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Aerodynamic shape optimization of civil structures: A CFD-enabled Kriging-based approach

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ABSTRACT

In the case of mega-structures such as tall buildings and long-span bridges, the mitigation of the intensity of the wind excitation through aerodynamic tailoring of the external shape can be fundamental for meeting the performance goals. The search for the best performing shape through an automatic CFD-enabled optimization methodology is potentially less expensive, less time-consuming and more thorough than the common trial-and-error approach based on wind tunnel test results, therefore very attractive. This paper investigates the possibility of carrying out the multi-objective aerodynamic shape optimization of civil structures through an approach in which evolutionary algorithms are used in synergy with ordinary Kriging surrogates. A specifically developed strategy is adopted to update the Kriging models making efficient use of additional CFD runs. Shell scripting, parallelized computations and mesh morphing algorithms are exploited for enhancing the framework's efficiency and consistency. As a case study, the optimization of the shape of a tall building cross-section in terms of both the lift and the drag coefficient is considered.

1. Introduction

In recent years, the number of high-rise buildings and long-span bridges constructed all over the world has exponentially increased, with a trend towards taller, or longer, more slender and lighter structures. A consequence of this trend is a heightened sensitivity to the action of wind, which makes the satisfaction of the required structural performance in terms of survivability, serviceability and habitability more challenging for the designers, even when the best possible choice of structural system is made. The mitigation of the intensity of the wind excitation through aerodynamic tailoring of the external shape can therefore be fundamental for meeting the performance goals, potentially eliminating the necessity of more expensive alternative solutions, which typically involve the use of auxiliary motion control devices. The advantages that can be had through a suitable choice of the shape are indeed well known. In the case of high-rise buildings, it has been observed that modifications of the cross-section such as chamfering and recession of corners can significantly reduce the alongwind and acrosswind response (Kareem et al., 1999); also, variations along the vertical axis, such as variation of the cross-section, tapering, or the introduction of helical profiles or setbacks (e.g. Kim et al., 2011; Tanaka et al., 2012) are known to have beneficial effects. For bridges, aerodynamically tailored slotted box sections are often adopted in order to minimize the aerodynamic loads and shift flutter to higher wind speeds; also, edge treatments such as fairings and deck extensions are used to improve the aerodynamic behavior, even in the case of retrofitting (Kareem et al., 2013a).

To take advantage of the aerodynamic shape tailoring in the case of extreme structures particularly affected by the wind action, what is commonly done is to consider, in the preliminary phases of the design process, more than one configuration in order to identify the less aerodynamically demanding (e.g. Abdelrazaq et al., 2005; Baker et al., 2007; Xie, 2014). Typically, wind tunnel tests are used to characterize the aerodynamic behavior of the candidate shapes, selected a priori based on experience, therefore the number of configurations that can be considered is limited by the significant resources and time necessary to execute each test. As a consequence, a vast portion of the search space remains unexplored, and more conventional configurations are favored over innovative solutions.

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The possibility of taking advantage of computational fluid dynamics (CFD) simulations for the assessment of the aerodynamic performance while using optimization algorithms to find the best aerodynamic shape is therefore very attractive as it would allow not only to rigorously and thoroughly investigate the search domain, but to do so automatically, also in principle eliminating the necessity of costly wind tunnel experiments. This idea is not new in the fields of mechanical, automotive and aerospace engineering, where CFD-based aerodynamic shape optimization (ASO) has been applied to discover optimal geometric configurations for vehicles, aircraft bodies and wings, compressor blades, laminar and turbulent flow diffusers, etc. (e.g. Madsen et al., 2000; Mohammadi and Pironneau, 2001; Thévenin and Janiga, 2008). In the field of civil engineering, however, ASO is only recently gaining interest (Kareem et al., 2013b, 2014; Spence et al., 2013). This is probably due, on one hand, to the fact that the traditional trial-and-error approach to the design has so far been proved sufficient for most structures. Also, the intrinsic link between the aesthetics of the structure and the structural form tends to raise skepticism regarding the applicability of ASO, which, suggesting that the shape of a civil structure can be found as the solution of a purely mathematical problem, appears incompatible with architectural considerations. On the other hand, the implementation of ASO which relies on CFD simulations is intrinsically difficult for civil structures, due to the bluff nature of the bodies, the turbulent and separated nature of the flow field and the presence of the boundary layer in which the structures are immersed, the high values assumed by the Reynolds number, the multi-objective nature of the design problem.

