9th International Colloquium on Bluff Body Aerodynamics and Applications
University of Birmingham, Birmingham, UK
29th July – 2nd August 2024

Local and Global Optimum Design in Aero-Structural Optimization of Long-Span Bridges Considering Flutter

Miguel Cid Montoya [a], Santiago Hernández [b], José Ángel Jurado [b]

[a] *ASTRO Lab, Texas A&M University-Corpus Christi, Corpus Christi, TX, USA*
[b] *Structural Mechanics Group, University of Coruña, A Coruña, Spain*

SUMMARY:
The aero-structural design of bridges is mainly controlled by the deck cross-section design. Design modifications on bridge decks impact the deck aerodynamics and the deck mechanical contribution, which also affect the bridge aeroelastic responses. The nonlinear inherent nature of bluff body aerodynamics combined with the nonlinearities of multimodal aeroelastic analyses result in complex relationships between the full bridge aeroelastic responses and deck shape design variables. This fact impacts the design process as it may lead to the development of complex feasible design regions in the chosen design domain, including disjoint feasible regions that may cause local minima. Given the limitations of metaheuristic optimization methods to deal with optimization problems with large sets of design variables, as required in holistic bridge design problems, gradient-based optimization algorithms can be recast to address global optimization problems. In this study, we propose the use of tunneling optimization methods to address this challenge.

Keywords: Wind-resistant design, Long-span bridges, Aero-structural optimization, Disjoint feasible regions, Global optimization, Tunnelling method.

1. INTRODUCTION

Flutter is one of the most relevant wind-induced phenomena and a matter of concern in the design of long-span bridges. Thus, all project specifications always provide a wind speed value that the structure must undergo before flutter onset. The idea of designing long-span bridges combining structural analysis, aeroelastic studies of flutter, buffeting, and aerostatic instability, and numerical optimization algorithms was initiated by these authors several years ago, and the results obtained show the capabilities of this approach to produce better designs that the conventional scheme based in sequential heuristic modifications of the initial design. Previous research on aero-structural optimization showed that the feasible design region where the optimum design must be found can be composed of several separated regions, what is called a disjoint feasible region (Cassis and Schmit, 1976). In these circumstances, the optimization algorithm can converge at a local minimum instead of a global one. In that regard, it is very convenient to have algorithms that, after reaching a local minimum, can restart a new search until obtaining another local optimum and proceed in that way several times until finding the global optimum. Such techniques are called global optimization algorithms. In this paper, we apply one of these algorithms, the tunneling method, to the aero-structural optimization of a cable-stayed bridge of 1316 m of main span subject to flutter, displacements, and stress constraints. In this optimization problem, the feasible region comprises two separated surfaces with local optima in each one. In a previous work (Cid Montoya et al., 2018b), the aero-structural optimization was carried out by adopting the gradient-based Sequential Quadratic Programming SQP (Arora, 2011), including 83 design variables and 1104 design constraints, where 1103 are related to structural responses involving displacements and stress levels and 1 is the critical flutter velocity. The optimization algorithm was able to obtain drastic improvements in reducing the objective function, i.e., saving material, and guarantee flutter safety. However, a global optimum was missed as the algorithm was not able to reach the disjoint feasible region containing the global optimum. In this study, we address this issue providing a gradient-based methodology capable of achieving the global minima in a complex aero-structural optimization problem involving multiple variables and constraints.

2. AERO-STRUCTURAL OPTIMIZATION

The aero-structural optimization problem must be formulated in a holistic fashion aiming at addressing all requirements typically included in project specifications and construction codes. Resilience and safety goals involves formulating design constraints including structural or mechanical responses, such as stress levels and displacements under several combinations of loads, and also aeroelastic responses due to the action of wind. On the other hand, classical structural design optimization problems pursue the minimization of costs or material use to address sustainability and cost-effectiveness goals. Hence, the optimization problem can be formulated as:

$$\min F(\mathbf{x}) = \min V(\mathbf{S}_d, \mathbf{x}_s),$$

subject to

$$g_r^{Str}(\mathbf{x}) = \frac{R_r(\mathbf{x})}{R_{r,max}} - 1 \leq 0,$$

$$g_r^{U_f}(\mathbf{x}) = \frac{U_{f,min}}{U_f(\mathbf{x})} - 1 \leq 0,$$

where F is the objective function, V the material volume, and $\mathbf{x}$ is the full set of design variables, including deck shape design variables $\mathbf{S}_d$ and size design variables $\mathbf{x}_s$, such as plate thickness and cable cross-section areas. g_r^{Str} indicates structural constraints, R_r are the r structural responses, and $R_{r,max}$ their imposed threshold, while $g_r^{U_f}$ stands for the flutter constraint, U_f is the critical flutter velocity of the bridge and $U_{f,min}$ is the minimum allowed value for the critical flutter velocity. More aeroelastic constraints can be added as needed (Cid Montoya et al., 2022).

