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Element Modeling and Dynamic Property Parameters Analysis of Self-Anchored Suspension Bridge

H. B. Zhang

Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian 116023,China,
Email: everdalian@hotmail.com

ABSTRACT: In order to research the affection factors of Dynamic Properties of Self-anchored Suspension Bridge, four different conditions models are set up. Firstly the paper compares three methods of calculating dynamic properties of bridge. Based on the comparison and according to the structural property of Suspension Bridge, the three-dimension FE dynamic model is set up: the ridge mode is adopted to simplify the structure of bridge deck system, the analysis on simulation of other parts of bridge is conducted to be counted into geometric stiffness. The method and standard on adjusting the cable force of Suspension Bridge is acquired by static calculation, and the calculation analysis about bridge dynamic property is conducted to obtain the bridge frequency and vibration. At last, the paper concludes the factors of affecting dynamic property of Suspension Bridge from contrast calculation and analysis of dynamic property according to four different conditions: (1) Constant effect of gravity stiffness;(2) Not calculation of gravity and initial stress of main cable;(3) Including suspender's initial stress;(4) Not including of stress stiffening. The results show that initial stress of main cable and suspension cable is the important parameter to affect structural stiffness.

KEYWORDS: Dynamic property; Mode; Natural frequency; Suspension bridge.

INTRODUCTION

Vibration property is the basis to research the suspension bridge's dynamic response of anti-seismic Design, Wind Resistant Design, and vehicle-bridge vibration analysis; it is also the starting point of other analysis such as dynamics analysis, Response Spectrum analysis and harmonic response analysis.

No specific requirement is set for the dynamic property of Suspension bridge in China's highway code [1]. With the expansion of bridge span, it is necessary to research the Suspension bridge's dynamic property to provide reference for the management of bridge's design, construction and operation [2-5], and further reason is due to the Suspension bridge's flexible structure of feeble rigidity, which is easy of deformation and obviously systematic geometrical non-linearity.

Recently, many scholars made analysis and researches for affection factor of dynamic characteristics of suspension bridge. Huang Fuwei [6] indicated that spatial model is the only factor to effectively simulate suspension bridge's spatial and dynamic characteristic; Zhu Ledong [7]made further research for bridge modeling with suspension structure and proceeded true simulation analysis for setup of triple main span modeling and warping stiffness; furthermore, analytic accuracy for dynamic characteristics of suspension bridge is basic precondition and key factor of seismic response accuracy[8].Suspension bridge is with long-span flexible structure and many factors can impact bridge's mechanical properties, therefore, analysis for effective factors of dynamic characteristics of suspension bridge has important research value. Zhang Wenming [9]performed refinement analysis for comparison of dynamic characteristic of suspension bridge with small single main spanned large single main span and double main span. Wang Hao [10] proceeded research for multi-precision simulation technique of stiffness central buckle and its impact on dynamic characteristics of suspension bridge. Sun Shengjiang [11] and Jiao Changke [12]made research for main cable, suspender, stiffening girder and tower stiffness and its effective factors of dynamic characteristics of suspension bridge.

Other scholars [13-15] conducted multi-parameter analysis and research for affection factors of flexible structure and dynamic characteristic on suspension bridge which laid a solid foundation for further research of model modification and seismic response.

The paper simplifies the structure as beam and pole element system by using of FEA and conducts comprehensive imitation analysis on simplified model by application of large-scale program of ANSYS, meanwhile, four conditions are taken into consideration, which include (1) Constant load, including of affection of gravity stiffness; (2) Not consideration of affection of gravity, also not including of initial stress of main cable, only calculating as common

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model; (3) Including suspender's initial stress, adjusting initial stress of main cable and suspender to achieve ideal calculation status to make analysis; (4) Not including stress stiffening, just adding into gravity and prestress on main cable and suspender. Bridge's modeling can provide useful information for dynamic analysis of bridge with the same type and seek the effective solution for analysis of bridge structure by application of ANSYS; also the bridge modeling can provide guidance for actual project design.

SPATIAL FINITE ELEMENT MODELING

Main stress-carrying component from suspension bridge includes cable, beam, tower and pier, and calculation model focuses on simulation structure's rigidity, quality and boundary conditions.

Simulation of Bridge Deck System

Frequently-used model for bridge deck system includes ridge mode, Π-shaped mode, double main-beam mode and tri-beam main mode [16].

