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Full-order and multimode flutter analysis using ANSYS

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Abstract

This paper presents the full-order and multimode methods for analyzing coupled flutter of long-span bridges using commercial finite element (FE) package ANSYS. In the full-order method of flutter analysis, a novel FE model is developed to model the coupled wind-bridge system, in which a specific user-defined *Matrix27* element in ANSYS is adapted to model the aeroelastic forces and its stiffness or damping matrices are parameterized by wind velocity and vibration frequency. Variation of complex eigenvalues of the coupled system with wind velocity is then depicted by using this model together with complex eigenvalue analysis, and flutter instability can be determined from the variation diagram. In the multimode method, equations of motion for the coupled wind-bridge system are first represented using a modal superposition technique. This formulation leads to a single-parameter searching technique without iteration to determine the conditions of flutter instability when structural damping is not considered in solution. The contribution of participating modes to flutter instability is given in terms of modal amplitude and modal energy in the multimode method. Numerical studies are provided to validate the developed methods as well as to demonstrate both the procedures for flutter analysis using ANSYS. The proposed methods enable the bridge designers and engineering practitioners to analyze bridge flutter in commercial FE package ANSYS.

Keywords: Long-span bridges; Coupled flutter; Instability; Matrix27; ANSYS

1. Introduction

Owing to large flexibility and low structural damping, many flexible and slender structures such as long-span bridges, high-rise buildings and chimneys are susceptible to a variety of wind-induced vibrations [1]. Among them, wind-induced flutter instability is the most dangerous one in which the bridge oscillates in a divergent and destructive manner at some critical wind velocity. As a result, flutter instability is one of the major concerns in the design and construction of long-span bridges, and the lowest wind velocity inducing flutter instability of a bridge must exceed the maximum design wind velocity of that bridge. The objective of flutter analysis is to predict the lowest critical flutter wind velocity as well as the corresponding flutter frequency.

Since the collapse of the old Tacoma Narrow Bridge in 1940, considerable efforts have been made to develop procedures for analyzing coupled flutter of long-span bridges by integrating finite element (FE) techniques with the flutter derivatives determined either from Thoedorsen's theoretical formulation or from wind tunnel testing. Bleich [2] was among the first to perform the coupled flutter analysis of suspension bridges using the theoretical flutter derivatives. The coupled flutter analysis using the measured flutter derivatives from the spring-mounted bridge sectional model testing in wind tunnel was pioneered by Scanlan and his co-workers [3–5]. At present there are two general approaches for coupled flutter analysis of bridges: (i) the full-order flutter analysis approach where the aeroelastic loadings are applied directly to the physical coordinate of structures [6–9] and (ii) the multimode flutter analysis approach where the equations of motion for structures are represented using a modal superposition technique [9–19].

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Since the 1970s a number of commercial FE packages such as ANSYS, ABAQUS and ADINA have emerged and received wide applications in various disciplines due to the advancement of FE methods and computing technologies. These FE packages have friendly graphical user interface and powerful computational capability. However, the general purpose commercial FE packages commonly used in civil engineering community cannot be directly used for flutter analysis of bridges due to lack of the capability of calculating motion-dependent aeroelastic loads. Although it is possible to develop special purpose FE packages to tackle bridge flutter analysis such as ANSUSP [11] and NACS [14], the incorporation of functions or modules capable of flutter analysis into general purpose commercial FE packages provides an alternative way.

This paper presents two alternative methods, namely the full-order method and the multimode method, for analyzing coupled flutter of long-span bridges using ANSYS, with the main purpose of providing practical tools for researchers and engineering practitioners to analyze bridge coupled flutter problem using ANSYS. In the development of the first method, the coupled wind-bridge system is first modeled by a hybrid FE model which incorporates structural FE model with fictitious specific user-defined *Matrix27* elements used to represent the motion-dependent aeroelastic forces. The stiffness or damping matrices of *Matrix27* element are expressed in terms of wind velocity and vibration frequency. The complex eigenvalues of the low-order modes at varying wind velocities are then determined from this hybrid FE model together with complex eigenvalue analysis, and the real and imaginary parts of the eigenvalues are the logarithm decay rates and damped vibration frequencies of these modes, respectively. Flutter instability will occur when real part of any eigenvalue becomes positive. While in the multimode method, equations of motion for the structure subjected to aeroelastic forces are first reformulated with some selected low-order natural modes. A single-parameter searching technique without the need of frequency iteration is then described to determine the critical conditions of flutter instability when structural damping is not taken into account in solution. Contribution of the selected participating modes to flutter instability is also provided in terms of modal amplitude and modal energy in the multimode method. The flutter analysis of both a simply supported line-like bridge with the theoretical flutter derivatives and a real suspension bridge with the theoretical and measured flutter derivatives is carried out to validate the developed procedures and demonstrate the full-order and multimode flutter analysis of cable-supported bridges using ANSYS.