3. APPLICATION CASE

The long-span cable-stayed bridge used as an application example is shown in Figure 1. The deck shape used as baseline geometry and initial design in the optimization process is Scanlan's G1 cross-section (Scanlan, 1971). The deck shape design domain is defined by depth and width modification of up to $\pm 10\%$ of the baseline values, giving place to a large range of possible deck designs. Most of these designs can be assumed to be streamlined geometries. Hence, the flutter derivatives were estimated using an aerodynamic surrogate model trained with static CFD simulations and the quasi-steady theory (QST)-based formulation (Chen and Kareem, 2002). The accuracy of this approach was experimentally studied in Cid Montoya et al. 2018a. Besides the deck cross-section, the deck plate thickness and all stays cross-section areas are considered design variables, resulting in a total of 83 design variables. A detailed description of the optimization problem and the full set of constraints can be found in Cid Montoya et al. 2018b.

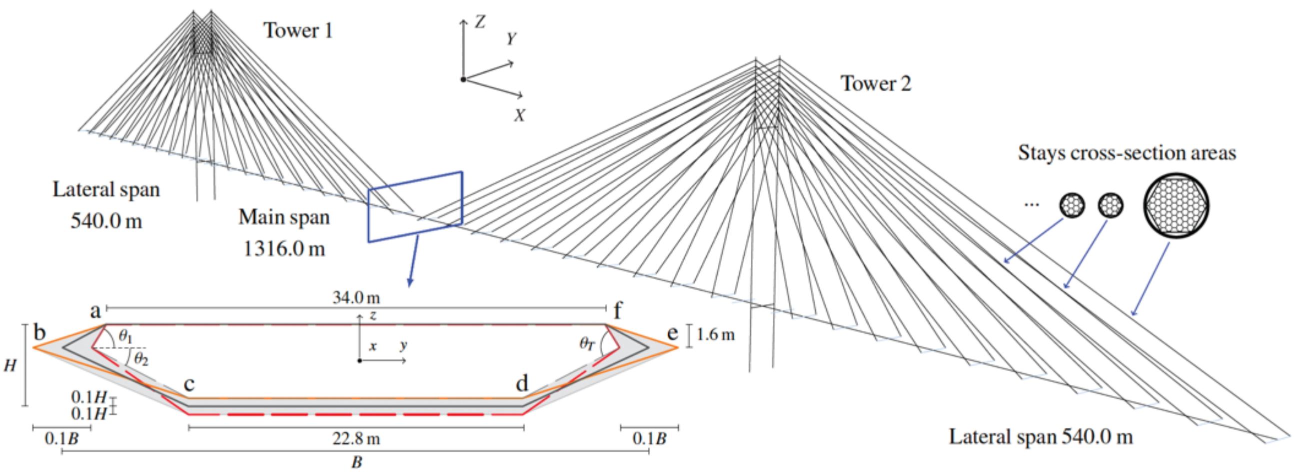

Figure 1. Layout of the cable-stayed bridge adopted as application example showing the deck shape variations considered in the aero-structural design optimization.

4. DISJOINT FEASIBLE DESIGN DOMAIN

The main characteristic of this optimization problem that motivates the present investigation is the presence of marked nonlinearities in the flutter velocity response surface over the shape design domain. Figure 2 shows the flutter response surface over the optimum design domain, i.e., the flutter response for structural optimum design for each deck design within the design domain. This representation facilitates the interpretation of the optimization results. On the right side of Figure 2 the objective function is also represented and compared with the feasible and unfeasible design regions. The nonlinear relationship between the flutter velocity and the deck shape, particularly for low values of δ_B and values of δ_H about -3%, leads to the definition of a disjoint feasible region for those deck geometries. This nonlinearity is caused by changes in the modal contributions during the flutter analysis driven by deck shape changes, as can be seen in Figure 3 by analyzing the change in the modal contributions of modes 11 and 12, which are the two main torsional modes. As shown on the right side of Figure 2, the objective function can be further minimized by moving to this feasible design region, which requires a global optimization strategy.

