Comparison and application of two time domain methods analysis to modal parameter identification of Songhuajiang River highway-railway bridge

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Abstract. In this paper, comparison and application of two time domain modal parameter identification methods of ERA and SSI in a steel truss bridge is discussed. Firstly, multidirectional comparison and analysis of structural modal parameter identification under environment excitation to the bridge are carried out. Then finite element model of the Songhuajiang River highway-railway bridge is established by MIDAS CIVIL, and the modal analysis of the structure is carried out. The first ten order modes of the structure are obtained, and some characteristics of the first ten order modes are analyzed and compared. And combining the partial trend of the finite element modal analysis, the vibration experiment of the Songhuajiang River highway-railway steel bridge under the environmental excitation is tested. Then the modal parameters of the structure are calculated, analyzed and compared through the ERA method and SSI method based on the state space model. Finally the accuracy of the two modal parameter identification methods is tested, and the feasibility of the two methods applied in the steel truss bridge structural analysis is verified.

1. Introduction

For large-scale bridges, due to the large size and complex structure, it is difficult to carry out artificial excitation with known input excitation, so the environmental vibration is often used as the input excitation in the relevant test. The traditional identification methods of modal parameters have many limitations in the practical application of bridge structures[1]. It has been more than 50 years since 60's of the 20th century to study the methods of modal parameter identification under environmental vibration. Through the field test of environmental vibration, we have not measured the actual input excitation, so the modal parameter identification method under environmental vibration only relies on the response output data of the structure to identify the modal parameters of the structure[2].

The frequency domain method based on environmental excitation is to identify the modal parameters of the structure after the response signals obtained from random excitation are transformed into power spectrum functions or matrices. The peak value method estimates the order of the structural model directly by observing the number of peak values of the power spectrum. However, when the
damping is large and the difference between the two adjacent peak values is small, the modal loss may occur, and the recognition accuracy is low. The frequency domain decomposition method is an extension of the peak method. It mainly decomposes the obtained power spectrum by SVD. The accuracy of this method is higher than that of the peak method. Polynomial fitting method uses power-based polynomials for curve fitting with high accuracy, but the numerical stability may occur when the order of polynomials is high. The least square complex frequency domain method (LSCF) has been extended and optimized to multiple reference points, which has better identification ability for data with high noise pollution and structures with dense modes and high damping[3]. The time-domain method based on environmental excitation uses the time history function of the response signal data of the structure under random excitation (such as random decrement function, correlation function, etc.) to identify the modal parameters of the structure. Among them, LSCE, ITD and STD are based on ARMA model[4]. However, SSI and ERA are state space models. The identification method based on the autoregressive moving average model (ARMA) has high resolution, but it has high sensitivity to noise and sampling frequency, and poor robustness (also known as anti variability), so it is not suitable for processing large amount of data. However, stochastic subspace recognition (SSI) and eigensystem realization algorithm (ERA) are belong to the state space models methods[5]. The method based on state space model uses SVD decomposition to eliminate the influence of part of the noise in the calculation process and to determine the order of the model. The calculation process is stable and the result accuracy is high. Overall, the frequency-domain method is more mature than the time-domain method in modal parameter identification because of the earlier development of fast spectral calculation[6]. But the frequency domain modal parameter identification method needs to transform the time domain signal into the frequency domain signal through the Fourier transform. In the process of the conversion, many data need to take the average value in the middle, which causes the problems of spectrum loss, overlapping and mixing, and low resolution. The transformation of time-domain signal into frequency-domain signal data will inevitably affect the accuracy of identification methods. Therefore, this kind of method is suitable for systems with small damping and scattered distribution of natural frequency. With the rapid development of related technology and operation ability, time-domain modal parameter identification method has also been developed. Because the time-domain modal analysis method can directly identify the modal parameters of the structure from the time-domain signal data, compared with the frequency-domain modal parameter identification method, it has a higher accuracy and is widely used in civil engineering. In the time domain modal parameter identification method, the application effect based on state space model is better than that based on ARMA model. To sum up, the time-domain modal parameter identification method is used in the analysis of Songhuajiang highway and railway dual-purpose bridge on Binbei line. Combined with the engineering application, this paper mainly studies two modal identification methods based on spatial state model, which are eigensystem realization algorithm (ERA) and stochastic subspace method (SSI).

