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Nonlinear flutter mechanism of typical box sections with energy maps

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SUMMARY:
Studying the flutter problem from the perspective of energy is an effective and explicable method, considering the abundance and complexity of existing flutter research. In this paper, synchronous measurements of the dynamic forces, torsional and vertical displacements in typical box sections at various vibration amplitudes and incoming wind speeds are obtained, from which energy maps, presenting evolutional trends in dimensionless aerodynamic work with vibration amplitudes and reduced velocity, are constructed. Next, the energy maps of different section types are compared, qualitative analyses of section types` influence on energy distribution are deduced. Energy maps of vertical and torsional degrees of freedom are compared, implying the low participation of vertical bending component in flutter vibration. Afterwards, from the perspective of aerodynamic energy input and dissipation, various stable and instable state of nonlinear vibration phenomena of streamlined box section with barriers are analysed at torsional degree, which reveals the nonlinear flutter mechanism from the perspective of energy.

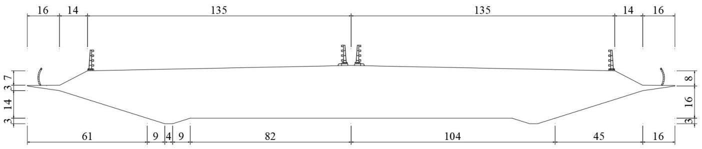
Keywords: typical box girder, nonlinear flutter mechanism, energy maps, vertical and torsional degrees of freedom, work done by SEFs

1. BACKGROUND

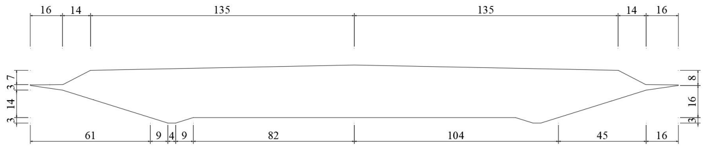
Through the past few decades, fluttering, as one of the most prominent wind-induced vibrations in long-span structures, has been receiving extensive attention from researchers all over the world and provoking unprecedented discussion on its mechanism, especially the nonlinear features. Half a century ago, Scanlan et al. (1971) proposed the linear flutter theory. Since then, the flutter analysis method has been prospering, along with the observation of various complex nonlinear flutter phenomena. Nevertheless, the sophisticated combination of structural nonlinearity and aerodynamic nonlinearity brought out abundant nonlinear vibration forms in the wind tunnel tests, e.g., soft flutter stable for small perturbation and instable for large perturbation (Zhu, et al., 2015) differs from the typical limit cycle vibration in soft flutter (Daito, et al., 2002). To explain such variations, Zhao et al. (2021) constructed, from the perspective of energy, an energy map by using the forced vibration tests, which reveals the relative energy distribution of dimensionless aerodynamic work in the plane composed of vibration amplitudes and reduced velocity. Liu et al. (2022) explored, with the angle of attack and vibration amplitude varying, the nonlinear aerodynamic characteristics of a quasi-flat plate at torsional vibration. Complicated nonlinear vibration phenomena on torsional freedom are well interpreted in research above from the perspective of energy. However, further exploration in the nonlinear flutter mechanism from energy relationships of different section types, of vertical and torsional degrees of freedom, even the bending-torsional coupled freedom degree, are rarely seen.

2. ENERGY MAPS IN VERTICAL AND TORSIONAL FREEDOM

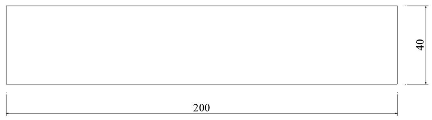
To construct the energy maps of typical box sections (Fig.1) in vertical and torsional degrees of freedom, forced motion vibration wind tunnel tests on the segmental model under uniform incoming flows are conducted. With the synchronous signals of dynamic forces, torsional and vertical displacements, aerodynamic work done by the lifting moment and lift force per unit length in a period is calculated according to Eq. (1), and the dimensionless work factor is defined in the form of Eq. (2). Based on the dimensionless work done by aerodynamic lift force and aerodynamic lifting moment, the energy maps of dimensionless work, considering the energy distribution features, are drawn in Fig. 2 to Fig. 4.



