The 2013 World Congress on
Advances in Structural Engineering and Mechanics (ASEM13)
Jeju, Korea, September 8-12, 2013

Estimation of randomness in aeroelastic loading affecting on the wind-induced response of a long-span bridge simulated by CFD

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ABSTRACT

This study focuses on wind-induced responses of a long-span bridge by assuming the presence of randomness in the aeroelastic input (i.e., flutter derivatives, FDs). FDs are the most important part of the wind loading. These derivatives are usually estimated either in a wind tunnel experiment or through computational fluid dynamics (CFD) simulations. The effects of bridge deck shapes on the estimation of flutter derivatives are investigated and applied to the calculations of critical wind speed. In this study the CFD simulation is used to extract the FDs to understand the influence of variability in FDs on the wind-induced response and later compared to results using the FDs obtained from wind tunnel experiments. In the CFD simulation the uncertainty in FDs are examined by changing the Reynolds number varying from 1,000 to 1,000,000 with various bridge deck shapes

1. INTRODUCTION

Flutter instability is one of major concerns in the design of long-span, flexible bridges. Aeroelastic instability occurs when a bridge is exposed to wind speed above a certain critical threshold. Beyond this limit, diverging vibration of the deck is possible, which may result in a catastrophic structural failure. Aeroelastic stability can be predicted by analyzing the aeroelastic coefficients of bridge decks, flutter derivatives (FDs, Scanlan and Tomko, 1971), which are employed for simulating the dynamic response of the bridge. FDs are motion-induced force coefficients per unit length, routinely measured in wind tunnel; these may become a time-consuming task for planning, actual testing and analysis often substantial and may be impracticable for bridge design studies. In order to overcome these issues, use of computational fluid dynamics (CFD) may be an alternative approach to obtain the aerodynamic data.

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In this study the CFD simulation is used to extract the aeroelastic coefficients (i.e. flutter derivatives, FDs) and the influence of variability in FDs was investigated. In the CFD simulation the uncertainty in FDs are examined by changing the Reynolds number varying from 1,000 to 1,000,000 with various bridge deck shapes (Kim 2013). Critical wind speed (i.e. flutter) was calculated for comparison purpose and later was also compared to results using the FDs obtained from wind tunnel experiments (Larsen and Walther 1998).

A second-order polynomial model was used in this study for fitting FD curves in terms of reduced wind velocity; more details can be found in (Seo and Caracoglia 2012). The dynamic response at flutter was examined by two-mode analysis (e.g., Jones and Scanlan, 2001).

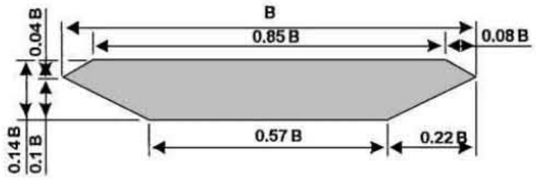
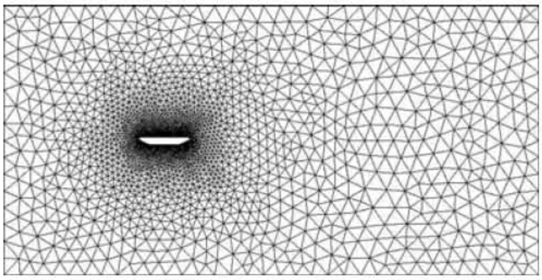
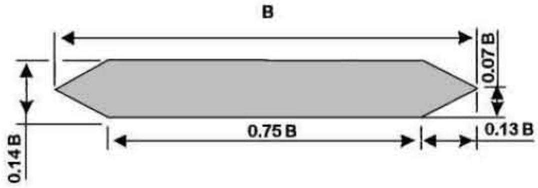
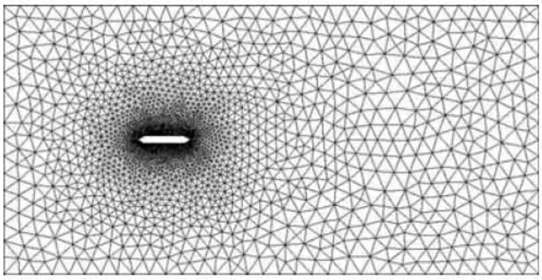
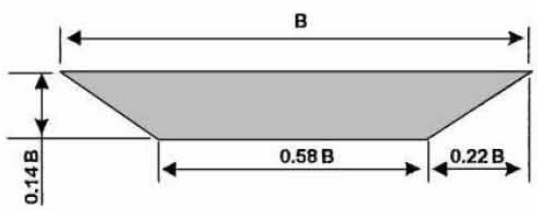
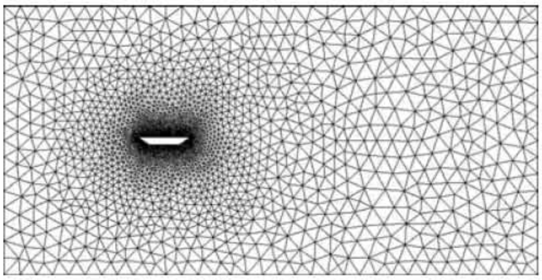
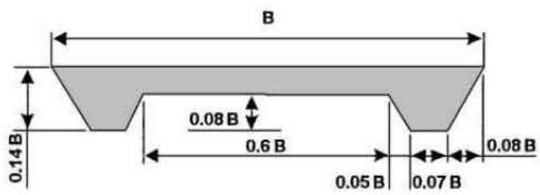
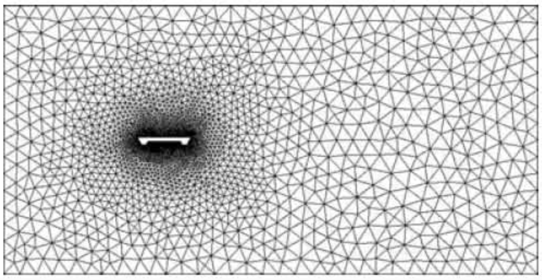
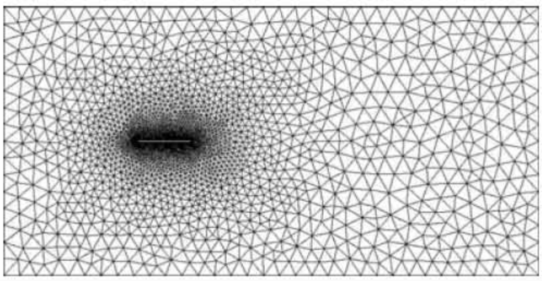
2. BRIDGE MODEL AND NUMERICAL EXAMPLE

