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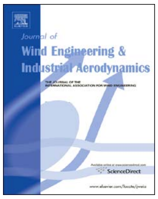

# Aeroelastic of bridge deck flutter with modified implicit coupling method

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ABSTRACT

An effective time-domain aeroelastic framework for bridge deck flutters is presented based on a modified implicit coupling algorithm with grid deformation techniques. The grid deformation is accomplished by radial basis function interpolation as well as by the rigid movement of the initial grid. In this paper, for computational efficiency, a coupling frequency control technique is adopted for the implicit coupling algorithm. To verify the time-domain aeroelastic framework by using the grid deformation technique, the vortex-induced vibration of the cylinder and H-section bridge deck flutter are computed, and the results are compared with published results. The effect of the coupling frequency with the grid deformation technique is presented for the flutter analysis of the Great Belt East Bridge suspension girder section.

## 1. Introduction

Current trends with respect to increasing the sizes of vessel sizes are largely due to the economy and efficiency associated with large ships. Consequently, newly constructed bridges are required to have longer spans to minimize the risk of vessel collision and to have large navigational clearances. However, with the increasing bridge spans being employed, aeroelastic stabilities such as flutter and galloping are likely to occur. Of these aeroelastic stabilities, flutter is the most catastrophic. When the wind speed exceeds a certain speed known as the "critical flutter speed," the non-linear interaction of the aerodynamic, inertial, and structural forces of the bridge induces unstoppable and uncontrollable structural deflections, eventually resulting in the total structural failure of the bridge. After the infamous collapse of the Tacoma Narrows Bridge in 1940, bridge engineers have been required to demonstrate that their bridge designs have sufficient flutter margins.

One of the successful methods for bridge flutter analysis is based on wind tunnel testing with a dynamically scaled model. The wind tunnel test results are directly applied to the design process. In addition, the wind tunnel tests should enhance the understanding of the aeroelastic motions of the bridge, and thus provide the means for the "calibration" of analytical procedures to be used in connection with design calculations (Larsen, 1993). In the preliminary design stage, a sectional model (or a taut strip model) test is usually carried out in order to assess the aerodynamic stability of the bridge deck section. After testing, a detailed full aeroelastic bridge model test is often carried out to predict the three-dimensional (3D) aerodynamic effects and the impact of complex surroundings such as suspension-bridge cables. However, wind tunnel experiments for flutter analysis are not only expensive, but also time-consuming.

Two types of numerical methods may be used to determine flutter characteristics such as the critical wind speed. One is the linearized method of flutter derivatives, and the other is direct simulation. The flutter derivative methods are the most commonly used approaches to obtain the aeroelastic behavior of the bridge (Scanlan and Tomko, 1971). In these methods, the aerodynamic forces and moment coefficients are assumed to be linear combinations of steady aerodynamic coefficients and aerodynamic derivatives of the bridge (Toshio Miyata, 2003). The aerodynamic derivatives are calculated from the force and moment responses of the heaving and torsional motions. The critical flutter speed can be estimated from the stability analysis of the linearized equations of motion. Larsen and Walther (1997) presented a method to determine the critical flutter speed by using this method. They used a numerical code based on discrete vortex simulation (DVS) for the computation of the aerodynamic responses. However, interactions between aerodynamic and structural dynamics can be nonlinear when there is significant deformation of the bridge. The linearized methods cannot take into account these nonlinear interactions beyond linear superposition (Wu et al., 2013).

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On the other hand, the direct simulation methods calculate the aeroelastic responses by using coupled fluid and structural analyses. The flutter speed can be computed from the dynamic behavior of the bridge deck condition. The flutter condition is defined when an oscillation of increasing amplitude is obtained. The direct simulation methods are more computationally intensive than the flutter derivative methods. However, with recent advances in computer technology and numerical analysis, numerical methods using computational fluid dynamics (CFD) and computational structural dynamics (CSD) are alternative analysis tools that provide a reduced cost and time to analyze the fluid–structure interaction (FSI). One of the main advantages of the direct simulation methods is that the unsteady aerodynamic forces and wind actions of the bridge can be obtained directly from the aeroelastic behavior, unlike the flutter derivative methods. In addition, they can simulate situations that are more complicated by the interaction of aeroelastic nonlinearities that are due to the large deformation, material nonlinearities, or complex damping properties (Wu et al., 2013). In addition, the direct simulation methods are cheaper and faster than the wind tunnel test. The results that were obtained based on these methods can be found in early studies (Selvam and Govindaswamy, 2001; Braun and Awruch, 2003; Frandsen, 2004).

