

Influences of local vibrations of cables on flutter behaviors of cable-stayed bridges

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ABSTRACT: The effects of local vibrations of cables on flutter behaviors of cable-stayed bridges are investigated by using the 3D flutter analysis method. The cables are treated as multi-link model, instead of single link model, and therefore can show the lateral degrees of freedom along the cables. After simulating the structural damping, the flutter behaviors including local vibration effects of cables for an example bridges, Yangpu Bridge in China, are investigated based on the 3D flutter analysis method. The calculated results show that for the Yangpu cable-stayed bridge with a 602m main span, the flutter critical wind velocity can be increased by 20.2% with the consideration of local vibration effects of cables and the aerodynamic forces acting on cables. The mechanisms of the local vibration effects of cables are also discussed in this paper.

KEYWORDS: cable-stayed bridges; flutter analysis; single-link model; multi-link model; lateral vibrations of cables

1 INTRODUCTION

The aeroelastic interaction between the flowing air and the cables of the cable-stayed bridges must exist and will exhibit some influences on the flutter behaviors of the bridge structures. The aeroelastic effects of cables include the aerodynamic forces acting on cables, the local vibrations of cables, and their interaction. The aerodynamic forces on cables are generally neglected due to the belief of their insignificant effects. For a long-span cable-stayed bridge, the effects of cable local vibrations on flutter should be investigated because the dense cable system of a cable-stayed bridge can form one or more powerful wind-resisting cable planes. The local vibrations of these cables as tightly tensioned chords can significantly impact the bridge-and-wind interaction. This interaction can be taken into account by using the flutter analysis method with the cable model which can show the local vibration shapes of cables.

The three-dimensional (3D) flutter analysis of bridges is based on structural 3D finite element (FE) models and the action of self-excited aerodynamic forces (Ge, 2008)^[1]. Many researchers have contributed to the bridge 3D flutter analysis. Xie and Xiang (1985)^[2] proposed the state space method. Agar (1989)^[3] treated the flutter as a 2M-order eigenvalue problem. Chen (1994)^[4] proposed a multi-mode search method based on the modal analysis method. Namini, et al (1992)^[5] presented the pK-F method, to solve the flutter equations. Ge (2000)^[6] proposed a full mode method to abstract the eigenvalues and eigenvectors without the need to select the participating modes. All these methods treated the cable as a single-link model and therefore cannot consider the local vibrations of cables.

Cheng (1999)^[7] took the aeroelastic effects of cables into account by using a finite strip model (Lau, et al, 2000)^[8] of the deck and the pK-F solving method. The lateral degrees of

freedom of cables are represented by sinusoidal generalized coordinates. However, since the modes representing the local vibration of cables are usually far away from the principal modes of bridges and cannot be selected by the pK-F method, the pK-F method cannot take into account of the effects of cable local vibrations very well.

If a method intends to take into account the cable lateral vibration effects, the method has to both include the degrees of freedom reflecting the cable local vibrating shapes and have the ability to abstract the modes of cable local vibrations as well as the bridge principal modes. Yang (2005, 2011)^[9, 10], Hua (2007)^[11] separately proposed a method to conduct the bridge 3D flutter analysis by using the commercial FE software (ANSYS)^[12], which is based on the existing functions of the software. This method could model the cable as a multi-link model with consideration of the geometric stiffness to show the lateral degrees of freedom along the cable and therefore make it possible to take the lateral vibration effects of cables into account. By taking an actual cable-stayed bridge with a middle span length of 602m as an example, this paper focuses to calculate the effects of local vibrations of cables on flutter critical state by the 3D finite element method for the flutter analysis.

2 3D FLUTTER ANALYSIS OF CABLE-STAYED BRIDGE

An example bridge needs to be employed to illustrate the 3D flutter analysis of cable-stayed bridges (Yang 2005, 2011)^[9, 10]. The Yangpu Bridge, opened to traffic in 1993, in Shanghai, China, has twin towers, twin cable planes and composite girders. The bridge spans over the Huangpu River by its main span of 602m. It was the longest span of cable-stayed bridges in the world when it was completed and opened to traffic. It has a span length pattern of 99+144+602+144+99 m. The cross section of the deck applies an open-style composite girder. It has two separate steel boxes of 2.67m deep and 1.5m wide each with a composite precast prestressed concrete deck slab of 0.26m deep. The overall width of the bridge deck is 32.5m. The FE model was established using the structural data used by Ding (2001, 2002)^[13, 14]. The structural FE model is shown in Figure 1.