Ridge mode is mostly used mode at present, which concentrates on vertical and latitudinal rigidity, torsional rigidity, transverse quality and moment of inertia in bridge deck system on the intermediate node, therefore, simulation of main beam's rigidity system and quality system is correct, but its defect is that cross beam's rigidity and main beam's camber rigidity cannot be fully taken into consideration. Bridge's main beam has closed section, both camber rigidity and relatively free torsional rigidity can be neglected, therefore, ridge model is adopted to analyze finite element of the Bridge and main bridge is taken to establish model.

Details Simulation

Role of bridge deck pavement is to prevent driveway abrasion from vehicle's tyre and spread the concentrated load from vehicles with heavy tyres, when designing the bridge deck pavement, load-carrying calculation will not be included, which will not combine into the whole main beam to endure structural inner force. Quality of bridge deck pavement is simulated and its rigidity will not be simulated when making modeling.

Bridge Tower is simulated by three-dimensional beam element, two cross beams on the upper and lower part of bridge tower belong to variable cross-section respectively, the lower cross-beam can be divided into four variable-section beam elements when undertaking the division; characteristics of cross-section of upper girder changed little which approximately act as four equal cross-section girder elements.

Beams on both sides of the main beam are to be simulated with beam elements. The cross section of the main beam ignores the eccentricity influence between Centroids and shear center, which focuses the characteristics of cross section on centroid of beam element.

LINK10 element simulation is conducted in ANSYS model due to main cable and suspender belonging to tension members, which belongs to the space elastic bar elements with the capacity of being only tension (or compression), whose status is defined in the paper. When being in tension status, element stiffness matrix is zero, which can simulate relaxation index. Initial strain of the main cable and suspender in the state of finished bridge can be input when defining the real constant of LINK10. Nonlinear effects of sag of the main cable weight can be made indirect correction by adjusting the elastic modulus of the material and using of Ernst formula. After calculation, horizontal projection in each section of the main cable of the Bridge is 6m long and elastic modulus correction factor is 0.9 999 998, the effect can be neglected completely, therefore elastic modulus is not corrected.

The intersection area of the component adopts rigid arm unit, and the practical approach is to input material's elastic modulus in this area according to 15 times of the true value, that is, rigid material method [17]. The connecting supporter between bridge tower and the main beam is pull-compressed spherical movable bearing, the supporters on inner pier and side pier are one-way and two-way movable basin-shaped supporter respectively, it means that the horizontal and vertical relative displacement of the main beam and bridge tower are constraint, which only with relative rotation and vertical limit displacement; the connection between main beam and side pier can be divided into (1)One-way movable supporter to restrict the horizontal and vertical displacement of main beam.(2)Two-way movable supporter to restrict vertical displacement of main bean. According to constrained displacement of supporter, by using of coupling function in ANSYS, we simulate the supporter as respective mechanical model. Connection between bridge tower and main cable adopts the fixed form according to the design.

About Stress Rigidity and Gravity Rigidity

Status of the surface inner stress of structural cable (axial force of main cable generated by structural weight) affects rigidity of plane of the structure. Coupling between inner stress and lateral stiffness is named as stress rigidization [18]. An auxiliary rigidity matrix—"stress rigidity matrix" can be produced by launching stress rigidity effect (SSTIF, ON) in ANSYS, which would be added on main rigidity matrix.

Gravity rigidity of suspension bridge is supplied by initial tension from main cable, and the axial tension generates from dead load. With the expansion of suspension bridge's span, anti-bending rigidity of the stiffening beam is much smaller than axial rigidity of main cable with large axial force [19] , therefore; affect of gravity rigidity must be taken into consideration when setting up the finite element modeling. Launching of rigidity effect includes structure rigidity affect by dead load, that is, gravity rigidity is solidified into calculation of the static structure in the form of initial prestress. The specific method is to assign an initial strain for cable element (LINK 10) when the modeling process becomes the structure as a prestressing system to make the calculation of prestressing and solidify the initial stress of the main cable in the structure.

After setting up of the Bridge model, a total of 1672 nodes and 1028 elements are produced, of which the main cable and suspender element are 278 elements, the main beam element 74, tower unit 148, and the remaining 591. Full-bridge mode is shown in Figure 1.