For a bridge example, the Golden Gate Bridge in San Francisco, California (USA) was selected with main span l = 1,263 m, deck width B = 27.43 m. Frequencies, modal inertias, modal integrals, modal damping were adapted from previous studies (Jain et al. 1996); the contribution of moving deck and cables was included in the aeroelastic analyses.

In this study, a number of different bridge deck cross-section shapes was investigated by (Scanlan and Tomko 1971) in order to provide the bridge designer with experimental data for assessment of aerodynamic (flutter) stability. In addition, a 1 to 5 H-shaped cross-section similar to the plate girder of the 1st Tacoma Narrows bridge was also considered (Larsen and Walther 1998). The geometry of the individual sections investigated is shown in Table 1. FDs for five generic deck girder shapes were extracted from CFD simulations. The CFD mesh grids are also shown in Table 1.

FDs are shown in Fig. 1 (A1s to A4s for torsion and H1s to H4s for heave) as a function of reduced wind velocity U_R = U/(nB), with U being the mean wind speed at deck level, n a frequency. These curves were obtained in the CFD simulation with changing Reynolds number from 1,000 to 1,000,000. In Fig. 1, a deck girder shape G1 from five generic sections is only shown for brevity. These aeroelastic loading coefficients are later used to estimate the critical wind speed in the following section.

Table 1 girder shapes and mesh G1~G5 (Kim 2013)