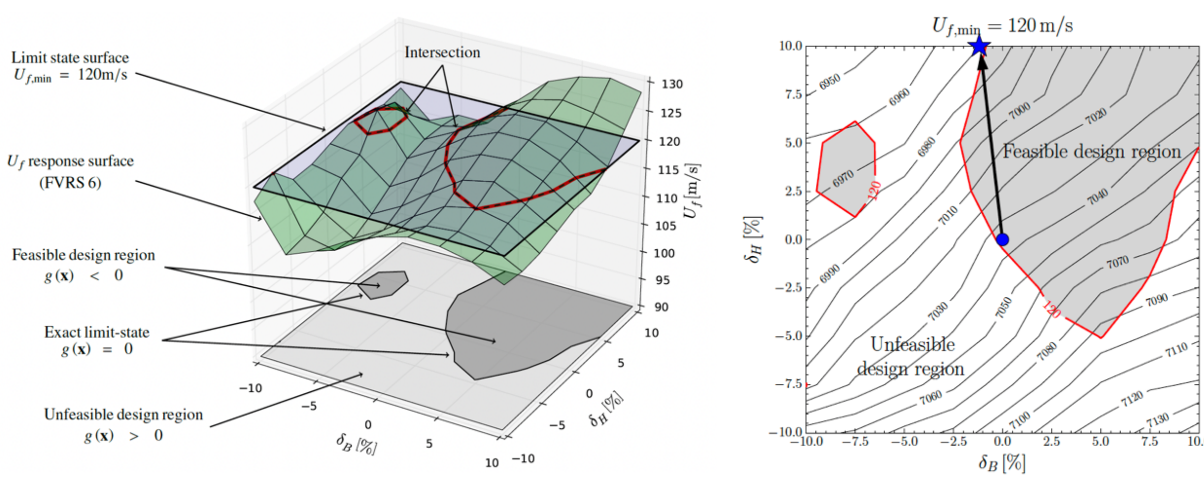

Figure 2. Flutter velocity response surface and definition of feasible and unfeasible design domains.

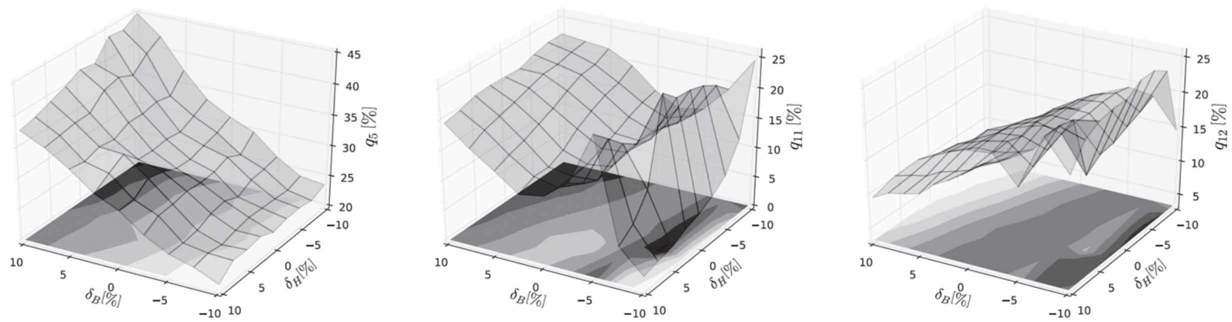

Figure 3. Contribution to flutter response of relevant mode shapes: #5 is the first symmetric vertical mode (0.213 Hz), #11 is the first symmetric torsional mode (0.414 Hz), and #12 the second symmetric torsional mode (0.449 Hz).

5. GLOBAL OPTIMIZATION AND CONCLUDING REMARKS

Metaheuristic algorithms, such as genetic optimization methods, are effective alternatives in design scenarios with a low number of design variables. As the number of design variables increases, gradient-based algorithms stand as the only alternative to effectively address holistic design optimization problems due to the course of dimensionality (Forrester et al. 2008). Tunneling algorithms (Gómez and Levy, 1982) are an effective alternative for dealing with this issue. This sequential iterative strategy consists of two different phases: (1) a *Minimization Phase* where the gradient-based optimization algorithm finds a local minimum satisfying the Kurush-Kuhn-Tucker convergence conditions, and (2) a *Tunneling Phase* where a global exploration searches for a different design with the same objective function value that is not a local minimum. The strategy iterates until finding the global minimum. The final results will be shown in the oral presentation.

ACKNOWLEDGEMENTS

The authors acknowledge the support received by the Spanish Ministry of Science and Innovation under grant number PID2022-138069OB-I00. Miguel Cid Montoya is also supported by the National Science Foundation (NSF) under Grant No. CMMI-2301824.

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