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Nonlinear flutter of a triple-tower suspension bridge via full aeroelastic model wind tunnel tests

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Abstract

Research on nonlinear aerodynamic force, as well as the nonlinear vibration aroused by it, needs to be conducted especially when longer-span bridges are mainstreaming in the future. The flutter-mode-evolution phenomenon, which was observed during full aeroelastic model wind tunnel tests of the Maanshan Bridge, a triple-pylon suspension bridge, is a rare case of wind-induced nonlinear vibration. Various types of nonlinear vibration are contained in the phenomenon, including vibration mode transition, soft-type flutter, and so on. Features of the oscillations were introduced in detail. Mechanisms of the oscillations were then discussed. The full-mode flutter analysis results indicates that the aerodynamic force of the middle tower is not the reason for the flutter-mode transition. The aerodynamic force on the deck is the most important exciting source to the full-bridge flutter. The first vertical bending mode frequency, mode A-T-1 frequency, and mode S-T-1 frequency approximately satisfy 1:4:5 double internal resonance relationship, which provides a new way to find out the mechanism of the flutter-mode-evolution phenomenon. This paper may contributes to deepening the understanding of wind-induced nonlinear oscillations.

Introduction

Due to bluff body characteristics of bridge deck sections, nonlinear components inevitably exist in the aerodynamic force. In other words, aerodynamic force of bridge deck is nonlinear in nature. Falco, Curami and Zasso[1] carried out several wind tunnel tests for the deck of the Messina Strait Bridge. High order harmonic components, mainly including the second and third order harmonic components, were observed in the aerodynamic forces. Diana[2] tested the aerodynamic forces of the deck of the Messina Strait Bridge by using forced vibration method, and observed the hysteresis relationship between the aerodynamic force and the instantaneous wind attack angle. The classical linear aerodynamic model[3] is powerless when it is used to explain aforementioned oscillations observed from sectional model wind tunnel tests.

During the full aeroelastic model wind tunnel tests of the Maanshan Bridge, a triple-pylon suspension bridge, we observed a rare case of wind-induced nonlinear vibration. Various types of nonlinear vibration are contained in the nonlinear vibration, including vibration mode transition, soft-type flutter, internal resonance, and so on. In this paper, features of the nonlinear vibration are introduced in detail. Mechanism of the nonlinear vibration is then discussed.

The Maanshan Bridge and its wind tunnel test

The Maanshan Bridge, spanned as 360+2×1080+360m, is a triple-tower suspension bridge, as shown in Figure 1. All three towers are 176 m high. The height of middle tower above the deck is 128 m; the height of each side tower above the deck is 143 m symmetrically. The deck cross section is an aerodynamically shaped closed box steel deck 38.5 m wide and 3.5 m high, as shown in Figure 2.

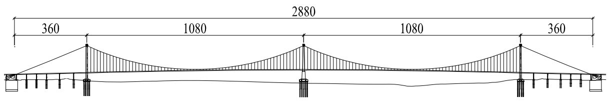


Figure 1. Elevation of Maanshan bridge (unit: m)

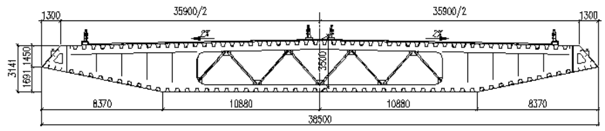
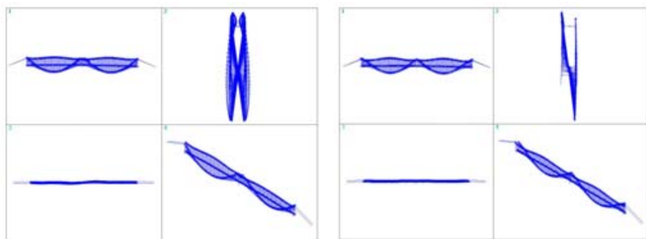


Figure 2. Cross section of deck (unit: mm)



(a) 1st torsion mode: A-T-1 (b) 2ed torsion mode: S-T-1

Figure 3. Torsion modes

The first and second torsion modes are shown in Figure 3. The first torsion mode is an anti-symmetric mode with a frequency of 0.2675Hz, while the second torsion mode is a symmetric mode with a frequency of 0.3386Hz[4].