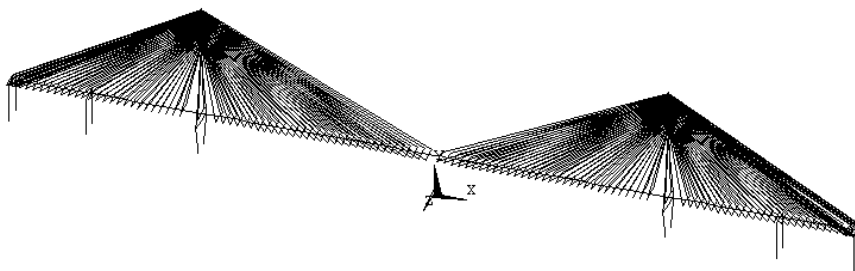


Figure 1. FE model of Yangpu Bridge with span pattern of (99+144+602+144+99) m

The mode damping ratio of the Yangpu cable-stayed bridge can be simulated by 1%. The two-parameter Rayleigh damping (Clough 1993)^[15] can cover two main participative modes. After the damping is simulated, the structural natural modes with the designed damping can be obtained. Using the data of flutter derivatives of the Yangpu Bridge deck, as same as in Ding 2001, 2002^[13, 14], the flutter analysis can be carried out, in which each cable with the top end connecting to the tower and the bottom end to the girder, is simulated as a single link model. The calculated results without local vibration shapes of cables (single-link model) and without aerodynamic forces acting on cables are listed in Table 1. The flutter mode is initiated from the

structural inherit mode of the first symmetric torsion and companied with the second symmetric vertical deck bending. The mode shape of the flutter critical state is shown in Figure 2.

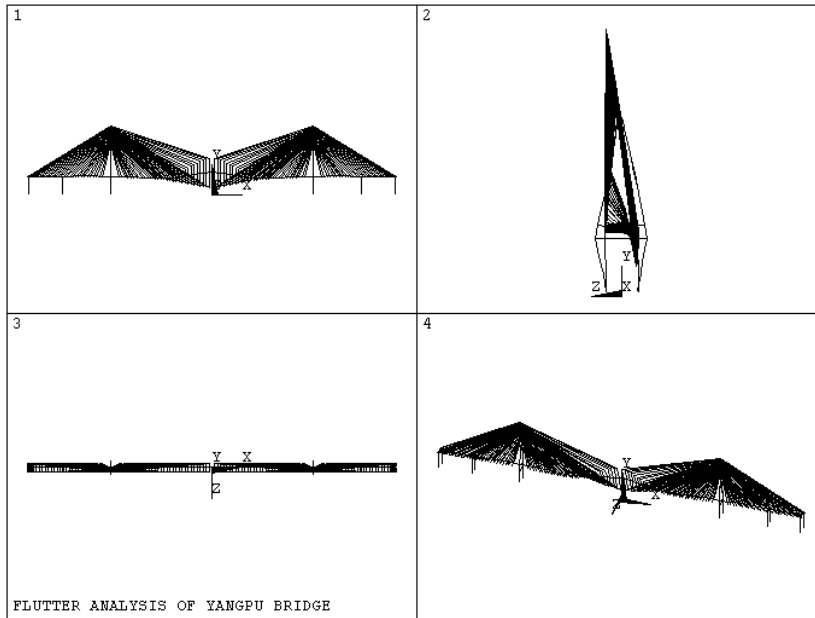
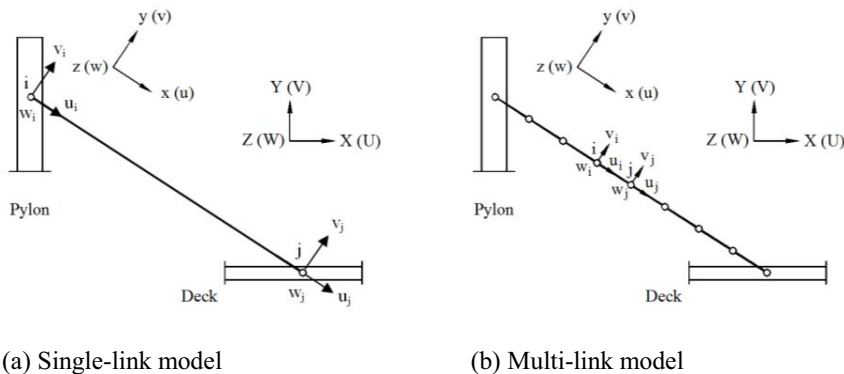