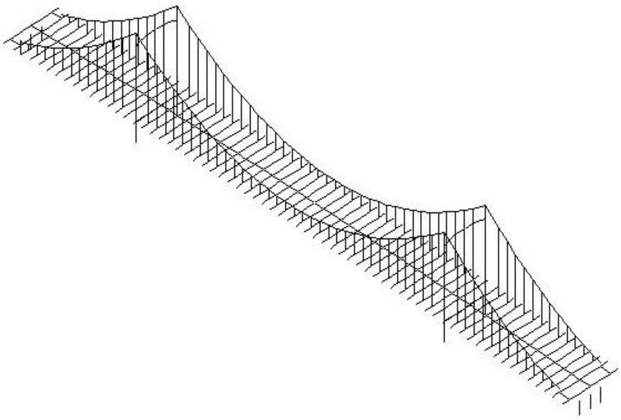


Figure 1. Spatial finite element model.

ANALYSIS OF DYNAMIC PROPERTY

The static calculation is undertaken firstly, initial stress of main cable is adjusted by repeatedly adjusting the initial stress of main cable and suspender so as to adjust gravity rigidity of main cable and gain the geometry location under the bridge status. Peng Dawen and Chen Yunming [20] think the optimal value of initial strain should meet the following conditions (1) the bridge with the smallest deflection under the role of constant load. (2) Rigidity beam with the minimum internal force under the role of constant load. (3)Internal forces of the main cable are in accordance with the value calculated according to elasticity theory formula $H = WL^2 / 8f$. When adjusting initial strain of main cable and suspender, the first two conditions should be met, but the third condition is open to be as question for the inner force according to elasticity theory formula which did not take the affect of large nonlinear displacement into consideration, and the result is obviously safer than the result calculated according to nonlinear finite element, which means the value is relatively larger. Therefore, strain of the Bridge is adjusted according to the first two conditions.

In the process of adjustment, the basic trend is that deflection and axial force on rigidity beam reduces with the increasing of initial strain of main cable for no linear corresponding relation is existed in axial force of stiffening beam and initial strain of main cable, therefore cross-node on stiffening beam is taken as reference point which is also the largest deflection point in the middle of span. Initial strain of main cable will be continuously adjusted until the above-mentioned two conditions are met. When initial strain value reaches 0.001566 and deflection across the middle nodes 0.0063mm, axial force of stiffening beam 67200KN, the model is consistent with the status of bridge completion, and rigidity of gravity achieves the best value. The model mentioned above is considered as the ideal model to make model analysis.

The paper conducts the modal analysis by ANSYS Modal Analysis Module and calculates the results with and without prestress, dead weight; stress rigidity and combination of several non-linear combinations of geometric conditions, combined condition can be divided as the followings:

(1) Constant load, adding into initial stress of main cable and stress stiffening, that is, effect of gravity stiffness.

(2) Not included into gravity, also not included into initial stress of main cable, only calculating and analyzing according to common mode, not making static analysis and just directly calculating models modal.

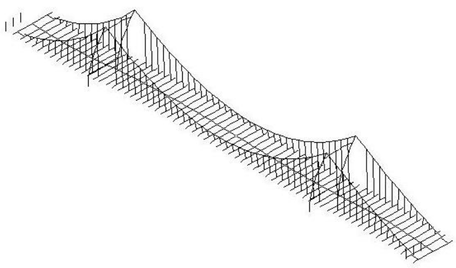
(3) Including suspender's initial stress, other settings are the same as condition 1 respectively adjusting initial stress of main cable and suspender to achieve ideal calculation status to make analysis.

(4) No including stress stiffening, just adding into gravity and prestress on main cable and suspender.

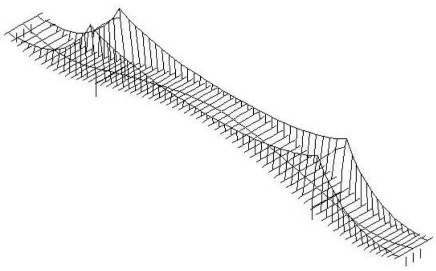
The first 50 frequency and modal is picked up when making calculation, comparison of the first 12 frequency under various conditions is listed in the Table 1, description of frequency mode in the condition 1 can be seen in figure 3.

Table 1. Frequency and model under various conditions.