The full-bridge aeroelastic model test was conducted in the TJ-3 wind tunnel at the State Key Laboratory for Disaster Reduction in Civil Engineering at Tongji University, China. The geometry scale and frequency scale are 1:211 and 14.5258:1, respectively[4].

Nonlinear flutter

Flutter mode transition

The torsional displacement at deck midspan of a main span tested in the wind tunnel is shown in Figure 4. The wind attack angle is 0°, so is the wind yaw angle. Wind speed in the wind tunnel is 6~6.2m/s with a continuous growth.

The torsional response in Figure 4 can be divided into three phases according to the torsional vibration mode. In the 1st, 2ed, and 3rd phase, the torsional vibration mode is A-T-1, A-T-1&S-T-1, and S-T-1, respectively. Time-dependent power spectrum of the torsional response was obtained by using the wavelet transform method, as shown in Figure 5 (a). Two slices of time-dependent power spectrum are shown in Figure 5 (b).

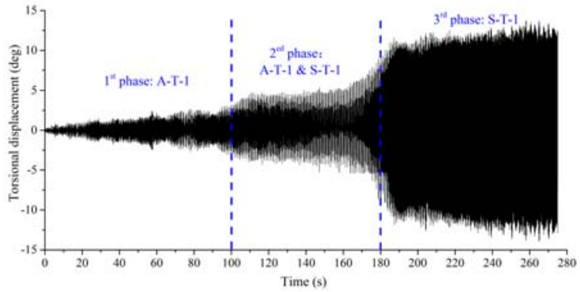
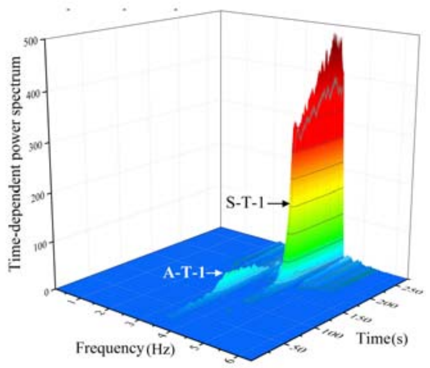
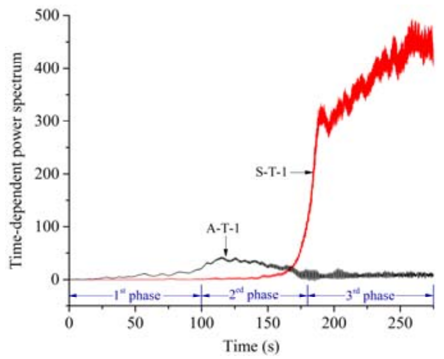


Figure 4. Torsional response at deck midspan of a main span



(a) Time-dependent power spectrum



(b) Slices

Figure 5. Time-dependent power spectrum and its slices for the torsional responses

Coincidentally, a similar vibration modes transition phenomenon occurred in the full-bridge aeroelastic model wind tunnel test of the Yangsigang Bridge, a single-main-span suspension bridge of 1700m. The wind tunnel test was conducted in the Southwest Jiaotong University. When the wind speed was low, the vibration modes were A-T-1 and A-V-1. With the increasing wind speed, the vibration modes transformed to S-T-1 and S-V-1, and divergent vibration happened at last.

Soft-type flutter

At the time of 100s and 180s in the Figure 4, amplitude shows a sudden increase, and seems to be divergent. However, the vibration dose not diverge, and transforms to equal-amplitude limit cycle oscillation. In the 3rd phase, the amplitude is about 13°, which is remarkable. The limit cycle oscillation is one of the features for the soft-type flutter, which is induced by the nonlinearity of aerodynamic force.

Preliminary study on the flutter mechanism

As a new type of bridge, long-span suspension bridges with multiple main spans have made a figure, and will have broad application prospects in sea-crossing and island-linking projects all over the world. They are flexible and slender structures, and prone to a variety of wind-induced vibrations due to their low natural frequency and mechanical damping. Extreme wind speed in strong wind conditions tends to be one of the key factors in designing and constructing long-span suspension bridges with multiple main spans. It is necessary to conduct an in-depth investigation on wind-induced vibrations and corresponding control measures.