Figure 2. Mode shape of flutter critical state for Yangpu Bridge
(single-link model, 1st symmetric torsion complex mode)

3 MULTI-LINK MODEL OF CABLES

When a cable-stayed bridge is vibrating, each cable vibrates locally and laterally as a tensioned chord in addition to the vibration as a straight link member along with the movement of the 3D spatial bridge structure. The single-link model, as shown in Figure 3 (a), cannot reveal the behavior of the local vibrations of cables. Instead, it can only reflect the global movement as a straight member connecting with the tower and the deck of the bridge structure. The multi-link model, as shown in Figure 3 (b), which includes the degrees of freedom reflecting the local vibrations of cables, can be introduced to take into account the lateral vibrations of cables. The geometric stiffness must be included for the multi-link model in order to avoid the zero lateral stiffness of intermediate nodes of a cable.



(a) Single-link model

(b) Multi-link model

Figure 3. Single-link and multi-link models of a cable

It is the lower local vibrating modes of cables that impact the dynamic behaviors of the whole bridge including the flutter behaviors. The model with 8 links in a cable can well reflect two half-sinusoids with 4 links in each. For the first mode, it is more perfect to display a half-sinusoid with 8 links. So, the 8-link model for a cable is appropriate.

4 EFFECTS OF LOCAL VIBRATIONS OF CABLES

Take the Yangpu Bridge as an example again. The flutter analysis is carried out based on the multi-link model. The earliest flutter critical state is still the vibration shape dominated by the first symmetric deck torsion. The calculated results by using the multi-link model are listed in Table 1. This table also shows the results of the single-link model and as well as the results considering of aerodynamic forces on cables for comparison. Figure 4 shows the mode shape of the flutter critical state of the first symmetric torsion of the Yangpu Bridge by using multi-link model which considers the aerodynamic forces acting on cables.

Table 1 Effects of cable local vibrations and cable aerodynamic forces on flutter critical state of Yangpu Bridge

Critical Wind Velocity (m/s) / Frequency (Hz)		Local Vibrations of Cables	
		Without (Single-Link Model)	With (Multi-link Model)
Aerodynamic Forces Acting on Cables	without	76.33 / 0.49044	84.36 / 0.50877
	with	77.88 / 0.48963	91.74 / 0.50104

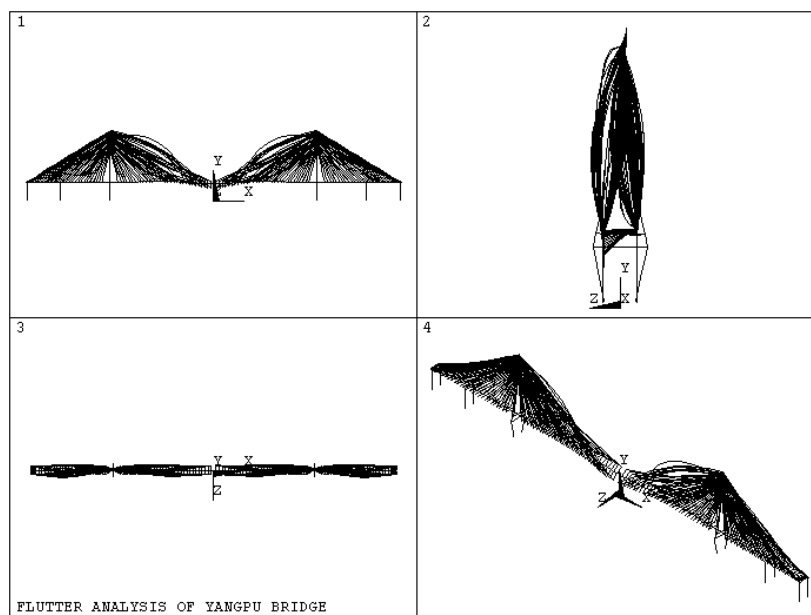


Figure 4. Mode shape of flutter critical state of 1st symmetric torsion of Yangpu Bridge (multi-link model, 8-link for each cable)