2. Modal test of Songhuajiang highway-railway bridge on Binbei line
The test and measurement bridge selected for this time is the Songhuajiang highway-railway dual-purpose bridge of Binbei line, with the structural form of steel truss bridge. Songhuajiang railway bridge on Binbei line is the earliest reconstruction project of the steel truss bridge crossing the river in China[7]. Songhuajiang highway and railway bridge of Binbei line is located on Songhuajiang River, which is located in extremely cold area. The design minimum temperature is -43.1℃. It is the first large-scale steel truss bridge with orthotropic deck in Northeast China[8]. The span of the bridge from south to north is: 2 × 96m + (96 + 2 × 144 + 96)m + 6 × 96m, in which the total width of the upper highway deck is 30m, and the width of the lower railway deck is 14m.

2.1. Calculation model of Songhuajiang highway-railway bridge on Binbei line
Build the bridge model in Midas civil software according to the process described in the previous section.
2.1.1. **Material properties.** The main material of Songhuajiang highway-railway dual-purpose bridge of Binbei line is steel, and concrete materials are laid on the highway and railway lanes. The material properties of steel and concrete are shown in Table 1[9].

| Material type | Yield strength (N/mm²) | Modulus of elasticity | Poisson's ratio | Coefficient of linear expansion | Density (g/cm³) |
|---------------|------------------------|-----------------------|----------------|---------------------------------|-----------------|
| Q370          | 370                    | 2.06×10⁵              | 0.3            | /                               | 7.85            |
| Q420          | 420                    | 2.06×10⁵              | 0.3            | /                               | 7.85            |
| C55           | /                      | 3.55×10⁴              | 0.2            | /                               | 2.549           |

Component dimension. In Midas civil modeling of Songhuajiang highway-railway bridge on Binbei line, beam elements are used for truss pole, stiffener pole, floor beam, etc., and stiffener plate elements are used for bridge deck. The railway and highway decks of the bridge on Binbei line adopt orthotropic plate steel decks with multiple beams and small longitudinal beams, but there are some differences in the specific size and distribution. The structural members and section dimensions of the bridge are shown in Table 2.

2.1.2. **Unit building, segmentation and model building.** At present, the horizontal layout of highway and railway can be divided into two categories: up and down stratification and highway-railway road parallel. The up and down stratification can be divided into two forms: Highway in the upper and railway in the upper. The highway-railway road parallel can also be divided into two forms: Railway in the middle and highway in the middle. The study to Songhuajiang highway-railway dual-purpose bridge of Binbei line adopts the form of upper and lower layers, and the highway is on the upper side and the railway is on the lower side[10]. Cells are created based on drawing node information and material properties, and the corresponding connection is set between cells. The selection of the number of cell divisions has a great influence on the results. Generally, the more the number of cell divisions, the more accurate the results can be obtained. This time, the deformation and displacement of piers are not considered in the modeling of Songhuajiang highway-railway dual-purpose bridge of Binbei line, so the piers are not modeled, but the boundary conditions are added at the piers to simulate[11]. Partial bridge models are compared as shown in Figure 1.
### Table 2. Some structural members and sectional dimensions.

