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Dynamic Characteristics Analysis of Large Self-anchored Suspension Bridge

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Abstract

The dynamic behavior of a large self-anchored suspension bridge was studied in this paper. A dynamic spatial finite element model of Taohuayu Yellow River Bridge, which is a super large span self-anchored suspension bridge, was created using MIDAS. Sub space iteration method was used to calculate its natural frequency and vibration mode, the dynamic characteristics and structure stiffness were discussed and analyzed on the basis of calculated results. Results show that the vibration modes are mainly vertical bending of deck, the stiffness of girder is small, in the first 10 vibration modes, out of plane sway and torsion of cable did not appeared, thus indicated this bridge was designed properly, and has a high performance in terms of anti-seismic. The results of this paper can also provide some references for the design, construction, health monitoring and maintenance of bridges of like.

Keywords: Taohuyu Yellow River Bridge, natural frequency, vibration mode, dynamic characteristic

1. Introduction

Self-anchored suspension bridge is different from earth anchored suspension bridge for that self-anchored suspension bridge is anchored on its girder instead of earth anchorage. The force distribution path of self-anchored bridge is: vertical loads such as deck weight and vehicle load are transferred to main cable through suspender. Horizontal component of main cable acts as prestess that makes girder compressed. Since the Cologne – Valdez Bridge built in Germany in 1915, many self-anchored suspension bridges have been built all over the world, and the span length is increasing. Taohuayu Yellow River Bridge with a span arrangement of 160 m + 406m + 160 m, further increased spanning ability of this type of bridge, therefore, analysis of its mechanical behaviors is becoming significantly important.

Anti-seismic capacity, wind resistance capacity and vehicle-bridge vibration problems are usually the main controlling factors when designing suspension bridge. In the seismic analysis, whether use design response spectrum theory or time history method, the dynamic characteristics of structure itself is inseparable. Therefore, bridge dynamic characteristics analysis is meaningful to bridge in terms of anti-seismic design, health inspection and maintenance.

The advantage of self-anchored suspension bridge is that the horizontal component of main cable significantly increased the stiffness of stiffening girder, so the dynamic characteristics of self-anchored suspension bridge is different from that of conventional earth anchored suspension bridge. Therefore, study on the dynamic characteristics of self-anchored suspension bridge is necessary. Taohuayu Yellow River Bridge has the largest span among self-anchored suspension bridge, so no data of self-anchored suspension bridge with the same span can be referred, to ensure its safety in service stage, study on the natural frequency and vibration mode was performed using spatial FEM model established through MIDAS.This paper presents the calculation method and results that not only laid the foundation for the anti-seismic analysis, wind resistance design and vehicle-bridge vibration analysis of Taohuayu Yellow River Bridge, but also provides some references for the design, construction and post operation management of bridges of like.

2. Bridge Description

Taohuayu Yellow River Bridge, as a part of Wuxi highway, is a super long-span self-anchored suspension bridge with three-span (160 + 406 + 160 m), which locates at the junction of Zhengzhou City and Jiaozuo City, crossing the Yellow River, through Mangshan Mountain in the northwest of Zhengzhou City. Integral steel box girders are adopted in this bridge, and the whole width and the net width of the bridge are 39 m and 30 m respectively. The bridge is designed according to the norms of two-way six-lane highway with a speed of 100 km/h and the design load is highway I × 1.3.

Two main cable planes are vertically arranged on both sides of steel box girder, rise to span ratio is 1/5.8 in the intermediate span. Suspenders are arranged at a constant distance of 13.5 m, suspenders on both sides of pylon is 14 m to the pylon center line, 10 and 29 pairs of suspenders are arranged in two side and intermediate spans, respectively. In each hanging point, two parallel cables are set as a suspender. In construction stages, to ensure that no tension force will appear in supports on pylon, counterweights are arranged on both sides of pylon. The pylon is made of box with variable cross section that is large on both ends and small in the middle, the cross section of pylon top is 5.8 m × 8 m, the thickness of pylon box is 0.8 ~ 1 m. And the cross section of pylon box reduces according to two slopes, namely 1/16 and 1/25 respectively, the all height of the pylon is 135.56 m 44 bored pile are used for pylon foundation. Taohuayu Yellow River Bridge has the longest span in self-anchored suspension bridge.