From Table 1, without the aerodynamic forces on cables but with the lateral vibrations of cables, the flutter critical wind velocity is increased by 10.5%. Without the lateral vibrations of cables but with the aerodynamic forces on cables, it is increased by 2.0%. When both the aerodynamic forces and the lateral vibrations of cables are considered, the flutter critical wind velocity is increased by 20.2%, from 76.33 to 91.74 m/s. It can be seen there exists an interaction

between the aerodynamic forces and the lateral vibrations of cables. The emergence of the cable lateral vibration shapes intensifies the action of the aerodynamic forces on cables, and therefore intensifies the absorption of the aerodynamic positive damping for cables.

5 EXPLANATION FOR MECHANISM

The mechanism of the effects of local vibrations of cables on the flutter characteristics of cable-stayed bridges can be further explained as follows.

After the introduction of the multi-link model, the increase of the flutter frequency is caused by the increase of the certain structural natural mode frequency since the flutter mode is originated from a certain structural natural mode.

The increase of the flutter frequency will generally cause the increase of the flutter critical wind velocity since the flutter derivatives, which represent the aerodynamic forces between the structure and the flow around it, are related to the reduced wind velocity defined as the actual wind velocity over the vibrating frequency. Therefore, the flutter with a higher vibrating frequency needs a higher wind velocity to activate.

However, the increasing extents in the wind velocity and the frequency should match each other according to the definition of the reduced wind velocity. But in this example, the increasing extent of the critical wind velocity predicted by the multi-link model is far more than that by the single-link model.

In fact, the flutter vibration shape of the first symmetric torsion in the multi-link model is much different from that in the single-link model in addition to the difference of the flutter frequencies. In the flutter vibration shape of the multi-link model (Figure 4), many first-order cable lateral vibration shapes emerge. Consequently, the component of the deck torsional displacement is decreased and is submerged in the lateral vibration shapes of stay cables. On the other hand, the flutter vibration shape in the single-link model is represented by simple torsional displacements of the deck. It is known that the aerodynamic negative damping should be absorbed by the deck torsional displacements, while the lateral vibration shapes of cables can only absorb aerodynamic positive damping. This is the very reason why the flutter critical wind velocity is much increased in the multi-link model.

In summary, the increase of the flutter critical wind velocity due to the effects of the aerodynamic forces on cables is limited. Only when the multi-link model is employed and the lateral vibration shapes emerge as a result, can the increase extent be significant due to the decrease of the component of the deck torsional displacements. The change of the critical wind velocity due to the change of the critical frequency is secondary. The decreasing extent of the deck torsional displacements is related to the participating extent of lateral vibration shapes of cables, namely the coinciding extent of lateral vibrating primary frequencies of cables as tension chords and the fundamental deck torsion frequencies of bridge structures.

6 CONCLUSIONS

Based on the developed method, the aeroelastic effects of cables on flutter behaviors are investigated by using the actual bridge examples. According to the analysis results, some conclusions can be summarized as follows:

(1) With the aerodynamic forces acting on cables but without the consideration of the local vibrations of cables, the flutter critical wind velocity can be increased by 2.0% for the cable-stayed bridge with a 602m middle span. This is because the cable aerodynamic forces only

include the positive aerodynamic damping but do not include the aerodynamic stiffness.

(2) Without the aerodynamic forces but with the local vibrations of cables, the flutter critical wind velocity can be increased by 10.5%. The participation of the cable vibrations weakens the component of torsional displacements of the deck in flutter mode. The emergence of local vibration shapes of cables increase the ability for the bridge to absorb positive damping; while the weakening of the deck torsional displacements decreases the ability for the bridge to absorb the negative damping.

(3) With both the aerodynamic forces and the lateral vibrations of cables, the flutter critical wind velocity can be increased by 20.2%, which is remarkable and much larger than the sum of both separate effects. The apparent impact reveals the interaction relationship between the aerodynamic forces and the local vibrations of cables.

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