| Number | Component                          | Steel  | Section type and size                                                                 |
|--------|------------------------------------|--------|---------------------------------------------------------------------------------------|
| 1      | Upper chord                        | Q370   | Box section with ribs, 1400mm in height, 1000mm in width, 20-40mm in thickness, and 800mm in length on both sides of the upper part |
| 2      | Lower chord                        | Q370   | Box section with ribs, 1400mm in height, 1000mm in width, 20-40mm in thickness, and 500mm in length for the extended flange plate on the upper side |
| 3      | Main truss box web                 | Q370   | Box section, 998mm in height, 1100mm in width, plate thickness is 24-44mm               |
| 4      | H-shaped web of main truss system 1| Q370   | H-section, 998mm in height, 720mm in width, plate thickness is 28-32mm                  |
| 5      | Transverse connection system 1 of  | Q370   | H-section, 400mm in height, 280mm in width, 12mm in thickness                           |
| 6      | Transverse connection system 2 of  | Q370   | H-section, 400mm in height, 400mm in width, plate thickness is 12mm                    |
| 7      | Transverse connection system 3 of  | Q370   | H-section, 400mm in height, 400mm in width and 16mm in thickness                      |
| 8      | Bottom crossbeam of railway bridge | Q370   | Inverted T-section, 1400-1520mm in height, 560mm in width, 16mm in thick web, 32mm in thick lower flange plate |
| 9      | Bottom crossbeam of highway bridge | Q370   | Inverted T-section, 800-1400mm in height, 560mm in width, 16mm in thick web, 24mm in thick lower flange plate |
| 10     | Stiffener vertical                 | Q420   | Box section with ribs, 1400mm in height, 1000mm in width, 44mm in thickness            |
| 11     | Stiffening chord 1                 | Q420   | Box section with ribs, 1400mm in height, 1000mm in width, 36mm in thickness            |
| 12     | Stiffening chord 2                 | Q420   | Box section with ribs, 1600mm in height, 1000mm in width, 50mm in thickness            |
| 13     | Transverse tie at stiffener        | Q420   | H-section, 500mm in height, 460mm in width, 16mm in thickness                         |
| 14     | Longitudinal connection at stiffen  | Q420   | H-section, 500mm in height, 500mm in width and 24mm in thickness                     |
2.2. Modal analysis of Songhuajiang railway bridge on Binbei line

Table 3. The first 10 modes of bridge structure obtained by Midas civil software.

| Order number | Period t (s) | Angular frequency $\omega$ (rad/s) | Frequency f (Hz) |
|--------------|--------------|-----------------------------------|-----------------|
| 1            | 0.3316       | 18.9463                           | 3.0154          |
| 2            | 0.3106       | 20.2281                           | 3.2194          |
| 3            | 0.2508       | 25.0565                           | 3.9879          |
| 4            | 0.2103       | 29.8840                           | 4.7562          |
| 5            | 0.1872       | 33.5641                           | 5.3419          |
| 6            | 0.1287       | 48.8038                           | 7.7674          |
| 7            | 0.1119       | 56.1524                           | 8.9369          |
| 8            | 0.1059       | 59.3511                           | 9.4460          |
| 9            | 0.0857       | 73.2971                           | 11.6656         |
| 10           | 0.0796       | 78.9452                           | 12.5645         |

In Midas civil, the multiple Ritz vector method in eigenvalue analysis and control is used to calculate the natural frequency and the corresponding vibration mode of Songhuajiang public rail dual-purpose bridge on Binbei line. The first 10 modal frequency results obtained by this calculation can only be considered when the effective mass coefficient is more than 90%. After comprehensive analysis, the first 10 natural frequencies of the bridge structure can be obtained as shown in the Table 3.
2.3. Field vibration test

2.3.1. Test equipment. The instruments used in the environmental vibration test of Songhuajiang highway and railway dual-purpose bridge(Figure 2) on Binbei line are: 941b vibration pickup (produced by Institute of Engineering Mechanics, CEA), 941b signal amplifier and DASP data collector(Figure 3). The graph data and text data are obtained by corresponding software.

2.3.2. Test method. The vibration test method of Songhua River public railway bridge on Binbei line is environmental excitation. In the process of data collection, we can receive the types of environmental excitation: impact excitation of water flow on piers, excitation caused by passing of large ships, excitation caused by passing of heavy vehicles on the bridge deck, excitation caused by passing of Railway Empty trains, excitation caused by passing of railway trains, excitation caused by passing of railway heavy trains, etc, by processing the measured data, the modal of the bridge is obtained. The model we built in Midas civil is simplified based on the actual bridge structure, which is bound to be different from the actual bridge structure to some extent. According to the past testing experience, combined with the actual bridge structure, the limitations of comprehensive instruments and testing conditions and other possible factors, we have set up a total of 6 measuring points on the bridge.