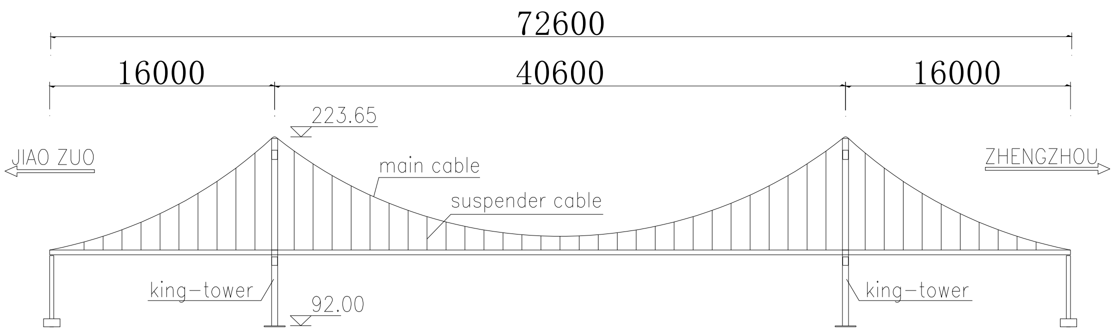


Figure 1. General arrangement diagram of Taohuayu Yellow River Bridge

3. Analysis of Finite Element Theory to Solve the Problem

The geometry, load conditions, boundary conditions and material properties are very complex for self-anchored suspension bridge, so usually accurate theory results cannot be obtained through dynamic analysis.therefore, FEM analysis is an effective method to solve this problem. When analysis the dynamic characteristics, mass matrix should be established, generally it can be divided into lumped mass matrix and consistent mass matrix according to research requirements.

In the lumped mass method, continuously distributed mass are transferred to joints of elements according to certain principles, connection parts between joints is massless but keeps the original elastic modulus. Thus the dynamic coupling of displacements between joints can be avoid, the obtained mass matrix is diagonal but not necessarily positive definite.

However, the calculation is relatively simple, the amount of storage required is less, but the natural frequencies of structures will be reduced. In the establishment of the element stiffness matrix, nodal displacement inside of element is described by joint displacement through shape function, nodal acceleration inside of element can also be described by joint acceleration through shape function.In consistent mass method, acceleration interpolation function is the same as that used to establish stiffness matrix. Inertial force is converted to equivalent nodal loads, according to the principle of minimum potential energy, variational method is adopted, virtual work inertial force is calculated in that of external force. Consistent mass matrix is positive definite matrix, thus more accurate vibration mode can be obtained.

General structural dynamic equation:

$$[\mathrm{k}]\{\delta\}+[m]\ddot{\delta}+[c]\{\dot{\delta}\}=\{f\} \tag{1}$$

Ignoring the effect of damping [C]=0,{F}=0, Equation (1) is simplified as:

$$[\mathrm{k}]\{\delta\}+[m]\{\ddot{\delta}\}+=0 \tag{2}$$

The eigenvalue equation is:

$$\det([k]-\omega^2[m])=0 \tag{3}$$

Many methods can be used to solve Equation (3), such as Rayleigh-Ritz method, generalized Jacobi method and subspace iteration method. The Rayleigh–Ritz method is a widely used. It is a direct variational method in which the minimum of a functional defined on a normed linear space is approximated by a linear combination of elements from that space. For simple structure, suitable initial subspace can be easily get that Rayleigh–Ritz method can yield approximated results, however, it is usually hard to find suitable initial subspace for complex structures.

The results of generalized Jacobi method are the whole eigenvalues and eigenvectors that are not suitable for large structures.For eigenvalue calculation of large structures, subspace iteration method is commonly used, which can directly yield the needed eigenvalues instead of the whole. Subspace iteration method is the combination of Rayleigh Ritz method and inverse iteration method, so it is also known as the joint iteration method, in which high order equation is projected into a low dimensional space (i.e. subspace) using Rayleigh Ritz transformation.

