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Computational models and methods for aerodynamic flutter of long-span bridges

Y.J. Ge*, H.F. Xiang

Department of Bridge Engineering, State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China

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Abstract

The evaluation of bridge aerodynamic instability is traditionally based on direct wind tunnel testing and theoretical analysis method with experimentally identified parameters from wind tunnel tests. With the development of computer technology and computational fluid dynamics, the theoretical analysis method is expected to be developed to theoretical models and pure computational methods for numerically analyzing aerodynamic flutter of long-span bridges. This paper introduces the models and methods for computationally determining aerodynamic instability of long-span bridges, and emphasis is placed on three aspects including self-excited aerodynamic force model, numerical identification of flutter derivatives and two-dimensional or three-dimensional flutter analysis method. Through a serious analysis of the thin-plate cross-section and its cantilevered structure, the H-shaped section and Nanpu cable-stayed bridge, the closed-box section and Höga Kusten Bridge, the main problems and the key prospects are concluded.

Keywords: Long-span bridge; Aerodynamic flutter; Theoretical model; Computational method; Parameter identification; Flutter analysis

1. Introduction

Though the collapse of the original Tacoma Narrows Bridge has resulted in research and development on aerodynamic flutter of long-span bridges for about seven decades, the mechanism of bridge flutter is still very complicated and profound with many variables and

*Corresponding author. Fax: +86 21 65984882.
E-mail address: yaojunge@tongji.edu.cn (Y.J. Ge).

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patterns of vibrations included. Evaluation methods for bridge flutter include the classical theoretical method, the direct experimental method and the combination method of theoretical models and experimentally identified parameters. The classical theoretical method was based on Theodorsen's airfoil theory which aims at analyzing the classical coupling flutter of thin airfoils (Theodorsen, 1935). After the great efforts made by Bleich, Klöppel, Thiele, Selberg and Van der Put, this theory was developed to achieve the approximate calculation of suspension bridge flutter. However, the theory is only suit for flutter analysis for streamlined cross-sections, for example, closed-box sections. Since the aeroelastic phenomenon of bridge flutter is related to the vortex shedding and flow separation and reattaching, approximate expression of self-excited aerodynamic force was hard to be found in that time. From 1950s, wind tunnel testing methods with bridge deck sections were developed by Förshing and Ukeguchi et al. After the development by Scanlan and Tomko (1971), King et al. (1991), Matsumoto (1994), and so on, the methods are thought to be most effective and reliable even upto now. There are sectional model, taut strip model and full bridge model experiments in direct experimental methods. The combination method of experiments and theoretical analysis was proposed by Scanlan in 1970s (Scanlan and Lin, 1978), in which six aerodynamic parameters which is called flutter derivatives and identified through sectional model testing were used to describe self-excited aerodynamic force. Flutter eigenvalues are solved after iterations with the aerodynamic force imposing on a 2D section model which can take the interactions between wind and structure based on the strip theory. After the progress made by Xie and Xiang (1985), Agar (1989), Jones and Scanlan (1991), Miyata et al. (1995), Ge and Tanaka (2000) and so on (Chen and Kareem, 2003; Chen et al., 2004), the combination method was extended to 3D flutter analysis in time domain and especially frequency domain including two-modes, multi-modes and even full-modes participation with 18 flutter derivatives.

Within the scope of the combination method, there are three important aspects including aerodynamic force model expressed by flutter derivatives, identification method for flutter derivatives and solution of flutter eigenvalue equations, among which only the identification of flutter derivatives relies on wind tunnel experiments. With the development of computer technology, computational fluid dynamics (CFD) was introduced in numerical flutter derivative identification (Walther, 1994; Walther and Larsen, 1997), which leads to a pure computational method or a numerical wind tunnel experiment. On one hand, if the result of a numerical wind tunnel experiment is precise enough, it is possible to replace physical wind tunnel experiment to some extent and to achieve rational progress from classical theoretical method to experimental method and then to computational method. On the other hand, the computational method is the only method to simulate a full scale model and the wind field around it, and can deal with bridge flutter problem at real Reynolds number as a prototype bridge. This paper involves in principles, models and methods for computationally determining flutter critical conditions, and the emphases will be placed on the development of rational self-excited aerodynamic force model, numerical identification of flutter derivatives and effective solution of flutter eigenvalue equations.

2. Self-excited force model

There are basically three important actions to induce aerodynamic forces on bridge decks, including flow fluctuation, vortex-induced excitation and interaction between wind