Girder shape	Mesh
G1  	
G2  	
G3  	
G4  	
G5  	

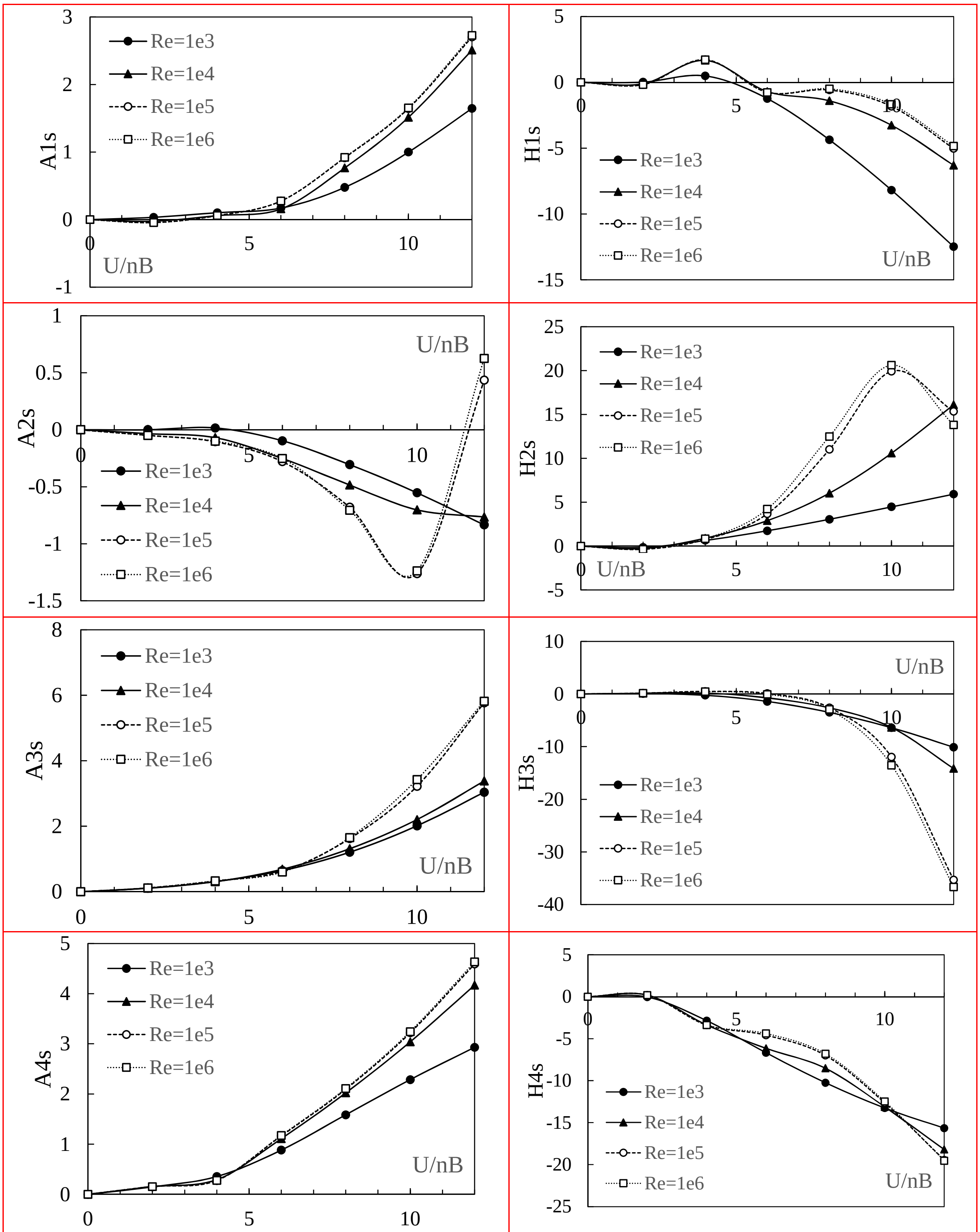


Fig. 1 Flutter derivatives as a function of reduced with speed (U/(nB)) with varying Reynolds number from 1,000 to 1,000,000 for deck shape G1

3. NUMERICAL RESULTS

In order to investigate the randomness of FDs as a function of Reynolds numbers, the flutter behavior of a realistic long-span structure, described in section 2, was analyzed in which the FD data obtained in the CFD simulations for five generic deck girder shapes was applied.

The dynamic response at flutter was examined by two-mode analysis (Jones and Scanlan 2001). The results of flutter analysis are shown in Table 2. Critical wind speed (Ucr) at flutter seems high with deck shape G3 and G4, Re above 100 m/s for most cases. Ucr for G1 tends to increase with increasing Reynolds number. Ucr for G5 shows a clear distinction between a low Reynolds number region (Re < 10,000) and a high Reynolds number region (Re > 10,000). G5 case was 1 to 5 H-shaped cross-section similar to the plate girder of the 1st Tacoma Narrows bridge. Due to the fact this bridge was collapsed by flutter at a low wind speed. FD data extracted with high Reynolds numbers could replicate the ones obtained in wind tunnel and maybe more realistic scenario. Based on Larsen's study (Larsen and Walther 1998), Ucr was equal to 165.3 m/s for G3 and 66.1 m/s for G5 deck shapes.

Table 2 Onset of flutter for deck girder shapes G1~G5 with Reynolds numbers Re=1e3~1e6

Deck shape	Critical wind speed at flutter, U_{cr} (m/s)			
	Re=1e3	Re=1e4	Re=1e5	Re=1e6
G1	40.1	65.0	71.4	70.0
G2	N/A	55.7	46.3	48.0
G3	N/A	95.3	144.4	140.9
G4	N/A	167.1	151.9	151.8
G5	199.2	176.5	40.0	40.2

4. DISCUSSION

This paper investigated the influence of selecting Reynolds number when the flutter derivatives are extracted in the CFD simulations. Comparison of simulations for critical wind speed at flutter was presented and two deck shapes for G3 and G5 are also compared to the literature. In order to replicate the wind tunnel experiment by using CFD simulations, it was suggested to use relatively high Reynolds number (Re > 10,000) in this study. The results also show that a use of FD data obtained in the CFD simulations underestimates the critical wind speed.

ACKNOWLEDGEMENTS

This research is based upon work supported the Korea Institute of Construction Technology (KICT). Any opinions, findings, and conclusions or recommendations are those of the writers and do not necessarily reflect the views of the KICT.

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