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Aero-structural design of bridge decks under non-synoptic winds using an aeroelastic surrogate comprising shape, reduced velocity, and mean angle of attack

Sumit Verma [a], Miguel Cid Montoya [b], Ashutosh Mishra [c]

[a] *Clemson University, Clemson, SC, USA, sumitv@clemson.edu*
[b] *Clemson University, Clemson, SC, USA, mcidmon@clemson.edu*
[c] *Texas A&M University-Corpus Christi, TX, USA, amishra1@islander.tamucc.edu*

SUMMARY:
Contemporary aero-structural design frameworks for wind-sensitive bridges are mostly based on the assessment of aeroelastic responses under synoptic winds. However, holistic design methodologies must address all potential wind scenarios, such as non-synoptic wind events and variations in the angle of attack due to complex terrains. This requires the evaluation of the aeroelastic responses considering the sensitivity of the fluid-structure interaction parameters with the angle of attack. Hence, this study proposes a Kriging-based multi-directional aeroelastic surrogate to emulate the flutter derivatives of bridge decks as a function of the deck shape, frequency of oscillation of the deck, and the mean incident angles of wind. This design tool is pivotal to properly modeling the nonlinear features of flutter derivatives at low reduced velocities and their sensitivity with the angle of attack. The aeroelastic surrogate will be later integrated into aero-structural design frameworks for the shape optimization of bridge decks under non-stationary winds.

Keywords: angle of attack, flutter derivatives, CFD simulation, bridge aeroelasticity, aeroelastic surrogate

1. INTRODUCTION

Current aero-structural optimization frameworks for wind-sensitive bridges (Cid Montoya, 2024) are driven by the assessment of several key aeroelastic responses, such as buffeting and flutter, under the action of synoptic winds, in which the impact of the time-variant angle of attack on the fluid-structure interaction parameters is negligible. However, studying alternative wind scenarios can be required, particularly when bridges are located in complex terrains (mountainous regions and fjords) that might strongly deflect the incident wind or when non-synaptic wind events, such as hurricanes or downbursts, are expected. In these cases, it is pivotal to analyze the impact of angle-of-attack-dependent flutter derivatives in bridge responses under non-stationary winds. Some studies have pointed out that the angle of attack can have dramatic consequences in the magnitude of flutter derivatives (Mannini et al. 2016; Diana and Omarini, 2020; Barni et al., 2022) and even instigate flutter instability at lower wind speeds. In addition, there are also some instances of experimental (Wu et al., 2020) and computational studies (Tang et al., 2018) carried out on flat plate sections to quantify the effect of angle of attack on flutter performance and stability. Besides, Liu et al. (2020) have also reported the flutter derivatives H_i^* and A_i^*,, where i = 1, 2, for the Taihong bridge using a 3D FE model while studying the turbulence effects on the aerodynamic flutter mechanism of the Taihong bridge. Hence, it is necessary to incorporate the effect of the angle of attack in the wind-resistant design, leading to a more general and versatile methodology capable of handling both synoptic and non-synoptic wind design scenarios. Similarly, previous design frameworks have assumed frequency-independency for the shape-dependent fluid-structure interaction parameters (Cid Montoya et al., 2021). This was advanced in Verma et al., (2023), where a shape- and frequency-dependent aeroelastic emulator was proposed to incorporate the effects of flutter derivatives nonlinearities in the lower reduced velocity range into the design process. In the present investigation, we expand this approach by proposing a Kriging-based aeroelastic emulator that simultaneously considers the deck shape S_d, the reduced velocity U^*, and different mean incident angles of wind α on the deck cross-section to obtain the flutter derivatives for the aero-structural design of bridge decks under non-stationary winds. Verified and validated forced vibration simulations using 2D URANS k-ω SST turbulence model and individual degree of freedom deck system analyses are adopted to extract the 18 Scanlan´s flutter derivatives. The aeroelastic surrogate will be later integrated into aero-structural design frameworks for the shape optimization of bridge decks, considering all frequency- and angle-driven nonlinearities involved in the design of streamlined and bluff bridge decks.