(a) Streamlined box girder with barriers



(b) Streamlined box girder without barriers

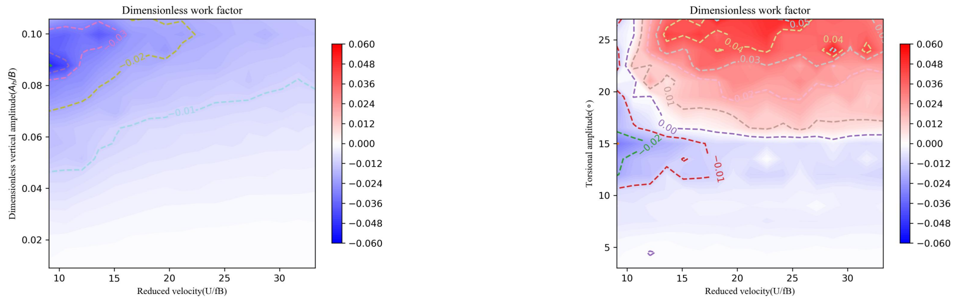


(c) Rectangular section with aspect ratio 1:5

Figure 1. Diagram of model cross section (mm)

$$W_\alpha = \int_0^T M_{se}(t)d\alpha \text{ and } W_h = \int_0^T L_{se}(t)dh \tag{1}$$

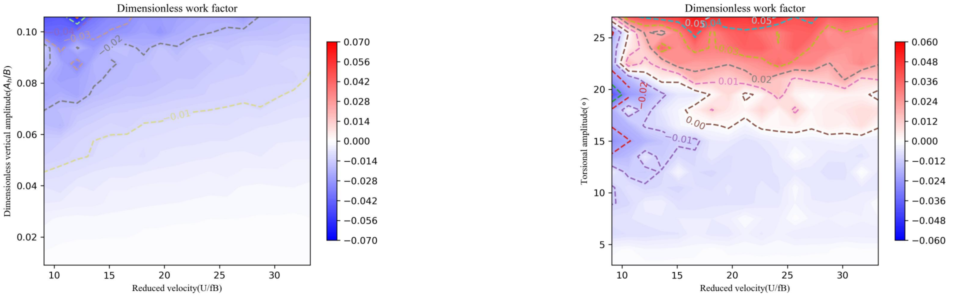
$$W_{non} = \frac{W_\alpha}{\frac{1}{2}\rho U^2 B^2} \text{ and } W_{non} = \frac{W_h}{\frac{1}{2}\rho U^2 B^2} \tag{2}$$



(a) contour map of dimensionless work done by aerodynamic lift force

(b) contour map of dimensionless work done by aerodynamic lifting moment

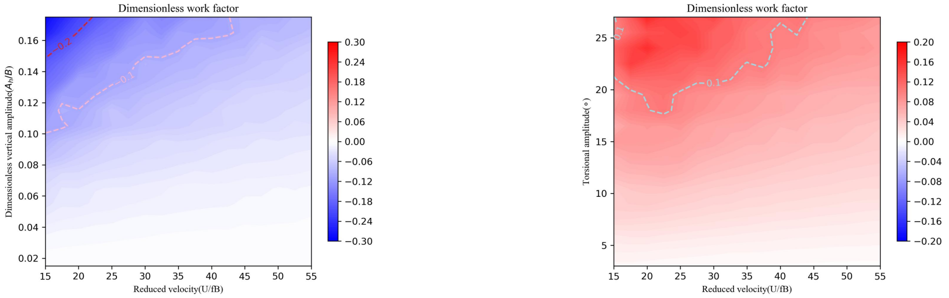
Figure 2. Energy maps of streamlined box girder without barriers