The feature of subspace iteration method is the Rayleigh-Ritz transformation, which is to solve a low-order Generalized Characteristic Equation in subspace after projecting higher order equation into subspace, then the solved low-order eigenvector is substituted back to the primary higher order equation and one orthogonal basis can be obtained. Finally, approximate eigenvector of the primary higher order equation can be obtained the approximate subspace. The whole process is alternatives between the iteration of eigenvector and the solution of low-order Generalized Characteristic equation, then approximating to the real solution through iterative analysis calculation; at the last step of iteration, approximate eigenvector of the primary higher order equation is obtained; This method can finally approximate the real mode of vibration.

4. Establishment of Finite-Element Model Description

According to “China seismic zoning map” (GB18306-2001) and seismic intensity zoning map of Henan Province, Zhengzhou seismic fortification intensity is 7 degree, the basic earthquake acceleration is 0.15 g, site soil type is soft soil, construction site categories is class III and class II in the north and south respectively. For 50 years transcendental probability of 63%, 10%, 3% horizontal peak ground acceleration are 61.3 gal, 163.8 gal, 310.1 gal respectively. Spatial dynamic finite element model of Taohuyu Yellow River Bridge is established using MIDAS, the effect of dead load to structure stiffness and mass and the effect of cable initial force to the bridge alignment have been taken into account. Dead load is transformed into three parts of mass in three directions respectively, tension force and of like nodal forces are transformed into mass, besides, the effects of tension force and of like nodal forces to structure stiffness and mass stiffness have been taken into account. To ensure that structure alignment is approximate to the final alignment, initial cable force has been taken into account when calculate the unloaded structure alignment. In FEM, beam element is used for pylon, saddle and stiffening transvers girder. Truss element is used for main cable and suspender.

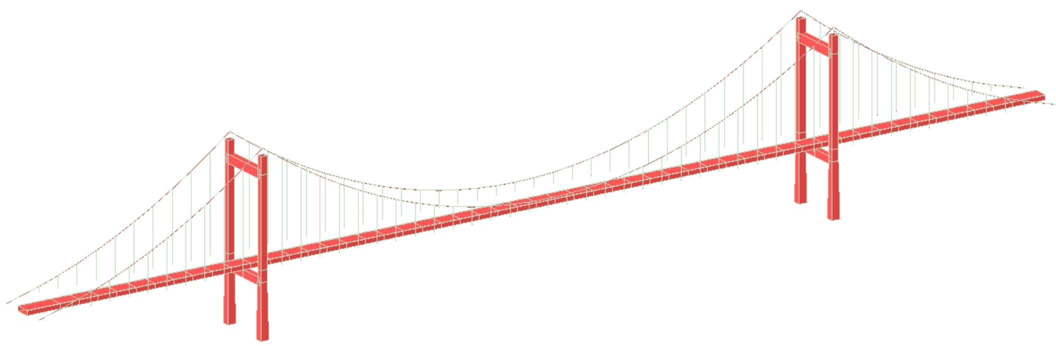


Figure 2. Finite element model of Taohuayu Yellow River Bridge

5. FEM Results and Results Analysis

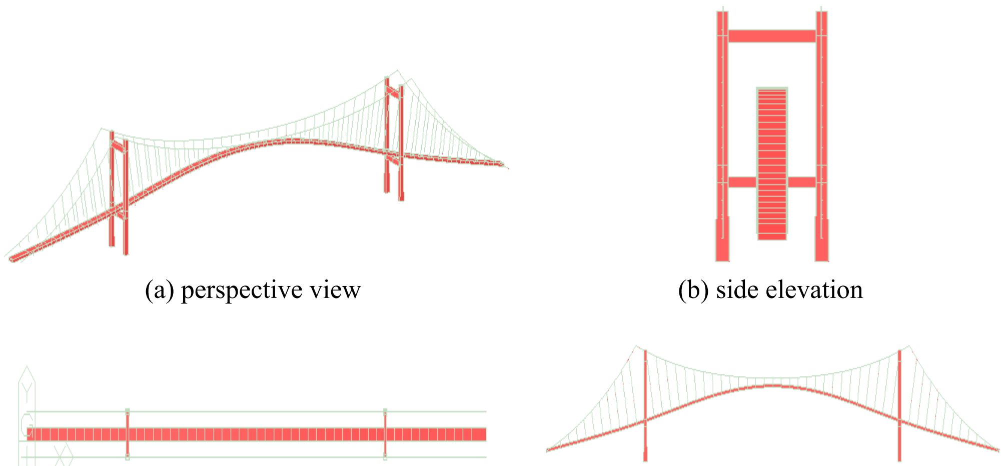
The initial forces of main cable become significantly large when the bridge completed, therefore, the bending stiffness of main cable increased, usually referred as gravity stiffness. With the span increase of self-anchored suspension bridge, the gravity stiffness of main cable is increasing, thus the structure stiffness contributed by stiffening girder is also increasing, and the former is much bigger than the later. Therefore, before the calculation of dynamic characteristics, the static calculation should be done at first and its results are used as the initial state of dynamic calculation.