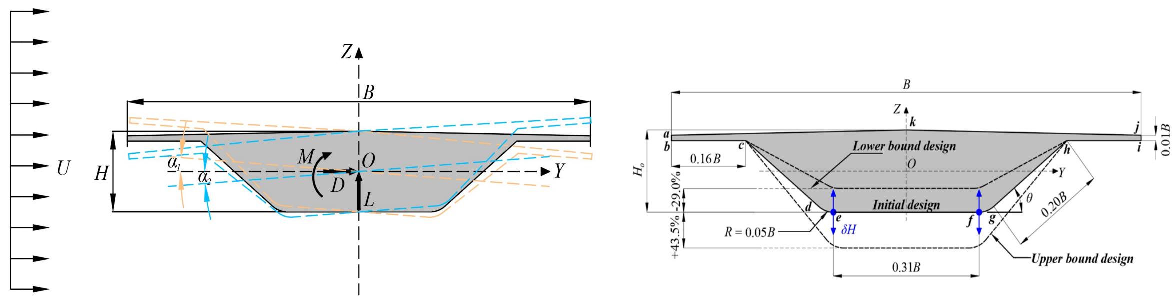

Figure 1. Demo of the variation in the mean angle of attack, oscillation frequency, and the design domain shape for training the aeroelastic emulator.

2. NUMERICAL FRAMEWORK

Flow around the bridge deck is modelled by incompressible Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations with k-ω SST turbulence model. A 2D flow is considered in a rectangular domain. For the aeroelastic analysis, forced harmonic oscillations are imposed on the deck using the Arbitrary Lagrangian Eulerian (ALE) formulation. A single degree of freedom system is considered for the CFD simulations in which the pitching, heaving, and the shoving motion are imposed as defined by $\alpha = \alpha_o \sin(\omega t)$, and $h = h_o \sin(\omega t)$, and $p = p_o \sin(\omega t)$ respectively. Further numerical details will be covered in the full paper. Data obtained from CFD simulation is used to train a Kriging surrogate model that emulates the values of flutter derivatives as a function of deck shape, reduced velocity, and the mean angle of attack. Kriging emulators are built using trending functions that are adapted to the data by training Gaussian process error models, which guarantees that the output response exactly reproduces all sample responses used in the training (Forrester et al., 2008). From a mathematical black-box perspective, the multivariate aeroelastic emulator of the self-excited forces $\mathcal{A}_{se}$ proposed in this work can be formulated as $\mathcal{A}_{se}(\mathrm{S}_d, U^*, \alpha) = [A_i^*, H_i^*, P_i^*]$, where the input is the surrogate domain $\mathcal{D}_s = [\mathrm{S}_d, U^*, \alpha]$ and the output is the complete set of 18 flutter derivatives A_i^*, H_i^*, P_i^*, where $i = 1,\ldots,6$.

3. PRELIMINARY RESULTS

It is important to ensure that the results obtained from CFD simulations follow the trend of real-world physical measurements. Thus, the flutter derivatives H_i^*, A_i^*, where $i = 2, 3$, obtained from the pitching mode of vibration for different mean angles of attack are compared between the CFD simulation and the experimental CRIACIV measurements (Mannini, 2006) in Figure 2.

