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Energy-related mechanism in nonlinear bending-torsional coupled flutter of a streamlined box girder

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SUMMARY:
Although it is widely confirmed by wind engineers that bridge flutter is a kind of self-excited vibration driven by aerodynamic negative damping, the specific mechanism of nonlinear flutter is still worth of further discussing. This paper deduced the relationship between amplitude-dependent flutter derivatives (amplitude-variant flutter derivatives) and aerodynamic damping ratio in bending-torsional coupled flutter, based on the principle of energy balance in aerodynamic force work. Energy maps suitable to analyze bending-torsional coupled flutter were constructed too. Next, the coupling mechanism of energy fluctuation between vertical and torsional degrees of freedom was revealed, and the mechanism driving complex nonlinear flutter phenomena observed in the experiment, such as classical soft flutter, soft flutter requiring initial excitation, and multi-stable state soft flutter, were explained from the perspective of energy balance. Identified aerodynamic damping showed complex nonlinear variations along with amplitude variations under constant wind velocity; and the vertical and the torsional motions formed a coupling relationship in which the two both promoted and restrained each other. In addition, the segmental model test system was also affected by nonlinear structural damping. The combined effect of nonlinear aerodynamic damping and structural damping leads to a complex relationship between the system's total damping and amplitude, and finally the test system got equilibrium points (the point where the total damping is zero) of different quantities and stabilities, which were further manifested as classical soft flutter and other complex nonlinear flutters.

Keywords: streamline box girder, nonlinear flutter, bending-torsional coupling energy map, equilibrium points, multi-stable soft flutter

1. BACKGROUND

It is pointed out in the linear flutter theory that bridge flutter is a kind of divergent flutter driven by aerodynamic negative damping (Scanlan, et al., 1971). However, due to the effect of structural nonlinearity and aerodynamic nonlinearity, flutter on bridge sections in the test always show obvious nonlinear characteristics, such as soft flutter (Daito, et al., 2002; Gao, et al., 2018; Wu, et al., 2020), soft flutter requiring initial excitation (Zhu, et al., 2015), soft flutter dependent on wind velocity and wind path (Amandolese, et al., 2013), and other complex phenomena. All these phenomena have proved the complicity of nonlinear flutter, making it a key topic to study and reveal the mechanism of nonlinear flutter. Zhu et al. (2015) analysed, from the relative relation between structural damping curve and aerodynamic damping curve, the internal mechanism driving torsional soft flutter of the twin-side-girder bridge section. Zhao et al. (2021) established, by using the forced vibration test, an energy map considering reduced wind velocity and amplitude and studied, from the perspective of energy, the internal mechanism driving the limit cycle vibration in soft flutter of the old Tacoma Bridge and inversed the whole process aerodynamic instability of the old Tacoma Bridge from vortex vibration to large-amplitude torsional flutter. The above work explained the energy mechanism of limit cycle vibration but their studies focused on torsional freedom only due to section restrictions.

2. NONLINEAR FLUTTER BEHAVIORS

This paper conducted the wind tunnel test on the segmental model in free vibration under uniform incoming flows, for a streamline box girder section (Fig.1). Results showed the flutter of such streamline box girder section had obvious nonlinear characteristics which were wholly manifested as bending-torsional coupling soft flutters. Such soft flutters can be divided into three kinds of nonlinear phenomenon, namely, typical soft flutter, soft flutter requiring initial excitation, and multi-stable soft flutter, according to detailed vibration characteristics. Fig.2 shows the curve of steady-state amplitudes of soft flutter along wind velocity variations under all kinds of initial angle of attack (0° and +3°) in the test. Up arrows in Fig.2 means divergent flutter or amplitudes beyond the scope of effective measurements. For details of test layouts, please refer to the earlier work.

