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Numerical simulations and experimental validations of force coefficients and flutter derivatives of a bridge deck

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ABSTRACT

This paper presents the results of the application of the large eddy simulation (LES) numerical method with the aim of investigating static coefficients and nonstationary flutter derivatives for a common symmetric bridge deck section. The results are compared with those of the unsteady Reynolds-averaged Navier–Stokes (URANS) study. The results of the investigated numerical simulations are validated by force and pressure measurements from wind tunnel experiments. In addition to the commonly used representation of flutter derivatives based on the integrated forces, the paper uses cross-sectional representation by tracking the contributions of nonstationary coefficients around the bridge deck section. Besides providing a better insight into the physical mechanism, the cross-sectional representation seems to be a powerful tool for identifying deficiencies in visualizing the impact of flow separations on flutter derivatives.

1. Introduction

Complex unsteady flow around the bluff body accompanied by flow separations and alternating reattachments give rise to fluctuating surface pressures resulting in dynamic wind forces. These forces have the potential to generate an aeroelastic mechanism between the flexible structure and the circumfluent wind. One such example is flutter, where the energy drawn from the flow increases the energy of the bridge deck oscillations. This can lead to violent oscillations, therefore causing dynamic divergence in the structure. Due to the complexity of the mentioned aeroelastic interactions, wind tunnel testing of bridge decks continues to be an integral component of long-span bridge design. Nevertheless, currently, considerable effort is being made in the area of computational fluid dynamics (CFD).

Due to the turbulent nature of flow around bridge decks, especially more complex in the case of fluid–structure interaction, the accuracy of predicting aeroelastic forces is strongly influenced by the use of the turbulence modeling approach. For the computational prediction of aeroelastic forces, generally two approaches are considered: unsteady Reynolds-averaged Navier–Stokes (URANS) or large eddy simulation (LES). A proper simulation at the fixed cross section of the bulk parameters can be used as an important indicator to successfully and accurately conduct computational simulation of the aeroelastic forces, such as the mean and standard deviation of force coefficients and the Strouhal number, as done in Sun et al. (2009). Recently, Bartoli et al. (2008) proposed a Benchmark on Aerodynamics of 5:1 Rectangular Cylinder (BARC) to contribute to the analysis of the high Reynolds number, and turbulent, separated flow around the fixed rectangular cylinder with a width to height ratio of $B/D=5$. This is an interesting case study as the used cross section resembles common bridge decks. As a part of this study, Bruno et al. (2010) used three-dimensional (3D) LES and a proper orthogonal decomposition technique to outline the significant 3D features of the flow. They also investigated the relationships between vortex shedding and the instantaneous pressure fields and aerodynamic forces, identifying the dominant contribution to the lift force to be related to the mean pressure recovery region. As a continuation of the mentioned study, Bruno et al. (2012) presented a systematic study on the spanwise length and spanwise grid density. The application of URANS simulations was shown to be sensitive enough to correctly model the effects of different Reynolds numbers over a fixed rectangular cross section (Mannini et al., 2010a). Bruno et al. (2014) presented a more detailed summary of the BARC study. Several numerical studies employ fixed real bridge deck configurations. The study by Bruno and Khris (2003) sheds light on the existence of several Strouhal numbers corresponding to different

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shedding processes of the flow around the Great Belt East Bridge. Both the URANS and LES turbulence approaches are investigated in a number of parametric studies, where the effect of grid spacing and discretization schemes on the flow field is assessed. In addition, the influence of the Smagorinsky constant on the LES sub-grid scale model is analyzed. The role of small geometrical details on the trapezoidal bridge deck section, in particular the degree of corner sharpness, is highlighted in numerical studies of Mannini et al. (2010b), Bruno and Khris (2003), and Fransos and Bruno (2010).

The usual computational strategy of obtaining aeroelastic forces is adapted from well-established experimental methodologies. For flutter analysis in particular, a harmonically forced or free vibrating deck can be simulated. Sun et al. (2009) deals with a similar example of the computational prediction of aeroelastic forces around a rectangular cross section with a width to height ratio of $B/D=4$ using the forced vibration technique. The authors used the URANS turbulence model to investigate effects on the flutter derivatives of two inflow conditions. Shimada and Ishihara (2012) employed a rectangular cross section ($B/D=4$) and a box girder section to illustrate flow fields related to torsional vortex-induced vibrations and flutter, based on the free vibration numerical simulations. The critical onset velocity was well predicted using the two-dimensional (2D) URANS turbulence model. Using forced vibration methodology and LES, Sarwar et al. (2008) examined the influence of geometrical modifications and section details on the aerodynamic characteristics of the streamline box girder section. The study covered both stationary and nonstationary coefficients (i.e., flutter derivatives).