The most dangerous one among various aeroelastic instabilities is flutter which is a dynamic instability phenomenon, wherein at some critical wind speed the bridge oscillates in a divergent and destructive manner. As a result, flutter instability is prohibitive during the design of long-span bridges, and the critical flutter wind speed of a bridge must exceed the design value. The objective of employing flutter control measures is to raise the critical flutter wind speed, and therefore enhance the safety redundancy of bridges.

Actually, the flutter-mode transition behavior is a potential flutter control measure for suspension bridges with multiple main spans. Before the full bridge aeroelastic model tests, sectional model tests of the Maanshan Bridge and full-mode analysis were conducted for checking the aerodynamic stabilities under smooth wind. The sectional model testing result indicates that the critical flutter wind speed for the A-T-1 mode is 76.3 m/s, so does the result of flutter analysis using full-mode method. Therefore, the transition from mode A-T-1 to mode S-T-1 raised the critical flutter wind speed from 76.3 m/s to 90.2 m/s. Since the flutter-mode transition behavior can raise the critical flutter wind speed of the Maanshan Bridge sharply, the reasons for the behavior are worth to be found out. At the same time, if the precipitating factors of flutter-mode transition from a low-order torsional mode to a high-order one are available, they can be used as a helpful and brand new flutter control measure to improve the flutter performance of long-span suspension bridges with multiple main spans.
Based on repeated observation of the flutter-mode transition phenomenon in a wind tunnel and recorded video, and careful analysis of the experimental data, the authors made two inferences of the reasons for the flutter-mode transition behavior[4]. The first inference is soft-type flutter induced by the nonlinear aerodynamic force of the middle tower. The second one is internal resonance.

Effect of middle tower vibration

In order to study the effect of middle tower vibration on the full-bridge flutter, we compared two situations, with the aerodynamic force of the middle tower and without, in the full-mode flutter analysis. The column section of the middle tower is shown in Figure 6. The CFD was used to identify the flutter derivatives, as shown in Figure 7. The flutter derivatives of deck were obtained in the sectional model wind tunnel testing.

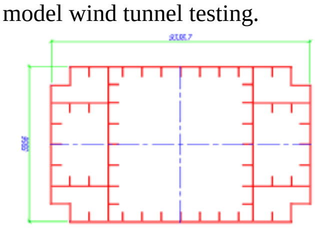
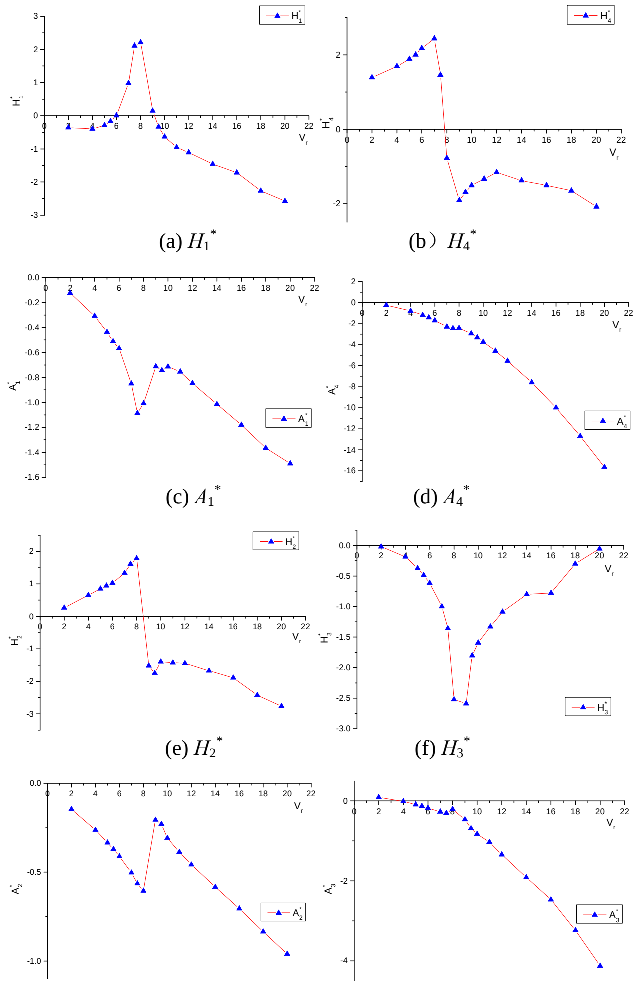