This paper investigates the possibility of carrying out the multi-objective CFD-based ASO of civil structures through a surrogate-based approach. The basic idea is to use a limited number of CFD simulations to build surrogate models which, being far less expensive to evaluate, can be explored through evolutionary algorithms to find the optimal solutions. In particular, in this work the possibility of using ordinary Kriging for the construction of the surrogates is investigated. A specifically developed strategy is adopted to update the Kriging models making efficient use of additional CFD runs while taking advantage of shell scripting and parallelized computations. Suitably defined constraints are used to define the range of admissible shape variations. As a case study, the optimization of the shape of a tall building cross-section in terms of both the standard deviation of the lift coefficient and the mean drag coefficient is considered, where URANS (unsteady Reynolds-averaged Navier–Stokes) CFD simulations are adopted for modeling the turbulent flow and therefore also for calibrating the Kriging models.

2. Problem statement

The idea behind shape optimization is to allow the boundary of a body to be modified while satisfying certain constraints in order to attain the best possible performance. After having described the geometry in terms of a set of n parameters collected in the vector of the design variables $\mathbf{q}$, the shape optimization problem can be posed as follows:

$$\text{Find} \quad \mathbf{q} = (q_1, q_2, \ldots, q_n) \tag{1}$$

$$\text{to minimize} \quad \mathbf{G}(\mathbf{q}) \tag{2}$$

subject to

$$C_r(\mathbf{q}) = 0, \quad r = 1, \ldots, R \tag{3}$$

$$D_s(\mathbf{q}) \le 0, \quad s = 1, \ldots, S \tag{4}$$

where $\mathbf{G}(\mathbf{q}) = [G_1(\mathbf{q}),..., G_N(\mathbf{q})]$ is a vector collecting the N objective functions, while Eqs. (3) and (4) represent R equality constraints and S inequality constraints, respectively, imposed on the design variables. The set of feasible solutions is given by all the vectors $\mathbf{q}$ that satisfy the constraints of Eqs. (3) and (4). A feasible vector $\mathbf{q}_*$ is a Pareto-optimal solution of the multi-objective optimization problem if it is not possible to find another feasible solution for which an improvement in one objective does not correspond to a degradation in one or more of the others. In mathematical terms, a vector $\mathbf{q}_*$ is a Pareto-optimal solution if it is feasible and there exists no other feasible $\mathbf{q}$ such that (1) $G_j(\mathbf{q}) \le G_j(\mathbf{q}_*)$ for all j and (2) $G_i(\mathbf{q}) < G_i(\mathbf{q}_*)$ for at least one i. In general, the various objective functions are competing, and more than one Pareto-optimal solution exists. From the viewpoint of the mathematical problem formulation these solutions are all equally good. It is therefore for the decision-makers to choose, based on additional considerations, the "best" trade-off solution among the ones belonging to the Pareto-optimal set, and for the optimization algorithm to find Pareto-optimal solutions as diverse as possible in the objective function space. This in particular is not trivial due to the high non-linearity often characterizing the mapping between design variables and objective functions (Forrester et al., 2008).

Being here of interest the study of the aerodynamic behavior of the body, one or more of the objective functions and/or of the constraint functions of the optimization problem will be in terms of aerodynamic quantities that have to be evaluated through CFD simulations. The significant computational effort required to carry out even the simplest CFD simulations represents the crucial difficulty of ASO, as it makes unfeasible the straightforward use of classic optimization strategies which need numerous function calls. The following section presents the strategy used here to tackle this challenge.

3. Solution strategy

3.1. Optimization algorithms

The strategy proposed in this work for solving the ASO problem entails the use of evolutionary algorithms (EAs). These algorithms mimic the evolution of species and the survival of the fittest by considering a population of individuals, each one characterized by a genome, evolving from generation to generation through biologically inspired mechanisms such as crossover, mutation and selection. The genome of an individual is a set of values assumed by the design variables while the fitness of the individual is described by the values of the objective functions. EAs have often been preferred to gradient-based techniques in the case of ASO problems due to several advantages that make them successful in a variety of applications. In particular, their robustness allows them to handle very large design spaces that are characterized by irregular landscapes, without getting trapped into local optima; they are also easy to parallelize (the performances of the various individuals of the population are independent of each other), easy to hybridize with alternative methods and simple to program. Even more importantly in the case here considered, EAs are particularly suitable for multiobjective optimization problems because they are able to find the entire range of Pareto-optimal solutions while keeping them as diverse as possible (Deb, 2001; Arias-Montaño et al., 2012), while gradient-based methods can