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Shape- and Frequency-Dependent Self-Excited Forces Emulation for the Aero-Structural Design of Bluff Decks

Sumit Verma [1], Miguel Cid Montoya [2], Ashutosh Mishra [3]

[1]*ASTRO Lab, Texas A&M Univ.-Corpus Christi, USA, sumit.verma@tamucc.edu*
[2]*ASTRO Lab, Texas A&M Univ.-Corpus Christi, USA, miguel.cidmontoya@tamucc.edu*
[3]*ASTRO Lab, Texas A&M Univ.-Corpus Christi, USA, amishra1@islander.tamucc.edu*

SUMMARY:
The shape design and optimization of bluff bodies prone to aeroelastic phenomena require emulating the fluid-structure interaction parameters as a function of the body shape and frequency. This is particularly relevant for long- and medium-span bridges equipped with deck cross-sections that are far from being considered streamlined. The success of aero-structural design frameworks, which are inherently iterative, relies on the efficient and accurate numerical evaluation of the wind-induced responses. This study proposes emulating the fluid-structure interaction parameters of bluff bodies using surrogate modelling techniques to integrate them into aero-structural optimization frameworks. The surrogate is trained with data extracted from the forced-vibration CFD simulations of a typical single-box deck to emulate the values of the flutter derivatives as a function of the deck shape and reduced velocity. The focus is on low reduced velocities and on deck shapes ranging from streamlined to bluff cross-sections. This design tool is fundamental to finding the optimum balance between the structural and aeroelastic requirements that drive the design of bluff bridge deck geometries.

Keywords: bridge aeroelasticity, flutter derivatives, surrogates

1. INTRODUCTION

Developing aero-structural design tools for wind-sensitive structures requires the accurate numerical evaluation of the shape-dependent wind-induced responses. Previous frameworks developed for bridges with streamlined deck cross-sections resulted in effective and powerful design tools for improving the wind-resistant design by simultaneously reducing the material volume and increasing the structural and aeroelastic safety and serviceability goals (Cid Montoya et al., 2022). These frameworks harnessed the computational advantages of the Quasi-Steady Theory (QST), which shows a good performance for streamlined geometries at high reduced velocities (Chen and Kareem, 2002). However, the aerodynamic design of bluff deck geometries demands directly calculating the fluid-structure interaction parameters without relying on the QST assumptions, such as frequency independence. Hence, this study proposes a shape- and frequency-dependent aeroelastic surrogate that enables the accurate wind-resistant design of bluff decks overcoming the limitations of the QST, which permits the exploration of deck shape design spaces where the QST performs deficiently. This tool is fundamental for balancing the contradictory design demands by structural and aeroelastic requirements. While structural constraints lead shape design variables to produce deck designs with high depths, aeroelastic constraints tend to reduce them to produce streamlined designs. Depending on the project's specifications, bridge location, mechanical properties, and local climate, among others, the aero-structural optimum configuration can be a bluff cross-section whose aeroelastic performance must be assessed using frequency-dependent fluid-structure interaction parameters. Hence, the methodology adopted is conceived to explore wide shape design domains that include streamlined and bluff deck cross-sections. A kriging surrogate (Forrester et al., 2008) is trained to emulate the flutter derivatives of the bridge as a function of the shape and reduced velocity. Force-vibration simulations (Nieto et al. 2015, Mannini et al. 2016) are used to obtain the time history of aeroelastic forces for further computation of flutter derivatives. A typical single-box deck (Mannini et al., 2010, Xu et al., 2014) is used as a test case. Figure 1 shows the baseline geometry and how depth modifications are introduced by moving points a and b vertically.

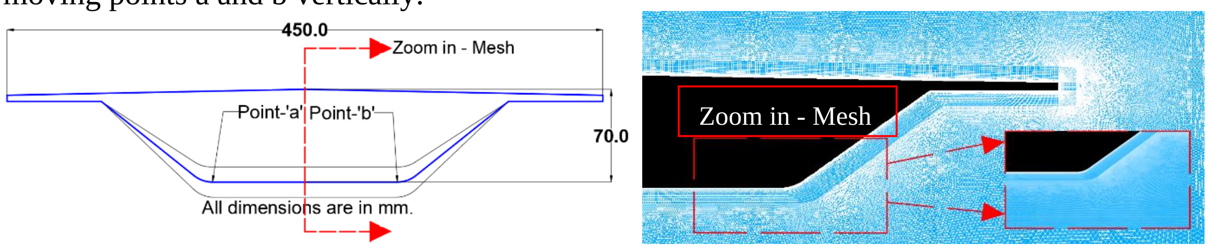

Figure 1. (a) Schematic diagram of shape modification as a function deck depth on a typical single-box deck section (b) Demo of mesh refinement for capturing the boundary layer of deck geometry

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 inside of which the deck of bridge is modelled. For aeroelastic study, forced harmonic oscillations are imposed on the deck section using the Arbitrary Lagrangian Eulerian (ALE) formulation. A single degree of freedom system is considered for the CFD simulation in which pitching, and heave motion are imposed by $\alpha = \alpha_o \sin(\omega t)$ and $h = h_o \sin(\omega t)$ respectively. Further numerical details will be covered in the full paper. Data obtained from CFD simulation is used to train a Kriging surrogate that emulates the values of the flutter derivatives. 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).