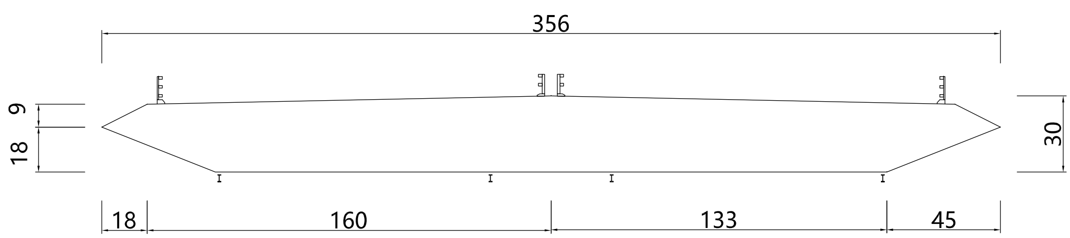
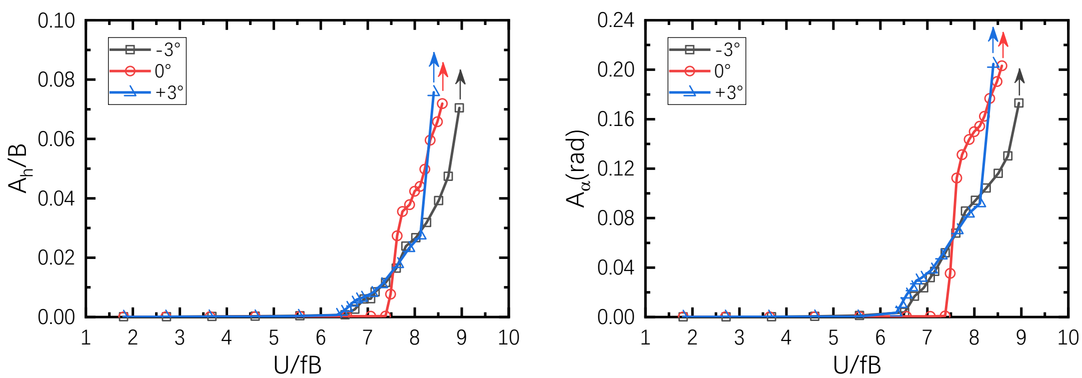


Figure 1. Diagram of model cross section (mm)

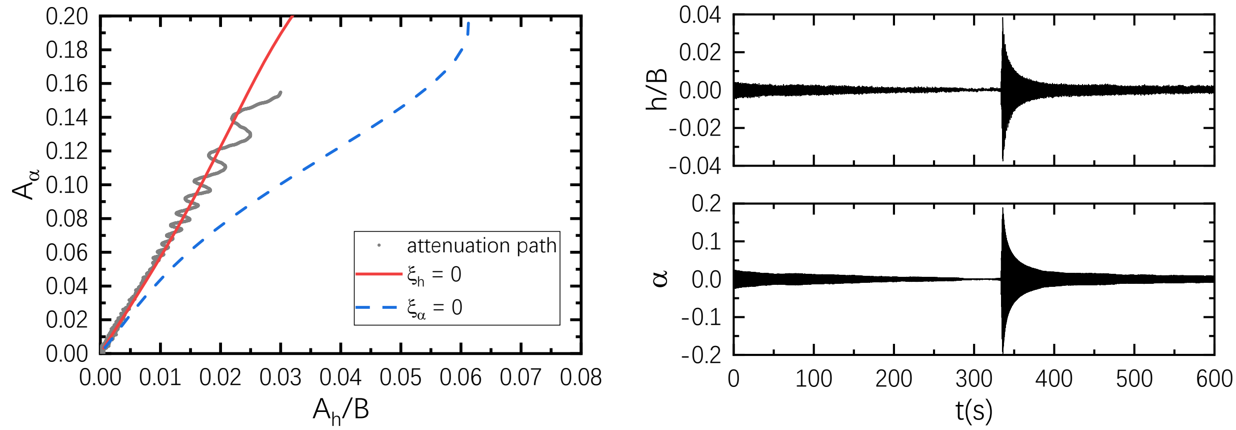


(a) Vertical amplitude (b) Torsional amplitude

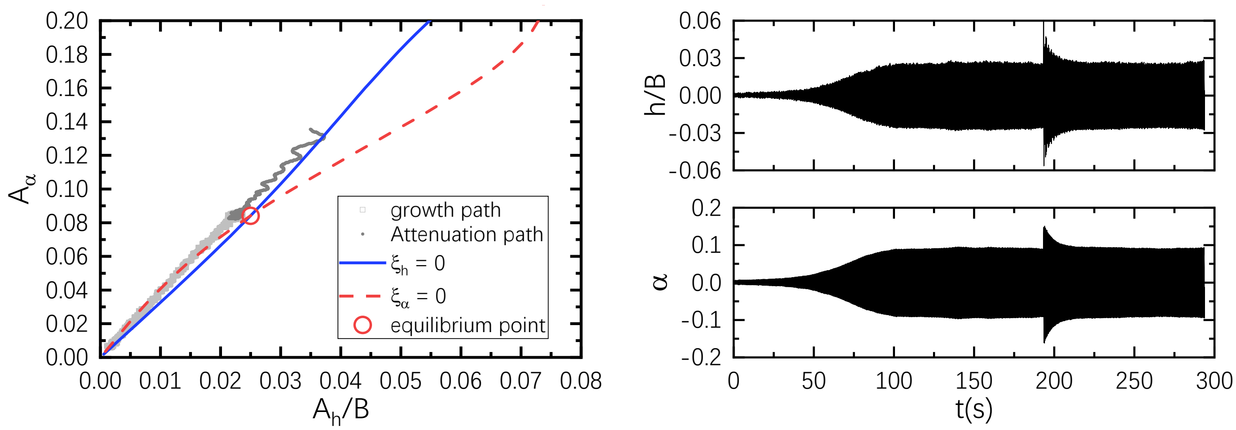
Figure 2. Relationship between soft flutter amplitude and reduced wind velocity