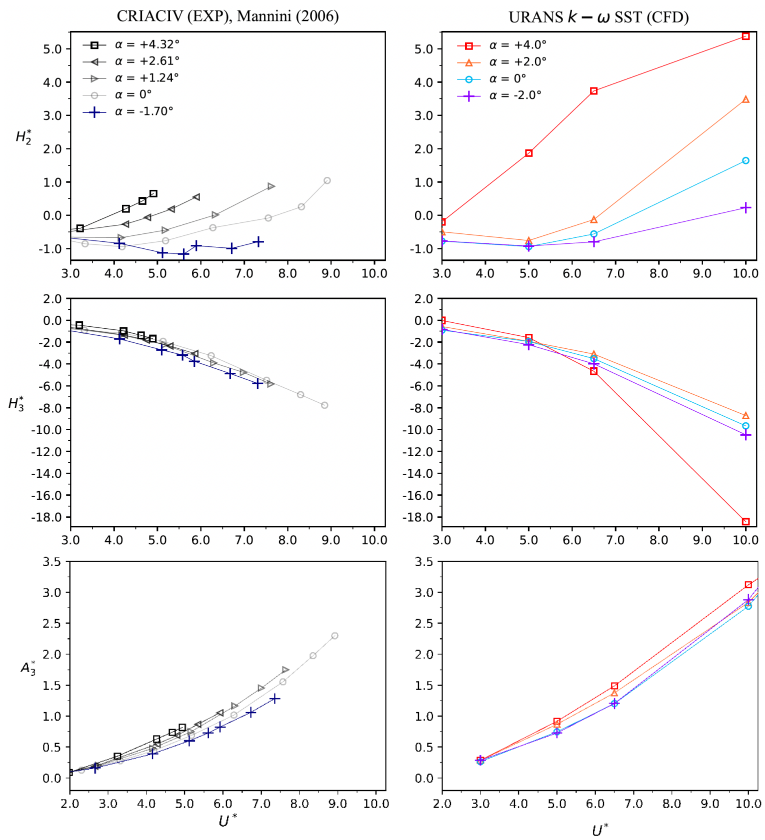

Figure 2. Comparison and Validation of flutter derivatives $H_i, A_i; i = 2,3,$ obtained from pitching mode of vibration for the Experimental CRIACIV section and baseline geometry considered in the current simulation.

It is to be noted that the mean angles of the CFD simulations are not the same but still lie in close proximity and thus serve as a reasonable basis for validation. From Figure 2, it can be readily observed that there is a good overall agreement between the CFD simulation results and the experimental CRIACIV section measurements. Furthermore, a set of dynamic simulations was carried out to train the surrogate model. After validating the CFD model, the surrogate model is built using the Kriging emulators to generate the response surfaces for the flutter derivatives as a function of deck shape, reduced velocity, and the mean angle of attack, as shown in Figure 3.

4. CONCLUDING REMARKS

This study proposes a multivariate surrogate model as a function of deck shape, the reduced velocity, and the mean angle of attack to account for the time-varying angle of attack in non-synoptic winds. Detailed validation studies are carried out for the dynamic simulations by comparing the flutter derivatives at different mean angles of attack as obtained from the CFD simulation using the 2D URANS k-ω SST turbulence model with that from the experimental CRIACIV section (Mannini, 2006). A kriging surrogate is trained using the CFD datasets to produce an emulator that provides the values of the flutter derivatives for a given shape, reduced velocity, and the mean angle of attack. The CFD datasets will be expanded to incorporate all three vibration modes (pitch, heave, and shove degrees of freedom) in the full paper. Future research will harness this tool in aero-structural design optimization frameworks.

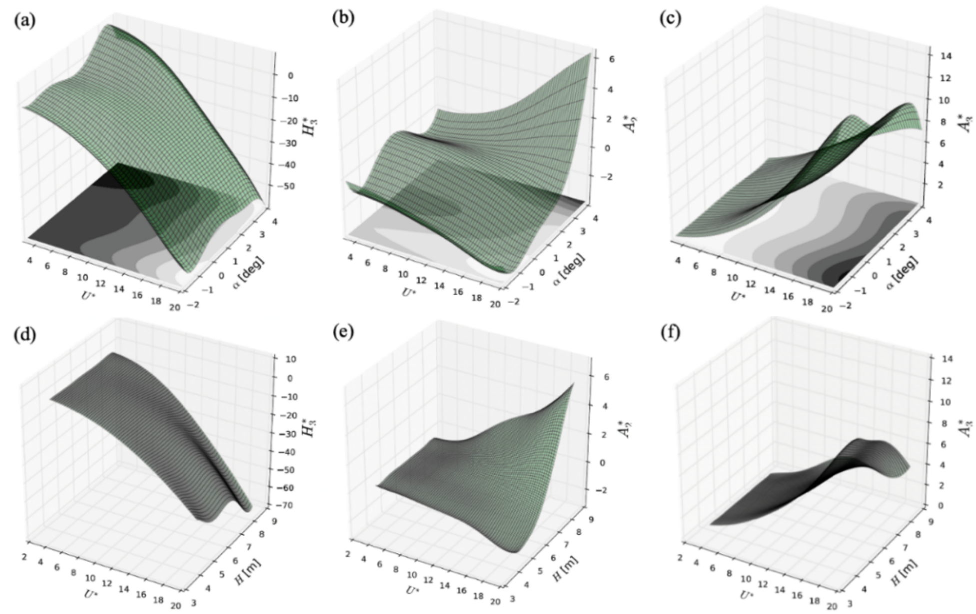

Figure 3. Response surfaces emulated by the multi-directional aeroelastic surrogate: (a), (b), and (c) show the flutter derivatives for the initial design as a function of U^* and α for flutter derivatives H_3^*, A_2^*, A_3^*, respectively. (d), (e), and (f) show the response surfaces for α = +2° as a function of U^* and the deck geometry.

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