Generally, participation factor of structure mass is concentrated in the first few vibration modes when doing dynamic analysis. For simple structures, firs three order modes are selected as the controlling vibration modes, for large and complex structures, more vibration modes should be selected as the controlling vibration modes. Taohuayu Yellow River Bridge is large self-anchored suspension bridge, therefore, subspace iteration method is used to calculate its vibration modes, besides, first 10 orders of vibration modes and natural frequencies are selected as controlling parameters of dynamic calculation.

The FEM calculation results are listed in Table 1.

Table 1. Parameters of dynamic characteristics

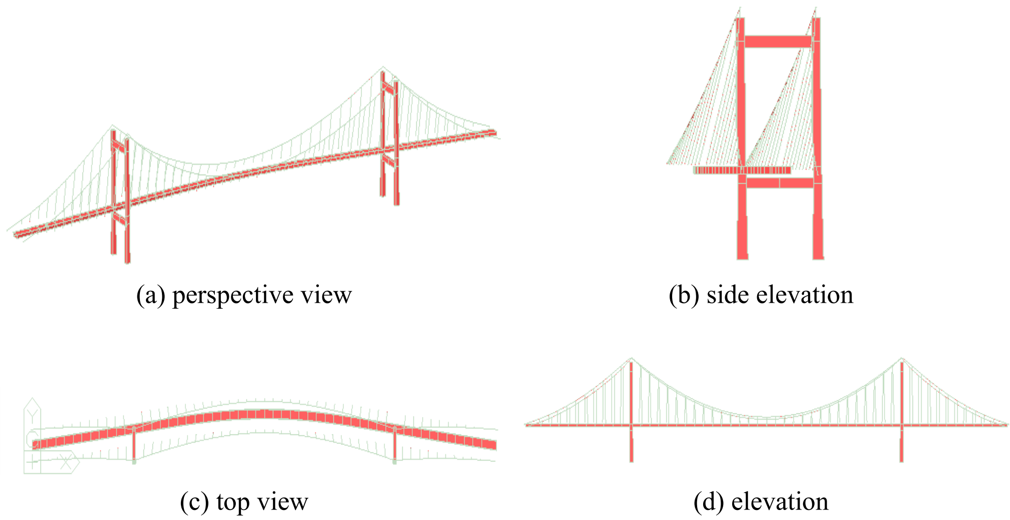
vibration mode	Natural frequency	Vibration mode description
1	0.310196	Deck vertically and symmetrically bended
2	0.519646	Cable plane swayed in the same direction
3	0.532737	Deck vertically but dissymmetrically bended
4	1.431805	Deck vertically but dissymmetrically bended
5	1.936083	Cable plane symmetrically swayed in the same direction
6	2.364529	deck vertically and symmetrically bended
7	2.744470	deck vertically and symmetrically bended
8	2.847787	Deck vertically but dissymmetrically bended
9	3.467948	Cable plane symmetrically swayed in the same direction
10	3.501919	deck vertically and symmetrically bended



