Modal Data Identification of the Prestressed Concrete Bridge Using Variational Mode Decomposition

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ABSTRACT

In this study, the variational mode decomposition (VMD) algorithm was used to identify the modal characteristics of the structure using the decomposition of the acceleration responses recorded by the sensors. This algorithm has advantages over other signal decomposition methods that is resistant to the noise and sampling frequency. Also, the VMD algorithm extracts the natural frequencies of the structure concurrently. In addition, the damping ratios of the structure were estimated by fitting a linear function to the logarithmic diagram of the modal response in the decaying amplitude and calculating the slope of this line. The efficiency and accuracy of this algorithm were investigated by decomposing the acceleration responses obtained from the sensors installed on a prestressed concrete bridge (PSCB) that is located under the load of passing vehicles. The VMD algorithm was used for signal processing in MATLAB to estimate the natural frequencies, damping ratios and mode shapes of the bridge and ARTeMIS was utilized for verifying the results. In addition, the finite element modeling and modal analysis of the bridge were performed in ABAQUS and the natural frequencies and mode shapes of the bridge were obtained. The results showed that the mode shapes estimated by the VMD algorithm was in good agreement with the finite element model and ARTeMIS. Also, the damping ratios estimated by this algorithm were obtained close to the damping value of the prestressed concrete bridge. The difference between the frequencies calculated by the VMD algorithm and ARTeMIS was about 1%, and the difference with the finite element model frequencies was close to 5%.

KEYWORDS

Modal data identification, Variational mode decomposition, Signal processing, Ambient vibration, Prestressed concrete bridge.

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1. Introduction

Bridges are damaged by various factors such as heavy loads, passing traffic and environmental factors. These damages over time lead to cracks in concrete members, decay of steel components and disruption of bridge operation. Dynamic characteristics of structures are powerful tools for health monitoring that detect abnormal conditions of structural members by processing information obtained from sensors [1-3]. One of the methods of monitoring the health of the structure is the use of ambient vibration test by which the dynamic characteristics of the structure under the operating load are obtained. Methods for identifying modal characteristics are divided into frequency domain and time domain, by which the amount of stiffness, mass and damping of the structure are estimated. One of the signal processing methods is the use of the empirical mode decomposition (EMD). This algorithm is a method to decompose a signal into a finite number of oscillating functions called intrinsic mode functions (IMF), each of which has a separate spectral bandwidth [4-6]. To reduce the limitations of this method in signal processing, the EMD was combined with Hilbert transform. To compensate for the weaknesses of the above methods in signal processing, a variational mode decomposition (VMD) was proposed. This algorithm, similar to the EMD, decompose the signal into a set of intrinsic mode functions and, unlike the EMD, is resistant to noise and sampling frequency [7].

The purpose of this study is to identify the modal characteristics of the prestressed concrete bridge (PSCB) by processing the acceleration responses obtained from sensors installed on the bridge. Due to the ability of the VMD in signal processing, this algorithm was used to decompose the acceleration responses in Matlab and the values of the main frequencies, damping ratios and mode shapes of the bridge were obtained. To evaluate the efficiency of this method, a finite element model of the PSCB was developed in Abaqus and modal analysis was used to obtain the modal characteristics of the bridge. Also, to validate the results obtained from the VMD method, Artemis was used to decompose the acceleration responses and calculate the bridge modal information. Finally, the modal characteristics of the PSCB under ambient vibration were calculated with high accuracy using the VMD.

2. Methodology

In order to process the acceleration responses obtained from the ambient vibration and to detect the modal characteristics of the highway prestressed concrete bridge [8], the VMD was used [7, 9]. Then, by averaging the frequencies obtained from all sensors in each mode, the main frequencies of the bridge were calculated. Also, by fitting a linear function to the logarithmic diagram of the modal response at the decaying of amplitude and calculating the slope of this line, the damping ratios of the bridge were estimated. In addition, by considering the minimum or maximum modal response value simultaneously in all sensors for each mode, the mode shapes of the bridge were identified [10].

3. Results and Discussion

The frequency values for each of the four sensors were first obtained to calculate the main frequencies of the first four vibrating modes of the bridge. Then, the value of the main frequency of that mode was calculated by taking the average of them in each mode, which are equal to 5.896, 6.773, 10.636 and 20.208 Hz for the first to fourth modes, respectively. Also, damping ratios of the first four modes of the bridge were estimated by averaging the values obtained for all four sensors in each mode, which are equal to 1.88, 2.11, 2.18 and 1.25 percent, respectively. These values are close to the damping value of the PSCB. In addition, to identify the mode shapes of the bridge, the amount of modal response at a local point was the minimum or maximum response in each mode and for all sensors simultaneously was considered and the shape of the first four vibration modes of the PSCB was obtained.