The numerical approaches to the FSI problems can be categorized as two types of approaches: the monolithic approach and the partitioned approach. The monolithic approach combines the fluid and structural equations into a single formulation. The prominent feature of this approach is that conservation can be maintained. Moreover, it has improved time-accuracy and stability properties. However, it is difficult to formulate this approach in a single numerical form. The partitioned approach is more common. Coupled fluid and structural systems are solved sequentially by using existing CFD and CSD solvers to determine the converged fluid and structural coupling solutions. The advantages of this approach are computational efficiency and simplicity of implementation. These advantages come from the modularity used in this approach.

The coupling of fluid and structural systems using the partitioned approach can be achieved either with an implicit (strong) coupling method or with an explicit (loose) coupling method. Fig. 1 depicts these two coupling methods of the partitioned approach. The implicit coupling method iteratively determines a coupled solution at each time step. On the other hand, the explicit coupling method seeks the coupled solution by solving the dynamic equations with a time-delayed fluid force and the fluid equations with a time-delayed geometric movement. The implicit method is more accurate, while the explicit method is more efficient. Care should be taken to ensure conservation on the fluid–structure interface when the partitioned approach is chosen.

To correctly study the aeroelastic behavior of a bridge deck near the water surface or the ground, automatic grid generation is required to generate the grid system over the bridge deck. It is well known that the ground effect significantly changes the aerodynamic forces and moments of bodies near the ground. When the bridge deck moves relative to the water surface or the ground, the lower part of the outer boundaries should be fixed to in order to account for the ground.

The grid system can be completely regenerated every time by using transfinite interpolation (TFI) (Byun and Guruswamy, 1998) or can be obtained by deforming the initial grid system. The linear spring analogy (Batina, 1990) or torsional spring analogy (Farhat et al., 1998) can be used to obtain the grid system automatically. While TFI is efficient and fast, it can only be applied on structured grids. The linear spring analogy replaces the grid edges inside the computational domain with a network of springs, and the new grid points are determined as equilibrium points. Greater control over deformation can be achieved with the addition of a torsional spring system. Spring analogy methods can be used for both the structured grid and the unstructured grid. However, these methods are known to be inadequate for highly deforming grid systems. On the other hand, the radial basis function (RBF) interpolation method (Rendall and Allen, 2008) can create a good quality grid system from the initial grid points. In this approach, the deformed grid quality or the deformation efficiency can be controlled by the number of surface grid points used to determine the interpolation coefficients.

In this paper, we propose an efficient analysis framework for the aeroelastic simulation of bridge deck flutter. This framework uses the implicit coupling method for fluid–structural coupling and the free oscillation method for determining the critical wind speed. An incompressible Reynolds averaged Navier–Stokes (RANS) solver based on a finite volume method (FVM) is used for flow analysis, while the dynamic equations of the bridge deck section are used to determine the dynamic response. To reduce the computational burden of coupling aerodynamic and structural solvers, a modified implicit coupling method is adopted. The RBF interpolation method is used to automatically generate a grid system around the bridge deck.

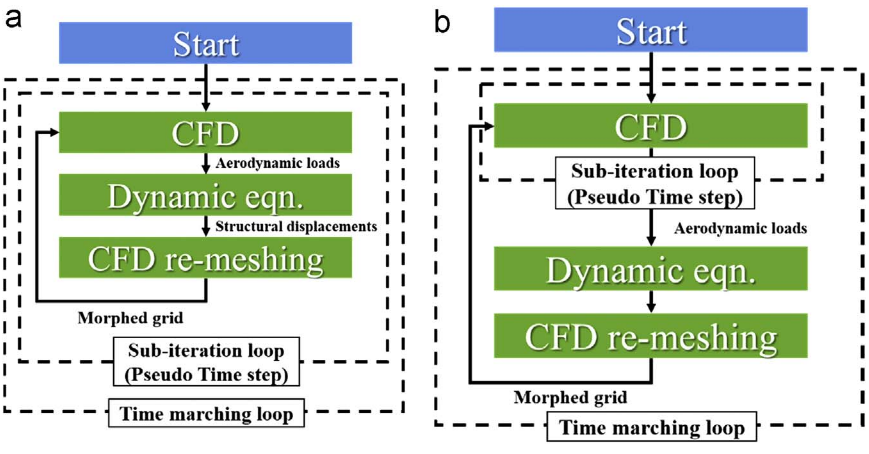

**Fig. 1.** Partitioned coupling approach: (a) implicit coupling, (b) explicit coupling.