(a) perspective view (b) side elevation

(c) top view (d) elevation

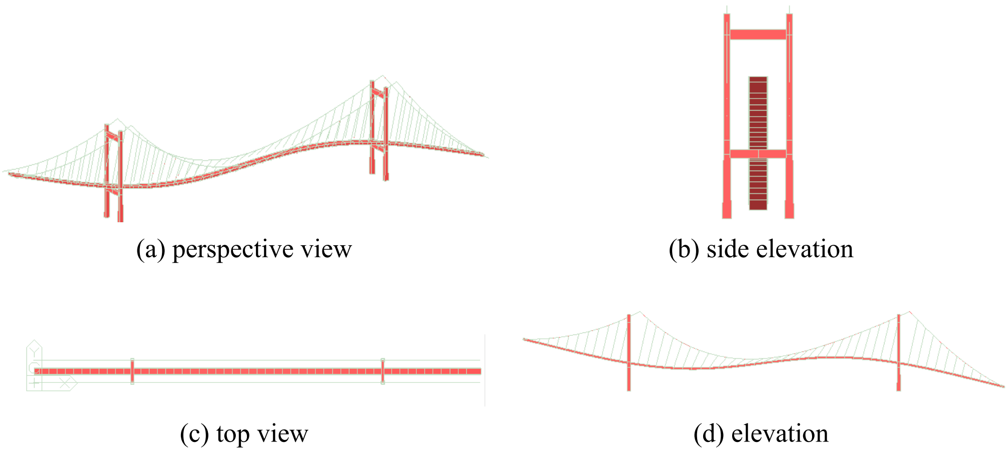
Figure 3. First order vibration mode



(a) perspective view (b) side elevation

(c) top view (d) elevation

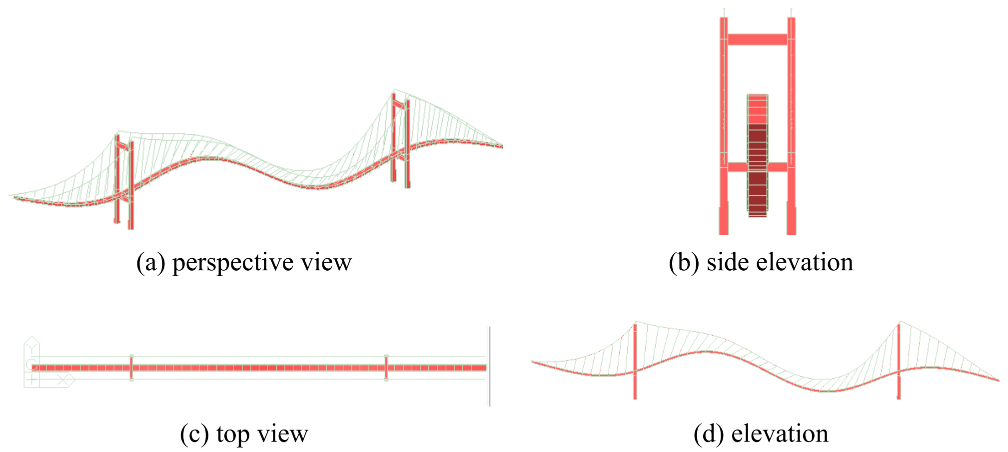
Figure 4. Second order vibration mode



(a) perspective view (b) side elevation

(c) top view (d) elevation

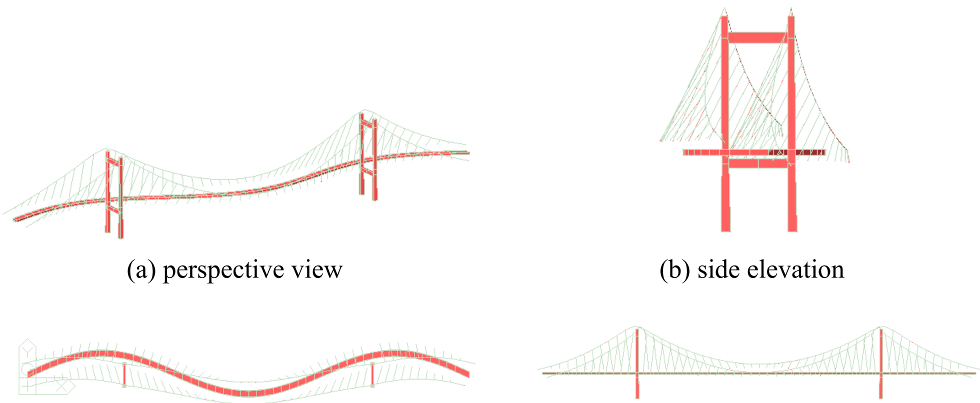
Figure 5. Third order vibration mode



(a) perspective view (b) side elevation

(c) top view (d) elevation

Figure 6. Forth order vibration mode



(a) perspective view (b) side elevation

(c) top view (d) elevation

Figure 7. Fifth order vibration mode

6. The Difference between Self-Anchored Suspension Bridge and Ground-Anchored Suspension Bridge

To compare Self-anchored Suspension Bridge with Ground-anchored Suspension Bridge, the FEM modal is changed into the corresponding modal of Ground-anchored Suspension Bridge. The condition is in common except that the main cable is anchored in ground. The FEM calculation results of Ground-anchored Suspension Bridge are listed in Table 2. Table 2 also gives the relative difference of frequence between the two kinds of bridges.

Table 2. Comparing of dynamic characteristics

vibration mode	Natural frequency	
	Self-anchored	Ground-anchored
1	0.310196	0.350456
2	0.519646	0.549656
3	0.532737	0.662747
4	1.431805	1.454205
5	1.936083	1.979283
6	2.364529	2.407429
7	2.744470	2.894370
8	2.847787	2.898787
9	3.467948	3.526548
10	3.501919	3.678439

Comparing the dynamic property of the two kinds of bridge, we can know that the biggest difference of dynamic property is the modal shape decided by king-tower. Because main cable gives different restriction degree to the displacement of tower top, the lengthwise bends frequency decided by king-tower of the Self-anchored Suspension Bridge is lower than that of Ground-anchored Suspension Bridge.

For the modal shape decided by girder, the frequency of Self-anchored Suspension Bridge is lower than that of Ground-anchored Suspension Bridge. It is because that the girder of Self-anchored Suspension Bridge bears horizontal component from the main cable, which weaken the girder's geometric stiffness.

There is little difference between the frequency decided by main cable.

7. Summary and Conclusions