3. PRELIMINARY RESULTS

It is important to ensure that the results obtained from CFD simulation are mesh independent; so, a mesh verification study was performed using three different meshes. The total cell count of three meshes and the mean force coefficient, their standard deviations and Strouhal number is reported in Table 1. Since, the results from the three meshes converge towards a similar value, a grid independent solution is obtained. For all further studies, the medium mesh is used unless otherwise stated. In addition to mesh convergence study, the results obtained from current CFD simulation are also validated with the datasets from experimental CRIACIV section and URANS-LEA (R/B = 0.05) CFD simulation case from Mannini et al., 2010. Furthermore, the results are also compared with datasets from Fransos and Bruno, 2010. A good agreement is observed between the simulated datasets from current study and experimental as well as computational results.

Table 1. Comparison of force coefficients, their standard deviations and Strouhal number between three different meshes at $\alpha = 0°$

Cases	No. of Cells	C_d	C_l	C_m	S_t	C_d'	C_l'	C_m'
Coarse Mesh	244576	0.0671	-0.0911	0.0971	0.2790	0.00059	0.04994	0.01044
Medium Mesh	283486	0.0668	-0.0990	0.0969	0.2860	0.00064	0.05062	0.01064
Fine Mesh	365875	0.0669	-0.0999	0.0968	0.2819	0.00065	0.05093	0.01070

Table 2. Comparison of force coefficients and Strouhal number between the current CFD simulation and URANS – LEA model and Experimental CRIACIV section from Mannini et al., 2010 and Fransos & Bruno (2010)

Case	C_d	C_l	C_m	S_t	C_d'	C_l'	C_m'
URANS – LEA (Mannini)	0.067	-0.024	0.102	0.252	0.0011	0.068	-
CRIACIV section	0.107	-0.191	0.101	0.206	-	-	-
Current CFD Simulation	0.067	-0.099	0.097	0.286	0.0006	0.051	0.0106
*Fransos & Bruno (2010)	0.076	-0.096	-	0.279	0.0003	0.002	-

* Values reported in Table 2 are obtained after digitization and interpolation of plots from Fransos and Bruno (2010)

A nice overlap in the zero mean aeroelastic lift coefficient history from three meshes in Fig. 1(a) serves the purpose of dynamic mesh verification in Fig. 1 (a). Similarly, a good agreement observed in the superimposed aeroelastic lift coefficient history from current study and that of Mannini et al, 2016 serves the purpose of validation for dynamic CFD simulations.

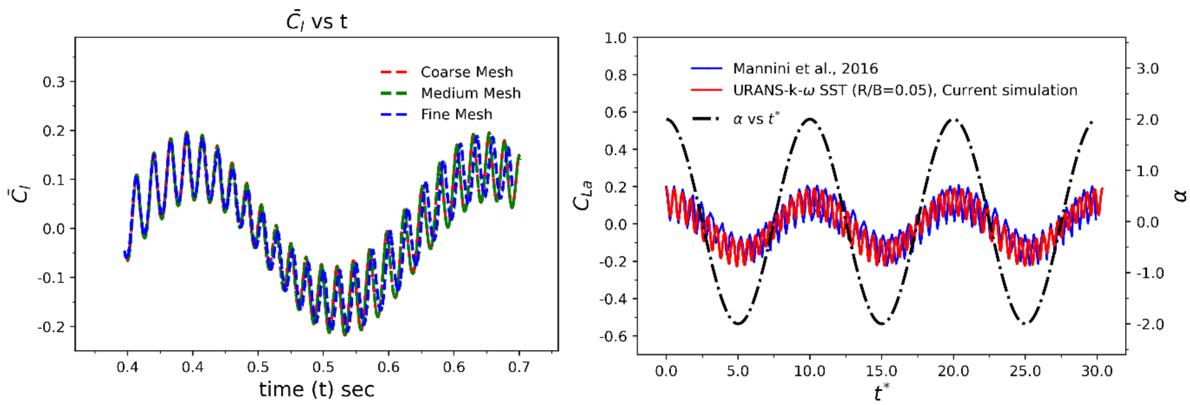

Figure 1. Forced vibration simulation (a) Mesh verification study (b) Validation with Mannini et al, 2016