By examining the amount of the main frequencies obtained in the finite element model of Abaqus (equal to 6.0443, 7.773, 11.158 and 20.023 Hz) and the VMD, the first four vibrational modes of the bridge in these two methods were determined. There is a difference of 3, 15, 5 and 1%, respectively, which is due to the consideration of some assumptions in the modeling of finite element and the approximate strength characteristics of the PSCB materials.

Artemis calculates structural modal information through various signal processing methods in the frequency domain and time domain. To obtain the amount of main frequencies, damping ratios and mode shapes of the PSCB, the accelerated responses recorded by the sensors were processed using Artemis and various methods in the frequency domain and time domain. It was found that the difference between the frequencies of the first, third and fourth vibration modes in all methods was about 1% by examining the frequencies obtained from the processing of acceleration responses using the frequency domain and time domain methods. Also, the amount of frequencies calculated for the second mode in the frequency domain is about 6% higher than the same value in the time domain. Therefore, the difference between the frequencies of the first four modes of the bridge in the finite element model of Abaqus and Artemis model are 3%, 5%, 4% and 2% in frequency domain methods and are 3%, 11%, 4% and 2% in time domain methods, respectively.

By examining the amount of frequencies obtained by two signal processing methods with Artemis and the VMD, it was found that the difference between the main frequencies of the first, third and fourth vibration modes of the bridge is about 1% and the frequencies of the second vibration mode are 9% and 3% in the frequency and time domain methods. Also, the damping ratios estimated by the VMD have less error than the time domain methods used in Artemis. In addition, by comparing the shape of the vibration modes obtained by the VMD with Abaqus model and Artemis, it was found that the shape of the vibration modes of the first four bridge modes identified by this algorithm are in good agreement with the other two methods and as shown in Table 1.

Table 1. Comparison of the mode shapes

Abaqus	Artemis	VMD	Beam number	Mode number
0.8948	1	1	1	First mode
0.9849	0.8507	0.9163	3	
0.9849	0.6859	0.8861	5	
0.8948	0.4728	0.6519	7	
-1	-0.6016	-0.9813	1	Second mode
-0.3419	-0.0690	-0.2549	3	
0.3419	0.5729	0.4064	5	
1	1	1	7	
1	1	1	1	Third mode
-0.5428	-0.7249	-0.6872	3	
-0.5428	-0.8709	-0.8432	5	
1	0.7742	0.7311	7	
0.3617	0.2664	0.2552	1	Fourth mode
-1	-0.9068	-0.9022	3	
1	1	1	5	
-0.3617	-0.4759	-0.4161	7	

4. Conclusions

The results of this study are:

1. Intrinsic modes of the bridge were identified and extracted with high accuracy and rapid with one run of the VMD.

2. Noise and unwanted signals from the ambient vibration test were detected and removed using the VMD.

3. Considering the limited part of the free vibration response of the bridge after the maximum acceleration response, the modal characteristics of the bridge were obtained by this algorithm so that the volume of signal processing calculations was significantly reduced.

4. The frequencies of the first four bridge vibration modes in the finite element model and the VMD are 3, 15, 5 and 1% different, respectively. Also, the differences between the frequencies of the first four modes of the bridge in the finite element model and Artemis model are 3, 5, 4 and 2% in the frequency domain methods and 3, 11, 4 and 2% in the time domain methods, respectively. In addition, the difference amount of frequencies obtained by the two signal processing methods with Artemis and the VMD for the first, third and fourth modes of the bridge is about 1% and for the second mode in the frequency domain 9% and in the time domain 3%.

5. The damping ratios estimated by this algorithm were obtained by fitting a linear function to the logarithmic diagram of the modal response at the decaying of amplitude and calculating the slope of this line close to the damping ratios of the PSCB. Also, the frequency domain methods in Artemis did not calculate the damping ratios of bridge accurately. In addition, the damping ratios estimated by the VMD have less error than the time domain methods used in Artemis.

6. The mode shapes identified by the VMD is very well with the mode shapes obtained from Abaqus and Artemis models, so that this algorithm accurately identified the flexural, torsional and combination mode shapes.

5. References

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