Figure 6. Column section of the middle pylon (unit:mm)



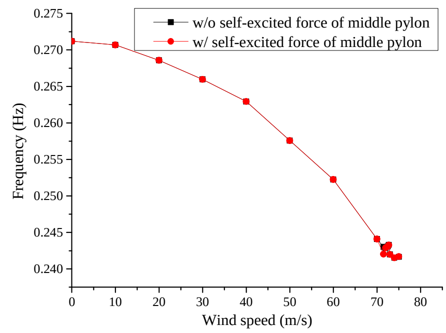
(a) H_1^* (b） H_4^*

(c) A_1^* (d) A_4^*

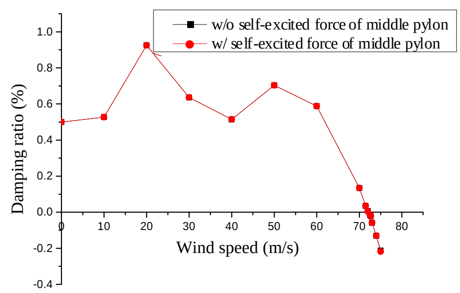
(e) H_2^* (f) H_3^*

(g) A_2^* (h) A_3^*

Figure 7. Flutter derivatives of the middle pylon column



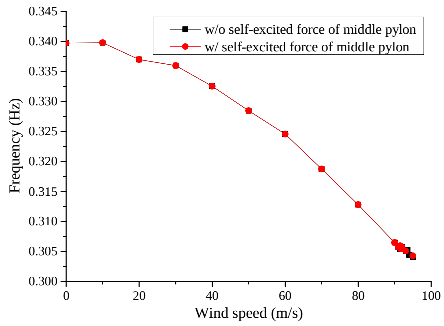
(a) Variation of frequency versus wind velocity



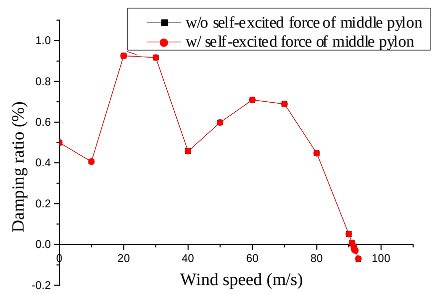
(b) Variation of damping ratio versus wind velocity

Figure 8. Frequency and damping ratio of A-T-1 mode

The variations of the frequency and damping ratio of mode A-T-1 versus wind velocity are shown in Figure 8, while those of S-T-1 are shown in Figure 9. As can be seen from Figure 8 and 9, the aerodynamic force of the middle tower has little effect on the full-bridge flutter, which suggests that the aerodynamic force of the middle tower is not the reason for the flutter-mode transition behavior. In other words, aerodynamic force on the deck is the most important exciting source to the full-bridge flutter.



(a) Variation of frequency versus wind velocity



(b) Variation of damping ratio versus wind velocity

Figure 9. Frequency and damping ratio of S-T-1 mode

Internal resonance

By using filtering, signals of mode A-T-1 and S-T-1 can be obtained, as shown in Figure 10. As can be seen from this figure, two signals fluctuate and shift, indicating that vibration energy transfers between mode A-T-1 and S-T-1. In this process, energy accumulates at the mode S-T-1. As a result, the signal of mode A-T-1 decays, while the signal of mode S-T-1 increases.

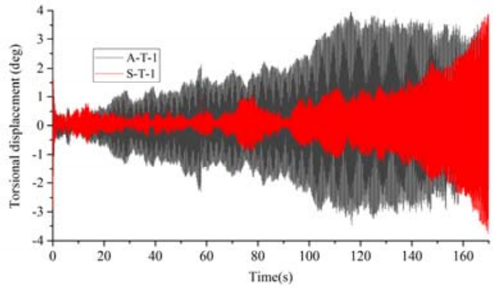


Figure 10. Responses of A-T-1 and S-T-1 mode

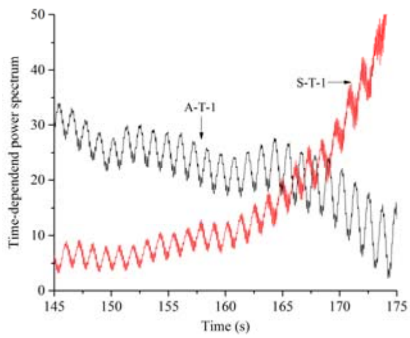


Figure 11. Local zoom of time-dependent power spectrum slices for the torsional responses