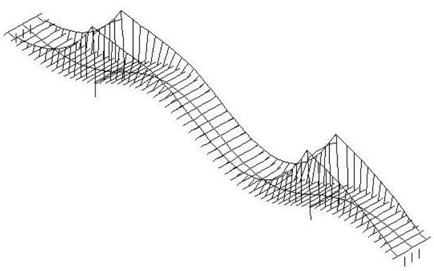
Step	Frequency [Hz]				Condition 1 Mode
	Con. 1	Con. 2	Con. 3	Con. 4	
1	0.2203	0.2196	0.2203	0.2098	Longitudinal drift
2	0.5347	0.5153	0.5350	0.4987	Symmetric vertical bending
3	0.6504	0.6110	0.6509	0.5793	Anti-Symmetric vertical bending
4	0.9349	0.9939	0.9364	0.9722	Lateral bending vibration focusing on tower
5	0.9956	1.0144	0.9968	0.9932	Tower&Cable anti-symmetric lateral vibration
6	1.0476	1.0279	1.0480	1.0027	Anti-symmetric vertical bending
7	1.0692	1.0549	1.0743	1.0294	Plane cable symmetric lateral and outward vibration
8	1.0862	1.2024	1.0866	1.1942	Symmetric vertical bending
9	1.1092	1.2888	1.1126	1.2850	Plane cable symmetric lateral vibration
10	1.2113	1.3854	1.2125	1.3832	Symmetric lateral bending
11	1.2184	1.5157	1.2253	1.4949	Cable plane symmetric torsion
12	1.2442	1.6520	1.2507	1.6450	Symmetric torsion, cable plane in the opposing direction



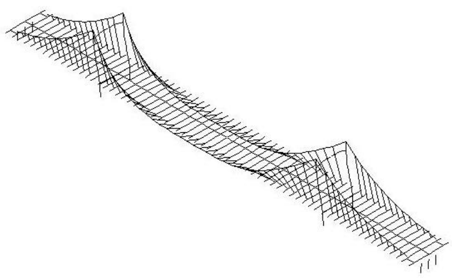
(1) Longitudinal drift in stage 1



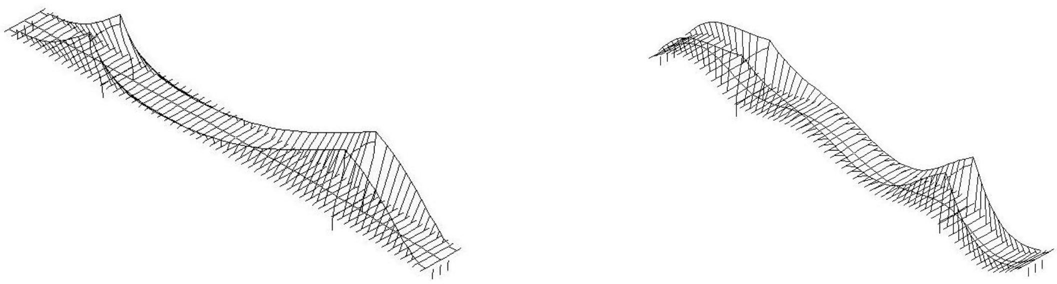
(2) Symmetric vertical bending in stage 1



(3) Anti-Symmetric vertical bending in stage1



(4) Lateral bending focusing on tower in stage 1



(5) Tower&Cable anti-symmetric lateral vibration (6) Anti-Symmetric vertical bending in stage2

Figure 2. Various vibration mode of the bridge (condition 1).

Calculation result analysis can conclude that the Bridge is with the characteristics mentioned below:

(1) With different fundamental frequency and vibration Properties compared with other general Large-span Suspension Bridge, this bridge's base frequency is 0.22Hz and its frequency is very high; furthermore, its first-stage vibration mode is Longitudinal drift which is also different from large-span Suspension Bridge's first-stage lateral bending. Vertical vibration mode emerged early than that of large-span suspension Bridge.

(2) First-stage mode is vertical vibration mode and other modes onwards are taking vertical stiffening beam vibration as main mode, which shows that longitudinal rigidity constraint for Suspension bridge's supporter for separation of tower and girder is the smallest, and vertical flexural rigidity for stiffening beam takes second place. Phenomenon for cable's lateral vibration and tower's lateral vibration appears from the 5th-stage vibration mode, which shows that main-cable's outward rigidity and bridge's lateral stiffness is small, and attention should be paid to response when conducting the analysis of seismic response spectrum. Ratio for torsional frequency and vertical curved frequency in first stage is 1.3995/0.5347=2.62, which complies with design requirement, but cable's vibration and torsional vibration appears early and intensively; also attention should be paid to proper increase of torsional rigidity for main cable and stiffening girder.

