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Sectional model tests and nonlinear flutter mechanism of old-Tacoma section under large attack angles and large amplitude

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SUMMARY:
In 1940, the old Tacoma Bridge collapsed due to a large-scale torsional flutter. For more than 80 years, many scholars have studied the flutter of the Tacoma Bridge through methods such as free vibration experiments, forced vibration experiments or CFD simulations, but there are also lots of puzzles. In this paper, with the aid of the large amplitude and large angle of attack free vibration experiment device developed by Tongji University, a synchronous force and vibration measurement experiment was carried out with the segmental model of the old Tacoma Bridge. The maximum amplitude of the experiment has reached more than 35°, and the experimental phenomenon is relatively close to the real bridge observation record of the Tacoma Bridge. The mechanism of the large amplitude flutter of the Tacoma Bridge is explained, and the bifurcation phenomenon of the Tacoma Bridge is discussed. The vibration situation is different under different attack angles, and the reasons are analyzed from the difference in force parameters.

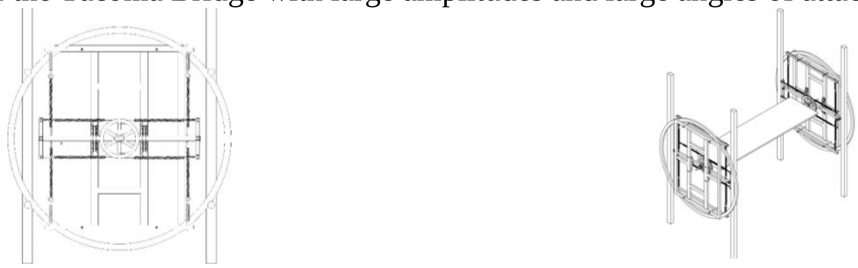
Keywords: the old Tacoma Narrows Bridge, soft flutter, bifurcation vibration

1. INTRODUCTION

For long-span bridges, flutter is the most dangerous type of wind-induced vibration phenomenon. The current flutter theory is based on the Scanlan linear self-excited force model. However, for some blunt bridge sections, the nonlinear flutter phenomenon commonly known as soft flutter occurs. Flutter cases of actual bridges also present the form of soft flutter. In 1940, the Tacoma Narrows Bridge experienced significant soft flutter. After vibrating at an amplitude greater than 35°, the main span deck collapsed (Ammann O. H. et al., 1941). In the following 80 years, scholars have conducted a large number of experimental studies on the Tacoma Bridge (Matsumoto M. et al., 2003). However, due to the limitation of free vibration experimental equipment, only small-amplitude free vibration tests can be carried out; the forced vibration method cannot simulate the vibration development process of the actual bridge.

2. THE EXPERIMENT OF THE OLD TACOMA NARROWS BRIDGE

In order to solve problems in the research on Tacoma Bridge, Tongji University developed a wind tunnel spring suspension free vibration device capable of performing large-amplitude model tests, and the stiffness of the two degrees of freedom of the model maintains a high degree of linearity within the range of torsional amplitude 0°-45° and vertical amplitude 0-10 cm. A schematic figure of the device is shown in Fig.1. And then we completed the segmental model experiments of the Tacoma Bridge with large amplitudes and large angles of attack.



（a）Figure of on side （b）Overall 3D axonometric drawing

Figure 1. Free vibration device of spring suspension of segmental model with large amplitude and large attack angle

The section model of the Tacoma Bridge segment model is shown in Fig.2. In order to make the test results consistent with the actual flutter conditions of the Tacoma Bridge, the section here restores the actual section of the Tacoma Bridge as much as possible, and the scale ratio is 1/35. The model in the wind tunnel in this experiment is shown in Fig.3.