Figure 11 shows a local zoom of the time-dependent power spectrum, which is captured from Figure 5. It is indicated that the phase position of time-dependent power spectrum for mode A-T-1 is opposite to that of mode S-T-1. The wave frequency of the time-dependent power spectrum for both modes is the frequency of first vertical bending mode for the full-bridge aeroelastic model.

Internal resonance is a peculiar phenomenon for the nonlinear system. The nonlinearity of the wind-bridge system comes from both deck aerodynamic force nonlinearity and bridge geometric nonlinearity. As for a multi-degree freedom coupling nonlinear vibration system, the mode interaction, internal resonance, may occur if there are several positive or negative integers, m_1, m_2, ……, m_n suitable for this formula

$$m_1\omega_1 + m_2\omega_2 + \ldots\ldots + m_n\omega_n = 0 \tag{1}$$

where, ω_1, ω_2, ……, ω_n are several inherent frequencies for the system. A lot of theoretical and experimental studies suggest that the internal resonance establishes an energy exchange way between modes of a multi-degree freedom nonlinear vibration system.

The first vertical bending mode frequency, mode A-T-1 frequency, and mode S-T-1 frequency approximately satisfy 1:4:5 double internal resonance relationship. Because of the internal resonance, system energy transfers to mode S-T-1 from mode A-T-1. The first vertical bending mode may play a role of medium for the energy transfer. At last, flutter-mode transition occur.

In fact, energy transfer induced by the internal resonance between structural modes has been reported. When finding out the reason for the sudden appearing of torsion vibration in the old Tacoma bridge, Arioli and Gazzola[6] found that internal resonances are the source of torsional oscillations. Because of the internal resonances between bending modes and torsion modes, vibration energy transfers to torsion modes from bending modes. As a result, bending oscillations decay, while torsion oscillation amplitude increases. Anderson, Nayfeh and Balachandran[7] found double internal resonance in the testing of a cantilever curved beam subjected to periodic excitation. The internal resonance results in the energy exchange between a low-order bending mode and two high-order bending modes. Ibrahim and Hijawi[8] observed the internal resonance between bending modes and torsion modes in the test of a cantilever beam subject to periodic excitation or random excitation.

Conclusions

Nonlinear flutter oscillations were recorded in the wind tunnel testing of the full-bridge aeroelastic model for the Maanshan Bridge. Features of the oscillations were introduced in detail. Mechanism of the oscillations were then discussed. Several conclusions can be summarized as follows.

(1) As can be seen from the time-dependent power spectrum and its slices for the vibration signals, the torsional response can be divided into three phases according to the torsional vibration mode. In the 1st, 2ed, and 3rd phase, the torsional vibration mode is A-T-1, A-T-1&S-T-1, and S-T-1, respectively.

(2) With the increasing wind speed and amplitude, soft-type flutter occurred. At the thresholds of 2ed phase and 3rd phase, amplitude shows a sudden increase, and seems to be divergent. However, the vibration dose not diverge, and transforms to equal-amplitude limit cycle oscillation. In the 3rd phase, the amplitude is about 13°, which is remarkable.

(3) The full-mode flutter analysis results indicates that the aerodynamic force of the middle tower is not the reason for the flutter-mode transition. The aerodynamic force on the deck is the most important exciting source to the full-bridge flutter.

(4) The first vertical bending mode frequency, mode A-T-1 frequency, and mode S-T-1 frequency approximately satisfy 1:4:5 double internal resonance relationship. Because of the internal resonance, system energy transfers to mode S-T-1 from mode A-T-1. The first vertical bending mode may play a role of medium for the energy transfer. At last, flutter-mode transition occur. It should to be noted that study on the internal resonance in this paper is preliminary, and further researches are on the way.

Acknowledgments

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