From Table 1 and Figure 2, the dynamic characteristics of Taohuyu Yellow River Bridge can be concluded as follows:

(1) The vibration modes of Taohuyu Yellow River bridge and bridges of like mainly include deck longitudinally displaced, deck vertically and symmetrically bended and cable plane symmetrically swayed in the same direction.

(2) The natural frequency of Taohuyu Yellow River Bridge in first order vibration is 0.310196 Hz, which is higher than that of conventional large suspension bridge. Besides, the deck longitudinal displacement did not appeared in the first few vibration modes, thus indicates the lateral stiffness of pylon and girder is relatively high. Provided that constraints of approach bridge to main bridge is taking into account, lateral stiffness of pylon and girder will be higher.

(3) Another significant feature of vibration is the vertical vibration of deck. This feature appeared in the first order vibration, and becomes more significant in the following vibrations. Vertical vibration of deck exists in the first 10 vibrations except for second and fifth order vibration, this indicates that the vertical stiffness of stiffened girder is weak, which is common for suspension bridge.

(4) In the first 10 vibrations, deck laterally bended in the second and fifth order vibration, which means that the lateral natural frequency is relatively small, the lateral stiffness of stiffening girder is weak, wind stability should be improved.

(5) In the first 10 vibrations, lateral out plane vibration of cable plane did not appeared, it just swayed with deck in different amplitudes, this shows that lateral stiffness of main cable and suspender is relatively high.

(6) In the first 10 vibrations, torsion did not appeared, it appeared in higher order vibrations.therefore, the torsional stiffness of this bridge is relatively high.

(7) The natural frequencies of Taohuayu Yellow River bridge are mainly concentrated in the scope that arranges from 0.3 Hz ~ 3.5 Hz. In the first 10 order vibrations, when subjects to load, first few order vibrations may be stimulated simultaneously, therefore, when mode superposition method is adopted to calculate the bridge dynamic response, multiple vibration modes should be considered simultaneously.

Acknowledgments

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