Advanced aerostatic analysis of long-span suspension bridges*

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Abstract: As the span length of suspension bridges increases, the diameter of cables and thus the wind load acting on them, the nonlinear wind-structure interaction and the wind speed spatial non-uniformity all increase consequently, which may have negligible influence on the aerostatic behavior of long-span suspension bridges. In this work, a method of advanced aerostatic analysis is presented firstly by considering the geometric nonlinearity, the nonlinear wind-structures and wind speed spatial non-uniformity. By taking the Runyang Bridge over the Yangtze River as example, effects of the nonlinear wind-structure interaction, wind speed spatial non-uniformity, and the cable’s wind load on the aerostatic behavior of the bridge are investigated analytically. The results showed that these factors all have important influence on the aerostatic behavior, and should be considered in the aerostatic analysis of long and particularly super long-span suspension bridges.

Key words: Long-span suspension bridge, Aerostatic analysis, Nonlinear wind-structure interaction, Wind speed spatial non-uniformity, Cable’s wind load

INTRODUCTION

Two examples of the great progress achieved in recent decades in the design and construction of long-span suspension bridges are the Akashi Kaikyo Bridge (1990 m) in Japan and the Great Belt Bridge (1624 m) in Denmark. Into the 21st century, longer suspension bridges are being planned, such as the Messina strait bridge in Italy (3300 m), and the Gibraltar bridge between Spain and Morocco (5000 m) (Astiz, 1998), etc. In China, five large strait crossing projects have been planned. These strait crossing projects will consist of some large suspension bridges with span lengths of 2000~3000 m (Xiang and Chen, 1998). Many of these bridges are built in straits frequently subjected to violent typhoon or hurricane. The rapid increase in span length combined with the trend to more shallow or slender stiffening girders in suspension bridges has raised concern on their behaviors under wind action, with wind resistance being an important factor controlling their design and construction.

The aerostatic behavior of long-span suspension bridges was comprehensively investigated by Boonyapinyo et al. (1994), Cheng et al. (2002), Xiao and Chen (2004). They developed a finite element method to predict the critical wind speed on the nonlinear lateral-torsional buckling instability of long-span suspension bridges, but the influence of some factors such as the nonlinear wind-structure interaction, the cable’s wind load and wind speed spatial non-uniformity on the aerostatic behavior has not been clearly clarified. With increase of bridge span, structural flexibility, the tower’s height and the cable’s diameter increase simultaneously, which will further enhance the above effects.

How these factors affect the aerostatic behavior of long-span suspension bridges is becoming a more and more serious problem, which must be further investigated. This work is aimed at investigating the roles of these factors in the aerostatic behavior of long-span suspension bridges.
MODEL OF THE AEROSTATIC LOAD

Spatial distribution of wind speed

Generally, wind speed changes in space, and can be expressed as (Xie and Xiang, 1985):

\[ U = \mu U_0, \quad \mu = \left[ 1 - \left( \frac{L - 2z + e(L_1 - L)}{L_1} \right)^2 \left( \frac{y}{10} \right)^\alpha \right], \]  

(1)

where \( U_0 \) is the basic wind speed at the height of 10 m from the ground at the bridge site; \( \mu \) is wind speed spatial distribution coefficient; \( L \) is the total length of bridge spans; \( L_1 \) is the width of wind distribution; \( e \) is the coefficient of wind speed distributing non-symmetrically, \( 0 \leq e \leq 1 \). When \( e \) is equal to 0, wind speed distributes symmetrically with midspan; \( \alpha \) is the exponential coefficient of wind profile, which is dependent on the roughness of the ground; \( y \) is the height from the ground.

Nonlinear aerostatic loads

Consider a section of bridge deck in a smooth flow, as shown in Fig.1. Assuming that under the effect of the mean wind velocity \( U \) with angle of incidence \( \theta_0 \), the torsional displacement of the deck is \( \theta \). Then the effective wind angle of attack is \( \alpha = \theta_0 + \theta \). As the spatial non-uniformity of wind speed is considered, three components of aerostatic loads, named as drag force, lift force and pitch moment, acting on per unit length of the deck can be expressed as

\[ F_z = \rho \mu^2 U_0^2 D C_d(\alpha_e) / 2, \quad F_y = \rho \mu^2 U_0^2 B C_y(\alpha_e) / 2, \quad M_x = \rho \mu^2 U_0^2 B^2 C_M(\alpha_e) / 2, \]  

(2)

where \( \rho \) is the air density; \( D \) is the deck’s vertical projected area; \( B \) is the deck’s width; \( C_d(\alpha_e), C_y(\alpha_e), C_M(\alpha_e) \) are the aerostatic coefficients obtained from the section model test in wind tunnel.

For cables and hangers, only the drag component is considered, and can be expressed as

\[ F_z = \rho \mu^2 U_0^2 D C_D / 2, \]  

(3)

where \( D \) is the diameter of cables and hangers, \( C_D \) is the drag coefficient, which is equal to 0.7 (Xiang et al., 1996).

SOLUTION PROCEDURE

The aerostatic analysis is aimed to predict the equilibrium position. Under a certain wind speed, the static equilibrium position must be solved by the iteration approach because of the non-linearity of both the structure and the displacement-dependent aerostatic loads. The iteration equation can be expressed as:

\[ [K(u)]\{u\} = P[F_y(\alpha_e), F_z(\alpha_e), M(\alpha_e)], \]  

(4)

where \([K(u)]\) is the structural stiffness matrix including linear-elastic stiffness matrix and geometrical matrix; \(\{u\}\) is the nodal displacement vector; \(P[F_y(\alpha_e), F_z(\alpha_e), M(\alpha_e)]\) is the total aerostatic load vector.

To solve the nonlinear Eq.(4), a two-iteration solution scheme is used. In the inner cycle of iteration, geometric nonlinear analysis of structure under incremental aerostatic loads is conducted using the incremental Newton-Raphson iteration method. Nonlinear analysis under incremental wind load, induced by the torsional deformation of the deck that in turn increases wind angles of attack, is performed in the outer cycle of iteration. The procedure can be summarized as follows: (1) Input the finite element model of the bridge and its aerostatic coefficients; (2) Compute the wind speed spatial distribution coefficients for each element of the bridge; (3) Perform structural nonlinear aerostatic analysis under the given wind speed \( U_0 \) to get the aerostatic equilibrium position.

The computing flow can be described as follows: (1) Calculate the aerostatic load \( \{F_0\} \) under the initial wind attack angles, and let \( \{F_z\} = \{F_0\}, \{F_y\} = \{0\}; \)