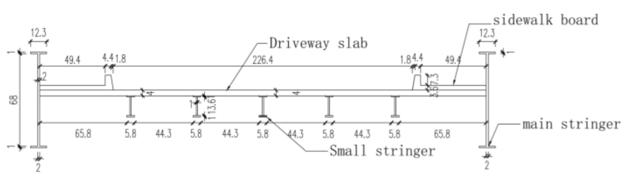


Figure 2.The section of the model of Tacoma Bridge(mm)

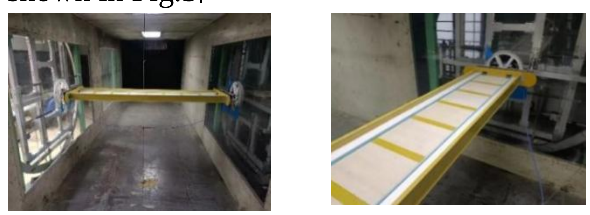


Figure 3. Wind tunnel experiment of Tacoma Bridge model

This experiment was carried out in the TJ-1 wind tunnel of Tongji University. The experimental model parameters and various working conditions are shown in Tab.1. In order to study the aerodynamic parameter characteristics at large angles of attack, and to explore the law of the self-excited vibration of the blunt body section at large angles of attack, experiments were carried out at -15°~15° angles of attack.

Table 1. the parameters of the Tacoma Bridge segmental model

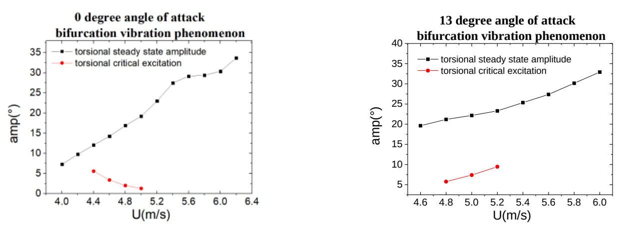
Size ratio	Wind speed ratio	Frequency ratio	Frequency of bend	Frequency of reverse	mass	mass moment of inertia
1/35	1/3	11.667	1.5Hz	2.62Hz	3.42kg	$0.1608 kg \cdot m^2$

3. RESULTS OF THE LARGE AMPLITUDE EXPERIMENT OF TACOMA BRIDGE

The wind speed-amplitude curves obtained from the experiment are shown in Fig.4 at positive and negative attack angles respectively. Through the summary and analysis of the experimental results, it can be found that in all angles of attack in the experiment, the segmental model of the Tacoma Bridge has a soft flutter phenomenon. In the soft flutter, there are constant limit cycle vibrations, and the amplitude of vibration increases gradually with the increase of wind speed. In addition, bifurcated oscillations occur in most attack angles.Fig.4 is a schematic diagram of the positive and negative angle of attack wind speed-amplitude curves of the Tacoma Bridge model. The wind speed-amplitude curves of small angle of attack and large angle of attack are slightly different, and the critical wind speed and maximum amplitude of flutter are also different, but the overall differences are not obvious.

(a)Wind speed-amplitude curve for negative angle of attack (b)Wind speed-amplitude curve for positive angle of attack

Figure 4. Wind speed-amplitude curves in different angles of attack



(a) bifurcation vibration in 0 degree angle of attack

(b) bifurcation vibration in 13 degree angle of attack

Figure 5. Bifurcation vibration at different attack angles

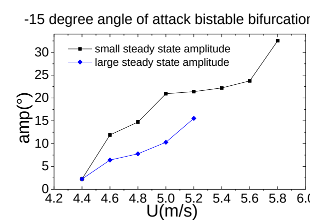
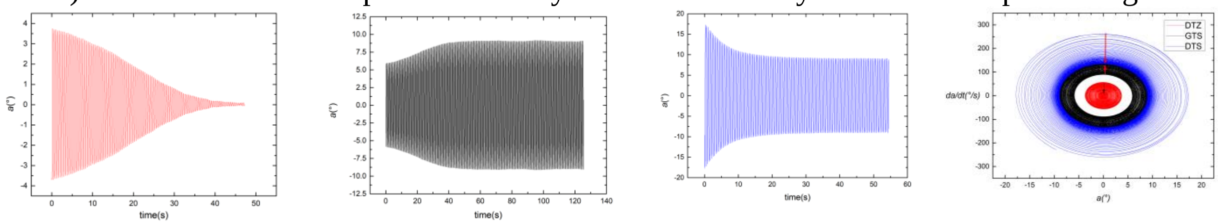