(a) contour map of dimensionless work done by aerodynamic lift force

(b) contour map of dimensionless work done by aerodynamic lifting moment

Figure 3. Energy map of streamlined box girder with barriers



(a) contour map of dimensionless work done by aerodynamic lift force

(b) contour map of dimensionless work done by aerodynamic lifting moment

Figure 4. Energy map of Rectangular section with aspect ratio 1:5

Comparing energy maps of the three box sections type, in the vertical DOF, dimensionless work values in the experimental range are all negative, which means the aerodynamic lift force plays the role of energy dissipation. The larger the value, the higher the efficiency. While in the torsional DOF, despite the energy maps of streamlined box sections with or without barriers are almost the same, the positive and negative distribution areas of dimensionless work value in streamlined box section and rectangular section with aspect ratio 1:5 are dramatically different. Positive values take the dominant place in rectangular section, versus the upper right corner in the streamlined section, leaving the rest negative. Inducing from the value distribution relationship, the pure torsional flutter is more intended to activated in rectangular section, representing the bluff body, while the bending-torsion coupled flutter is more common in streamlined section, with the potential energy input from the bending vibration. To simplify the problem, structural nonlinearity is neglected in the following discussion. Within the experimental range, dimensionless work of aerodynamic lift force in pure bending vibration is all negative while that of aerodynamic lifting moment in pure torsional vibration get more positive value involved, implying that in SEF in vertical DOF is relatively more likely to weaken the development of amplitude compared with torsional DOF, which indicates for the low participation of vertical bending component in flutter.

3. NONLINEAR FLUTTER ANALYSES

Take the energy map of torsional DOF in streamlined box girder with barriers for example, various nonlinear flutter phenomena can be interpreted to some degree, neglecting the structural damping effect for simplification. The upper right part of energy map is mainly occupied by positive values while the rest negative. Positive value of dimensionless work stands for the input of aerodynamic energy to the structure while the negative one stands for the dissipation of structural energy, corresponding to the increasing and decreasing of amplitude respectively, labelled in the form of "A+" and "A-" in Fig. 5. U* = U/fB denotes the reduced velocity. At U* = 9.3, the aerodynamic work continually dissipate the structural energy to a large amplitude. When U* = 16.5, the dimensionless work undergoes sequential interleaving of positive and negative values as the amplitude grows. The first transition form negative to positive presents the stability of zero position for small perturbation and instability for large perturbation (Zhu, et al., 2015); with the amplitude further growing, the second transition is achieved, the typical stable LCO of flutter phenomenon is manifested; if the stability of the system is broken through and the third instability point reached, the amplitude of the structure goes divergent. Further on, when U* reaches 18 or above, the amplitude goes divergent directly once the initial excitation exceeds the threshold.

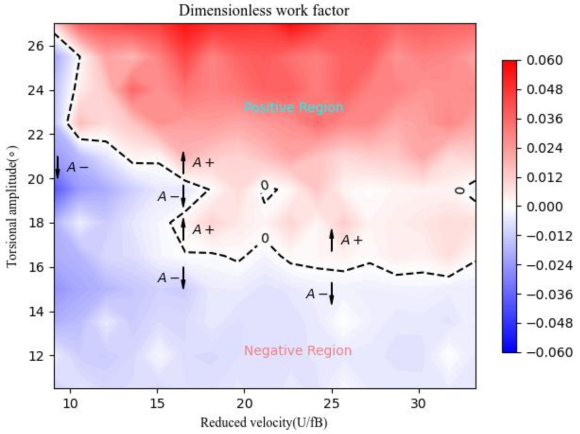


Figure 5. Analyses on nonlinear flutter phenomena with energy map

4. CONCLUSION

Energy maps of typical box sections are constructed both in vertical and torsional degrees by using forced vibration wind tunnel tests. It is illustrated that in torsional DOF, more positive values of aerodynamic work exist in rectangular section, within the experimental range, compared with streamlined section. Values of energy map in vertical DOF is all negative, explaining the low participation of vertical bending component in flutter. Various stable and instable state of nonlinear vibration phenomena are interpreted with the energy maps at torsional degree, from the perspective of aerodynamic energy input and dissipation.

ACKNOWLEDGMENTS

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