2. Full-order flutter analysis

2.1. Novel FE model for flutter analysis

The equations of motion for a bridge in the smooth flow can be expressed as

$$\mathbf{M}\ddot{\mathbf{X}} + \mathbf{C}\dot{\mathbf{X}} + \mathbf{K}\mathbf{X} = \mathbf{F}_{ae}, \tag{1}$$

where **M**, **C** and **K** are the global mass, damping and stiffness matrices, respectively; $\mathbf{X}$, $\dot{\mathbf{X}}$ and $\ddot{\mathbf{X}}$ represent the nodal displacement, velocity and acceleration vectors, respectively; and $\mathbf{F}_{ae}$ denotes the vector of nodal aeroelastic forces.

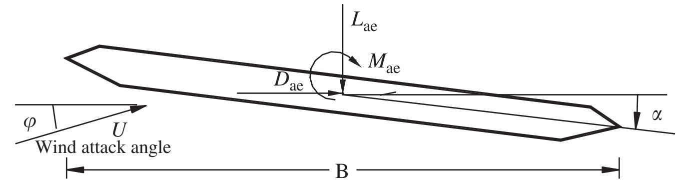

Fig. 1. Aeroelastic forces acting on bridge deck.

The motion-dependent aeroelastic forces distributed on unit span of bridge girder are expressed as a linear function of nodal displacement and nodal velocity [4,15]

$$L_{ae} = \frac{1}{2}\rho U^2(2B)\left[KH_1^*\frac{\dot{h}}{U} + KH_2^*\frac{B\dot{\alpha}}{U} + K^2H_3^*\alpha + K^2H_4^*\frac{h}{B} + KH_5^*\frac{\dot{p}}{U} + K^2H_6^*\frac{p}{B}\right], \tag{2a}$$

$$D_{ae} = \frac{1}{2}\rho U^2(2B)\left[KP_1^*\frac{\dot{p}}{U} + KP_2^*\frac{B\dot{\alpha}}{U} + K^2P_3^*\alpha + K^2P_4^*\frac{p}{B} + KP_5^*\frac{\dot{h}}{U} + K^2P_6^*\frac{h}{B}\right], \tag{2b}$$

$$M_{ae} = \frac{1}{2}\rho U^2(2B^2)\left[KA_1^*\frac{\dot{h}}{U} + KA_2^*\frac{B\dot{\alpha}}{U} + K^2A_3^*\alpha + K^2A_4^*\frac{h}{B} + KA_5^*\frac{\dot{p}}{U} + K^2A_6^*\frac{p}{U}\right], \tag{2c}$$

where ρ is air mass density; U is wind velocity; B is the width of bridge deck; $K = \omega B/U$ is the reduced circular frequency; h, p and α are the vertical, lateral and torsional displacements, respectively; A_i^*, H_i^* and P_i^* $(i = 1, \ldots, 6)$ are flutter derivatives which are expressed in terms of reduced wind velocity $\tilde{U} = U/(fB)$ and f is the natural frequency. The aeroelastic forces on bridge deck are illustrated in Fig. 1.

By converting the distributed aeroelastic forces of element e of bridge girder into equivalent nodal loadings at member ends, one obtains the equivalent nodal loadings for that element as

$$\mathbf{F}_{ae}^e = \mathbf{K}_{ae}^e\mathbf{X}^e + \mathbf{C}_{ae}^e\dot{\mathbf{X}}^e, \tag{3}$$

where $\mathbf{K}_{ae}^e$ and $\mathbf{C}_{ae}^e$ are the elemental aeroelastic stiffness and damping matrices for element e, respectively. Similar to the general procedures in formulating elemental mass matrix, both a lumped formulation and a consistent formulation can be used to derive the elemental aeroelastic stiffness and damping matrices [20]. When using the lumped formulation, the elemental stiffness and damping matrices are

$$\mathbf{K}_{ae}^e = \begin{bmatrix} \mathbf{K}_{ae1}^e & 0 \\ 0 & \mathbf{K}_{ae1}^e \end{bmatrix}, \tag{4a}$$

$$\mathbf{C}_{ae}^e = \begin{bmatrix} \mathbf{C}_{ae1}^e & 0 \\ 0 & \mathbf{C}_{ae1}^e \end{bmatrix}, \tag{4b}$$