Figure 6. -15 degree angle of attack bi-stable bifurcation phenomenon

The analysis of the wind speed-amplitude curves at each angle of attack shows that (1) in the range of -15°~15° angle of attack, the model has soft flutter phenomenon, and the flutter starting wind speed is between 4.0~4.4m/s. In the interval of 5.6~6.4m/s, the maximum torsional amplitude reaches about 35° . (2) The wind speed-amplitude curve of the Tacoma Bridge is different from that of the streamlined box girder. It does not increase completely linearly, but the slope changes. (3) In the case of high wind speed (greater than 5.4m/s), the greater the absolute value of the angle of attack, the amplitude will reach 35° at lower wind speed.

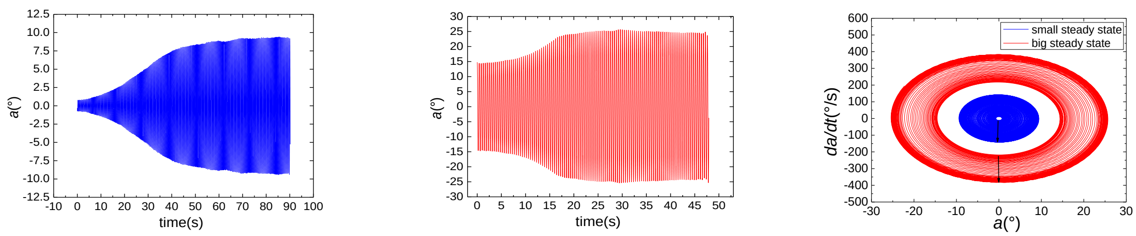
Due to the amplitude dependence of the self-excited force parameters of the bridge and the non-linearity of the structural damping, bifurcation vibrations appeared at most angles of attack in the experiment. Specifically, the bifurcation vibration of 0 degree and 13 degree angle of attack is analyzed. The black curve in Fig.5 represents the steady-state amplitude, and the red curve represents the critical excitation. The critical excitation value is the minimum torsional excitation required for the model vibration to diverge. At 0 degree attack angle, the critical excitation of bifurcation vibration decreases with the increase of wind speed. At 13 degree attack angle, the critical excitation of bifurcation vibration increases with the increase of wind speed.

The time history of bifurcation vibration is analyzed below. Fig.7 shows the time history and phase diagram of the bifurcation phenomenon at 4m/s at -3° attack angle. When the segmental model is given a small torsional excitation, the amplitude will decay to zero; when a medium excitation is given, the torsional amplitude will increase to the steady amplitude; when a large excitation is given, the vibration will decay to the steady amplitude. Fig.8 shows the bistable amplitude phenomenon at -15° angle of attack. When a small excitation is given, the vibration will increase to a small steady-state amplitude A, and when a large excitation is given to the model, The vibration will increase to a large steady-state amplitude B. In the research results of Shengyuan Liu et al., a similar multi-stable amplitude situation also appeared (Liu, S. Y., et al., 2021). The vibration development tendency can also be clearly seen from the phase diagram.



(a)Vibration decays to zero under small excitation (b)Diverge to steady-state amplitude under moderate excitation (c)Decays to steady-state amplitude under large excitation (d)Displacement-velocity phase diagrams under three excitations

Figure 7. The torsional vibration time-history and phase diagram of the bifurcation phenomenon at -3° angle of attack and 4m/s



(a) Diverge to steady-state amplitude A under small excitation (b) Diverge to steady-state amplitude B under moderate excitation (c) Displacement-velocity phase diagrams under two excitations

Figure 8. The torsional vibration time-history and phase diagram of the bifurcation phenomenon at -15° angle of attack and 5m/s

4. CONCLUSIONS

Soft flutter occurs at all angles of attack in the experiment of the old Tacoma Bridge. When wind speed is greater than critical wind speed, limit cycle vibration occurs, and amplitude increases with the increase of wind speed. At most angles of attack, the model will appear bifurcated vibration, and a certain initial excitation is required to diverge to a steady-state amplitude at some wind speed ranges. At some large angles of attack, there will be a bistable amplitude situation, and two steady amplitudes will appear at the same wind speed.

ACKNOWLEDGEMENTS

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