2.3.3. Test contents. The research object of this test is the Songhuajiang highway-railway bridge of Binbei line. At the time of the test, the lower railway has been opened and the upper highway has not been opened to traffic. According to the drawings, related papers and field survey data, we collected the vibration data of the bridge under various environmental excitations(Figure 4). The time of this test
is from 3.30pm to 5.30pm on September 20, 2017. The sampling frequency is 250Hz and the amplification factor is 100.

![Digital photographs of partial site environment incentives.](image)

(a) Excitation caused by heavy train passing  (b) Excitation caused by Empty train passing

**Figure 4.** Digital photographs of partial site environment incentives.

### 3. Data analysis and comparison between Midas calculation and ERA and SSI method

The ERA method and SSI method described in the above two sections are used for data processing in this test and compared. After the environmental vibration data is input into the calculation method, the spectrum diagram and stability diagram of the signal are obtained. Firstly, the approximate order of the bridge structure that should be extracted and the distribution of the natural vibration frequency of the structure can be determined according to the spectrum diagram and stability diagram, and then the above extracted frequency can be selected by MAC criterion Frequency with relatively high reliability. According to the definition of MAC criterion, the closer the MAC value is to 100%, the closer the corresponding frequency value is to the actual frequency of the building structure. Figure 5 shows the comprehensive analysis of the Fourier spectrum of the bridge along the radial cut and vertical three directions.

![Fourier spectrum of 6 measuring points](image)

(a) Radial Fourier spectrum of 6 measuring points
Figure 5. Spectrums and stabilization diagram.

(b) Tangential Fourier spectrum of 6 measuring points

(c) Vertical Fourier spectrum of 6 measuring point

(d) Stabilization diagram
From the above results, we can know that the MAC values of the frequency results selected by ERA method are all greater than 90%, which can reflect the actual frequency of the structure. At the same time, after the comparison among the results of MIDAS, ERA method and SSI method(Figure 6), we can found that the results of SSI method have omission in the second and the third modes. The maximum difference between the frequency identified by the two methods and the result of the model eigenvalue analysis is 8.6502%. The difference between the two methods is not big, and they are all within the reasonable error range. The reason for the mode omission of SSI method is also caused by the parameterization of the operation of the method. From the calculation process of the algorithm, it
can be seen that the parameter of system order n needs to be set in SSI method, and most of the parameters are judged by the assumption, and the inaccuracy of the parameters leads to the phenomenon of mode omission in the method. The maximum difference between SSI method and ERA method is 3.8860%.

4. Conclusion

(1). After processing and analyzing the data obtained from the test of Songhuajiang the bridge on Binbei line, comparing with the results of MIDAS (Table 3, and Table 4), it can be seen that both ERA method and SSI method, as time-domain modal identification method, can identify structural modes effectively in vibration test under environmental excitation.

(2). The results of SSI method have omissions in the second and the third modes, while the results of ERA method and Midas have no such omission, and the maximum difference between them is not greater than 6%.

(3). There are two main reasons for the relatively large difference among the results of FEA software simulation, ERA method and SSI method, based on the actual measurement data. (1) Although the FEA simulation is modelled out well according to the actual conditions as much as possible, there are some differences between the FEA software simulation and the actual situation in terms of boundary conditions, component interconnection, etc. (2) Due to the limitation of conditions, only 6 measuring points are set in this test, which can only reflect the main characteristics of this structure. Although the purpose of this test is to verify the accuracy of time-domain modal identification method in the application of the first 10 modal frequency results of a bridge structure, however the modal parameters obtained by the time-domain modal identification method are closer to the actual structure.

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