Figures 3 Frequency distribution in the same figure under various conditions, and Table2 Different rate between Condition1 and other conditions.

Lateral comparison can conclude that:

(1) Figure 3 and table 2 shows that frequency distribution under 4 conditions forms different groups , figures under condition1 and condition 3 get close to form a group (Group1), figures under condition 2 and condition 4 are close to be a group.(Group 2). Difference between group1 and group 2 appears apparently from stage 8. Grouping of vibration mode from latter stages is mainly generated due to stress stiffening from main cable. Re-grouping of vibration mode appears from stage 8. That is, group1 is vertical bending vibration mode and group 2 is lateral bending vibration mode. Therefore, calculation of main cable stress stiffening can impact plane's inner and outer rigidity, which has a great impact on Suspension Bridge's vibration mode.

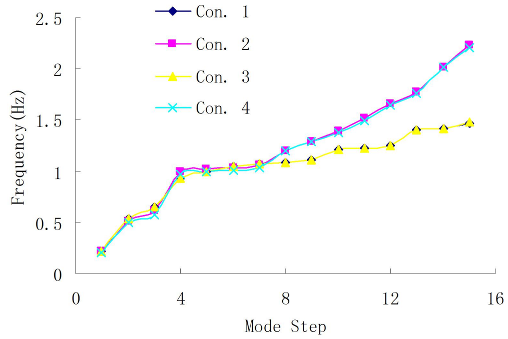


Figure 3. The different frequency under four conditions.

Table 2. The different rate of other three conditions compare with condition 1.

Step	Frequency [Hz]	Different Rate of compare with con. 1(%)		
	Con. 1	Con. 2	Con. 3	Con. 4
1	0.2203	0.32	0.00	4.77
2	0.5347	3.63	-0.06	6.73
3	0.6504	6.06	-0.08	10.93
4	0.9349	-6.31	-0.16	-3.99
5	0.9956	-1.89	-0.12	0.24
6	1.0476	1.88	-0.04	4.29
7	1.0692	1.34	-0.48	3.72
8	1.0862	-10.70	-0.04	-9.94
9	1.1092	-16.19	-0.31	-15.85
10	1.2113	-14.37	-0.10	-14.19
11	1.2184	-24.40	-0.57	-22.69
12	1.2442	-32.78	-0.52	-32.21

(2) Comparison between the latter three conditions and condition 1 shows that base frequency for structure's vertical vibration decreased by 3.63% without calculation of effection of gravity and initial stress and this rigidity is gravity stiffness, and vibration mode is no longer consistent anymore and phenomenon of re-grouping of vibration mode appears starting from the 10th stage; calculation of suspender's initial stress or not has no impact on structure rigidity and only frequency has tiny difference at certain stages, which means suspender's initial stress does not affect structural stiffness; Fundamental frequency for structural vibration reduced by 6.73% without consideration of stress stiffening and phenomenon of re-grouping of vibration mode appears starting from the 8th stage, which shows that inner stress of main cable can enforce stiffness of structural plane.

(3) Distrubution of frequency difference from table shows that frequency and vibration mode under condition 1 and condition 3 is close, which shows that including of suspender's initial stress or not has very tiny impact on Suspension Bridge's vibration mode, the biggest impact is from 11th stage's torsional vibration and its frequency increased by 0.57% when including suspender's tension.

(4) Frequency and vibration mode under condition 2 and condition 4 is close, which shows that including of gravity, main cable and suspender's initial stress (called as prestress) have different impact on suspension bridge's different states. Vertical bending frequency excluding of prestress in the 3rd stage increased by 5.19% among first 15 stages, which indicates that including of prestress hardly impacts other stage's frequency.

CONCLUSIONS

(1) For suspension bridge and cable-stayed bridge, initial stress of main cable and suspension cable is the important parameter to affect structural stiffness and location of bridge. The method and principles in this paper can be used to make test repeatedly when conducting the calculation until the ideal status is achieved.

(2) Changing of structural dynamic property can not only affect the rigidity-change of frequency but also regrouping phenomenon of structural vibration mode, which has great significance for seismic analysis of structure.

(3) Bridge border and initial conditions can be simulated effectively by making use of ANSYS program function of coupling and initial stress to set up three-dimensional finite element model of suspension bridge and find a feasible solution for analysis of suspension bridge by using of general finite element program.

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