3. ENERGY MAP OF BENDING-TORSIONAL COUPLED FLUTTER

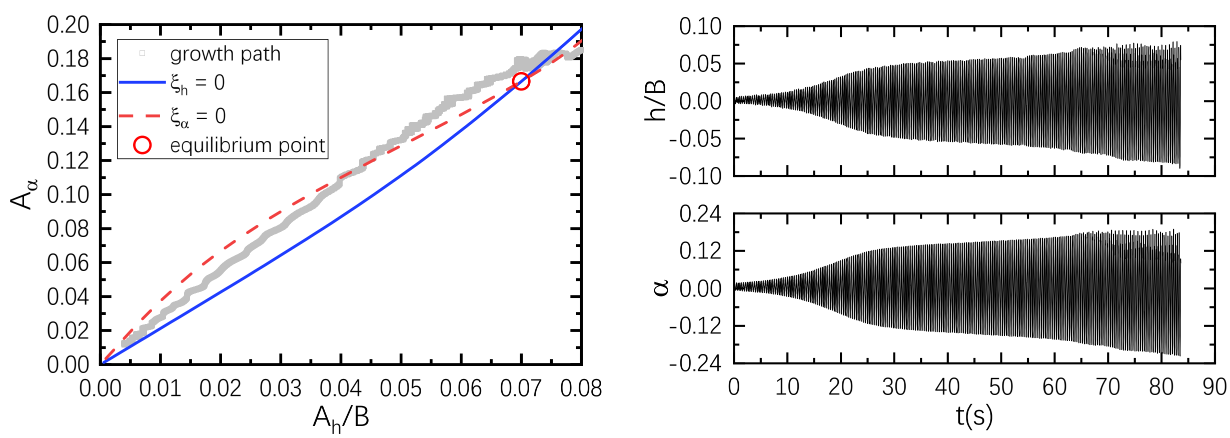
After understanding the concept of energy map, we can discuss the trend of changes of energy map corresponding to different stages of flutter. Taking the closed streamline box girder at AOA -3° as an example, Fig. 3 shows changes in energy maps and in measured displacement time histories at three stages: before the occurrence of flutter (stage I), during stable limit cycle vibration (stage II), and during divergent flutter (stage III).



(a) Pre-flutter stage (AOA = -3°, U* = 6.6)



(b) Stage of soft flutter (AOA = -3°, U* = 8.0)



(c) Stage of divergent flutter (AOA = -3°, U* = 8.6)

Figure 3. Energy map and corresponding displacement time history in different flutter states

Stage I: If flutter doesn't take place in the system when $U^* = 6.6$ (Fig.3a), the torsional zero-damping line in the energy map is thus at the right lower corner to the vertical zero-damping line but not intersect with the same (means intersection other than the origin, same below). At this time, the area enclosed by the two damping lines is in the specific amplitude plane, which means the system is stable, that is, the amplitude would attenuate to zero even if the model is excited by external forces, which matches the measured displacement time history. Stage II: At this stage, the system enters the stage of soft flutter, like $U^* = 8.0$ (Fig. 3b). At this time, the vertical and the torsional zero-damping curves in the energy map are close to each other and intersect (i.e., the equilibrium point). It can be further confirmed that the equilibrium point is stable according to damping characteristics near to the equilibrium point, which means the model will have stable limit cycle vibration, which complies with characteristics of the measured displacement time history too. What needs to be mentioned is that the measured fluttering path the in Fig.3b has deviated from the energy map to certain extent and such deviation is resulted from the error between computational results and test results. Stage III: This is the stage of divergent flutter, like $U^* = 8.6$ (Fig.3c), when the amplitude of model in the free vibration test exceeded the maximum level allowed by test conditions. Compared with conditions when $U^* = 8.0$, the size of energy area in the energy map was further enlarged, and the vertical and the torsional zero-damping curves are about to get away from each other. In Fig.3c, the vertical and the torsional zero-damping curves still have intersections due to impacts of test errors but it doesn't influence the determination of relationship between the energy map along the wind velocity.

5. CONCLUSION

This paper made researches on the nonlinear flutter characteristics of closed streamline box girder by conducting wind tunnel test on the segmental model in free vibration and three nonlinear flutter phenomena were observed, including classic soft flutter, soft flutter requiring initial excitation, and multi-stable soft flutter. Test results were analyzed with improved algorithms for complex model eigenvalues, variation characteristics of modal damping curves corresponding to the aforesaid phenomena were discussed, and kinetics mechanism driving related flutters were explained. Moreover, based on the energy map of bending-torsional coupled flutter, this paper revealed the coupling mechanism driven the growth and dissipation within the bending-torsional freedom degree.

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