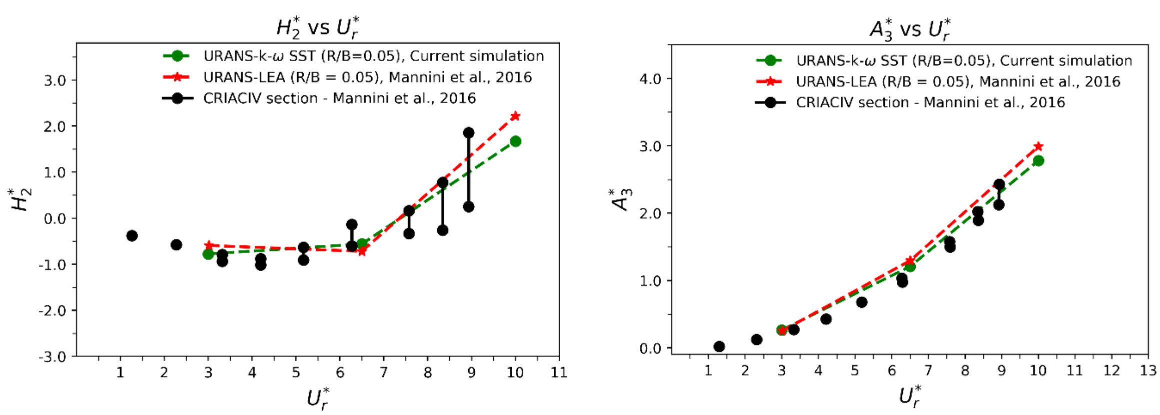

Figure 2. Comparison of flutter derivatives (H_2^* and A_3^*) between the current CFD simulation, experimental CRIACIV section and URANS-LEA (R/B = 0.05) from Mannini et al., 2016

Furthermore, a set of dynamic simulations were carried to train the surrogate model. A plot comparing the flutter derivatives (H_2* and A_3*) obtained from the current CFD simulation along with the experimental results from CRIACIV section and URANS-LEA simulation from Mannini et al., 2016 is shown in Fig. 2, in which a good agreement can be readily noticed. After validating the CFD model, the surrogate model is prepared using Kriging emulators to generate the response surfaces for flutter derivatives as a function of shape (depth of deck section) and reduced velocities.

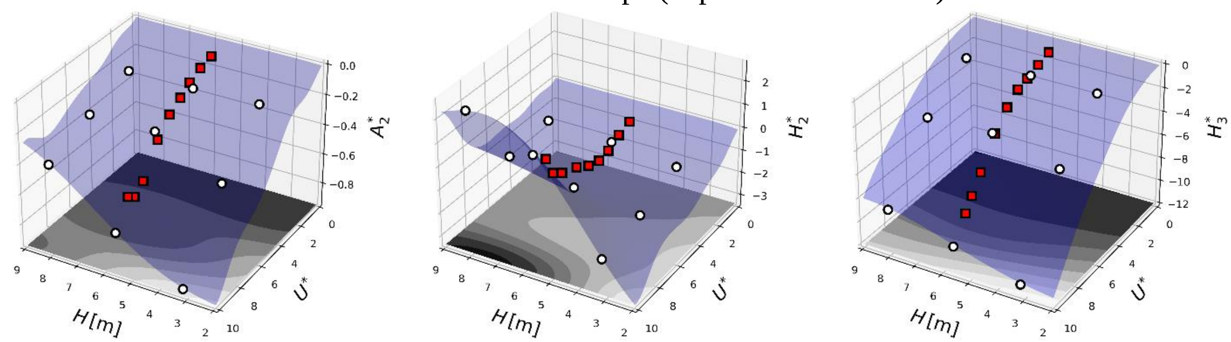

Figure 3. (a) Response surfaces for the flutter derivatives (A_2^*, H_2^* & H_3^*) obtained by Kriging surrogate model trained on CFD datasets (Red dots are the values taken from Mannini et al., 2016)

4. CONCLUDING REMARKS

This study proposes an aeroelastic surrogate to emulate the frequency-dependent self-excited forces for the design and optimization of bluff bodies. Detailed validation and verification studies of the static and dynamic simulations were conducted to evaluate the performance of 2D URANS Menter's $k\omega$-SST model simulations of a well-known single-box bluff deck. A kriging surrogate is trained using the CFD dataset to produce an emulator that provides the values of the flutter derivatives for a given shape and reduced velocity. The CFD dataset will be expanded in the full paper. Future research will harness this tool in aero-structural design optimization frameworks.

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