This paper highlights the aeroelastic behavior of a common symmetric bridge deck section. Primarily, a study on the use of 3D LES for assessing aeroelastic forces is presented. Validation data are provided using two independent experimental sensor systems, namely a duplex force balance and a redundant pressure sensor system. The results of the LES study are also compared with those of the URANS study using the same cross section as presented in Šarkić et al. (2012). The consistency between aeroelastic forces obtained using a computational approach and an experimental measurement is commonly checked by comparing the flutter derivatives evaluated from the net (integrated) wind forces acting over the bridge deck. In addition, this study focuses on the contributions of flutter derivatives along the cross section. The reason is twofold. First, it provides a more detailed validation of numerically obtained flutter derivatives. Second, by tracking these contributions and comparing them to the experimental reference values, specific limitations of numerics can be detected and related to the deviation from experimentally obtained net effects. In particular, this study shows the effects of under- and overestimation of separation bubbles at the upper and downside edges of the bridge deck section to pitch related flutter derivatives.

2. Flutter derivatives: sectional and cross-sectional representation

Sectional flutter derivatives are used as tools to assess the aeroelastic response of bridges. Typically, they are determined experimentally in wind tunnel tests for individual bridge deck geometries, as there is no general analytical solution for determining the flutter derivatives of bluff bodies in a real flow. According to Zasso (1996), the aeroelastic lift force and aeroelastic moment per unit length can be expressed using flutter derivatives as follows:

$$L_{ae}=\frac{1}{2}\rho V^2 B\left[-h_1^*\frac{i\omega z}{V}-h_2^*\frac{i\omega B\alpha}{V}+h_3^*\alpha+h_4^*\frac{\pi}{2V^{*2}}\frac{z}{B}\right] \quad (1)$$

$$M_{ae}=\frac{1}{2}\rho V^2 B^2\left[-a_1^*\frac{i\omega z}{V}-a_2^*\frac{i\omega B\alpha}{V}+a_3^*\alpha+a_4^*\frac{\pi}{2V^{*2}}\frac{z}{B}\right] \quad (2)$$

In the above equations, ρ is the air density; V is the undisturbed or mean oncoming wind velocity; B is the section width; ω is the circular frequency; z and α are the structural vertical displacement and rotation, respectively; and h_i*, a_i* ($i=1.\ 4$) are the flutter derivatives, the function of reduced velocity $V_\omega^*=V/\omega B$. V_ω^* is obtained using the circular frequency for normalization; similarly, frequency f can be used to obtain reduced velocity $V_f^*=V^*=V/fB$.

One method of identifying flutter derivatives is prescribing harmonical single-degree-of-freedom motions in turn for each direction of vibration, called the forced vibration method. The derivatives can be established by integrating the measured pressure time histories around the cross section or directly through force measurements. Examples of the former experimental approach, applied to identify the flutter derivatives of different rectangular prisms, can be found in Matsumoto (1996), Matsumoto et al. (1996), and Haan (2000).

The latter was first introduced by Diana et al. (2004) to identify flutter derivatives related to the Messina suspension bridge. This approach has the advantage of measuring the aeroelastic forces when considering a deck with windshields and traffic barriers. This is because the contribution of these devices to the generation of aeroelastic forces can be significant and can influence the pressure measurement integration method in such a way as to fail to reproduce the total aeroelastic forces.

In contrast to direct force measurements, besides the sectional representation of flutter derivatives (Eqs. (1) and (2)), discretized pressure measurements allow another representation, introduced in Argentini et al. (2012). Namely, the total aeroelastic lift and moment from Eqs. (1) and (2) can be treated as the sum of the contributions of the forces associated with each pressure tap. For example, the aeroelastic lift under pitch motion can be considered as follows:

$$L^\alpha=\sum_{j=1}^{N_{taps}}L_j^\alpha=\sum_{j=1}^{N_{taps}}p_j^\alpha\Delta x_j=\frac{1}{2}\rho V^2 B\sum_{j=1}^{N_{taps}}\left[-h_{2,j}^*\frac{i\omega B}{V}+h_{3,j}^*\right]\alpha \quad (3)$$

Comparing Eq. (1) with Eq. (3), the sectional (integrated) values of flutter derivatives can be treated as the sum of their cross-sectional values, for example,

$$h_{2/3}^*=\sum_{j=1}^{N_{taps}}h_{2/3,j}^* \quad (4)$$

These cross-sectional flutter derivatives can be further analyzed by exploiting the identification method involving pressure-based flutter derivatives presented in Matsumoto et al. (1996) and Haan (2000). As the applied forced motion is harmonic, measured pressure signals are assumed to be harmonic as well, and they can be related to the pressure fluctuation amplitude and the phase difference φ with regard to the prescribed motion. Thus, cross-sectional flutter derivatives can be further related to the cross-sectional unsteady pressure amplitude and phase shift by

$$h_{2,j}^*=\frac{V_\omega^*}{B}\left(\hat{C}_{p,j}\ \sin\ \varphi_j\Delta x_j\right) \quad (5)$$

$$h_{3,j}^*=\frac{1}{B}\left(\hat{C}_{p,j}\ \cos\ \varphi_j\Delta x_j\right) \quad (6)$$

In Eqs. (5) and (6), the unsteady pressure amplitude $\hat{C}_{p,j}$ is introduced, normalizing each pressure amplitude with the dynamic pressure and the amplitude of angular oscillation $\hat{C}_{p,j}=\hat{p}_j/(q_o\hat{\alpha})$, and φ_j is the corresponding phase shift related to the j-th pressure signal. Further, the cross-sectional values of the aeroelastic moment can be interpreted as the corresponding aeroelastic lift multiplied with the moment arm of each pressure