VBI model for the drive-by bridge modal identification is shown in Figure 1. The vehicle parameters are: m_v the mass of vehicle, k_s and c_s the stiffness and damping of suspension spring and damper, respectively. The equation of motion of vehicle can be expressed as

$$m_v\ddot{y}_v(t) + c_v\dot{y}_v(t) + k_v y_v(t) = F_{cp}(t) \qquad (1)$$

where y_v is the displacement response of vehicle. $F_{cp}(t) = k_v d_{cp}(t)$, and $d_{cp}(t) = w(\hat{x}_1(t), t) + r(\hat{x}_1(t))$ is the displacement input to the sensing vehicle at location $\hat{x}_1(t)$.
The multi-source excitations are considered as the road profile and a moving random operational load P (Sadeghi et al., 2020). he operational load enters the bridge ahead of the sensing vehicle with a moving speed v_1 and the speed of the sensing vehicle is v_2. The road surface roughness is given as follows:

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$$r(x) = \sum_{i=1}^{N_f} \sqrt{4S_d(f_i)\Delta f} \cos(2\pi f_i x + \theta_i) \quad (2)$$

where $S_d(f)$ is the displacement power spectral density of road surface roughness; $f_i = i\Delta f$ is the spatial frequency(cycles/m); $\Delta f = \frac{1}{N_f \Delta}$, and Δ is the distance interval between successive ordinates of the surface profile; N_f is the number of data points; θ_i is a set of independent random phase angle uniformly distributed between 0 and 2π. The degree of road roughness is determined by the $S_d(f_0)$ value, where $f_0 (= 0.1\ \text{cycles/m})$ is the reference spatial frequency. Class A road roughness defined using specified $S_d(f_0)$ value in ISO specification is considered.

The flowchart of the proposed drive-by bridge modal identification is shown in Figure 2.

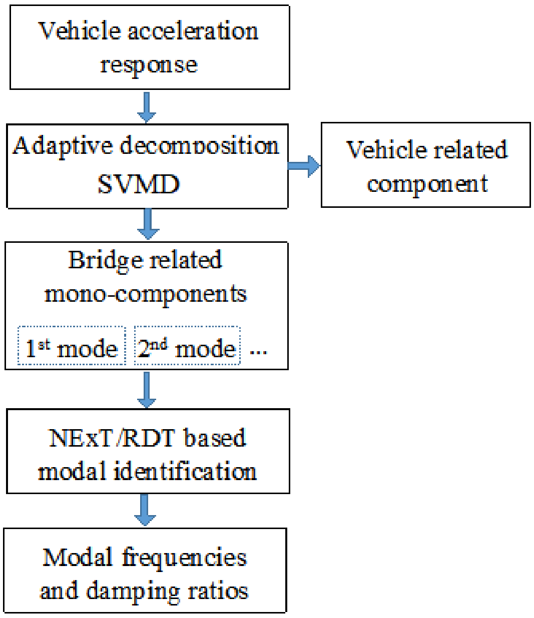

Figure 2 Flow chart of the bridge modal identification using moving test vehicle

3 DRIVE-BY BRIDGE MODAL IDENTIFICATION: NUMERICAL STUDY

Numerical study is conducted to analyze the effectiveness of the method for extracting mono-components from vehicle responses and drive-by bridge modal identification. The properties of the bridge are: length $L = 35\text{m}$, density $\rho = 5000\ \text{kg/m}$, and flexural rigidity $EI = 2.178\text{e}10\text{Nm}^2$. The damping ratio is set as 0.01 and the theoretical values of the first three bridge modal frequencies are 2.68, 10.71 and 24.09Hz, respectively. The properties of the sensing vehicle are: body mass m_v=466.5kg, suspension stiffness k_s=9.00e5 N/m, suspension damping c_s=0.14e3 N s/m and its fundamental frequency f_v is 6.99Hz. The vehicle speed is set as 2m/s and the operational load to simulate the traffic on the bridge is a randomly generated load.

The dynamic modes decomposed by SVMD are used to estimate the bridge frequencies. To evaluate the accuracy of the proposed drive-by bridge modal identification method, the Monte Carlo method with 50 simulations is used to generate the vehicle response dataset to simulate multiple passes of the sensing vehicle considering random operational load. Each of these responses is analyzed by SVMD, and the components related to the first two dynamic modes of bridge are used for the identification of frequency and damping ratio. Three different damping ratio values of bridge, i.e., 0.01, 0.02 and 0.03 are considered in simulating vehicle responses. The mean values and the standard deviation (std) of the identified frequencies for 50 passes are presented in Table 1. It can be seen that the mean values are very close to the theoretical values and the errors are all less than 1.5%. The results confirm that the bridge modal frequencies can be identified with high accuracy using the developed method.

Table 1 Identified frequency considering different damping ratios

Identified frequency (Hz)						
Damping ratio	0.01		0.02		0.03	
	mean	std	mean	std	mean	std
First mode	2.674	0.0561	2.667	0.0419	2.658	0.085
Second mode	10.589	0.0842	10.559	0.1012	10.549	0.182

4 CONCLUSIONS

This study investigates drive-by bridge modal identification under multi-source excitations based on the adaptive decomposition of vehicle responses using SVMD. The investigation confirms that the SVMD can be incorporated with the NExT/RDT to analyze the bridge related dynamic components to estimate the modal frequencies and damping ratios. The bridge modal frequencies are identified accurately by computing the mean value of multiple tests to reduce the effects of the multi-source random excitations. A more sophisticated operational traffic model is required to meets more realistic situation in the simulation. Besides, experimental investigations on actual bridges in operational condition are necessary to further verify the effectiveness and robustness of the proposed method.

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