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High-fidelity aerodynamic shape optimization using efficient orthogonal modal design variables with a constrained global optimizer

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ABSTRACT

Aerodynamic shape optimization of aerofoils using efficient orthogonal design variables is considered using a global search algorithm. A novel approach is presented for deriving shape design variables, using a proper orthogonal decomposition of a set of training aerofoils to obtain an optimally efficient set of aerofoil deformation modes that represent typical design parameters such as thickness and camber. A major advantage of this extraction method is the production of orthogonal design variables, and this is particularly important in aerodynamic shape optimization. These design parameters have previously been tested on geometric shape recovery problems and been shown to be efficient at covering a large portion of the design space, hence the work is extended here to consider their use in aerodynamic shape optimization. A global search algorithm with an efficient constraint handling method has been developed and used here to optimize a suite of inviscid and viscous compressible aerofoil test cases using varying numbers of modal parameters. Often, an artefact of inviscid optimizations is an oscillatory pressure distribution, so to alleviate this drag minimization with a modulus of curvature penalty is also considered for the inviscid optimizations, where the penalty is used to force smoother pressure distributions; this is not necessary in the viscous optimizations. Results indicate that often fewer than 10 design parameters are required to obtain shock free solutions even from highly-loaded aerofoils with significant shocks.

1. Introduction and background

Aerodynamic shape optimization (ASO) is the process often used to optimize a given aerodynamic shape within a computational environment to improve on a design requirement. Numerical simulation methods to model fluid flows are used routinely in industrial design, and increasing computer power has resulted in their integration into the optimization process to produce the ASO framework. The aerodynamic model is used to evaluate some metric against which to optimize, which in the case of ASO is an aerodynamic quantity, most commonly drag, subject to a set of constraints which are usually aerodynamic or geometric. Along with the fluid flow model, the ASO framework requires a surface parameterization scheme, mathematically describing the aerodynamic shape being optimized by a series of design variables. Changes in the design variables, which are made by a numerical optimization algorithm, result in changes in the aerodynamic surface. Numerous advanced optimizations using compressible computational fluid dynamics (CFD) as the aerodynamic model have previously been performed for aerofoil sections [1,2], full aircraft [3–5], aeroelastic aircraft [6], and rotor blades [7–10]. The authors have also presented work in this area, having developed a modularised, generic optimization tool, that is flow-solver and mesh type independent, and applicable to any aerodynamic problem [11,12].

The fidelity of results obtained by the optimization process is dependent on the fidelity and quality of each of the three individual components of the ASO process. To facilitate optimum compatibility between these components, each is often designed in a modular manner such that, for example, the aerodynamic model is independent of the parameterization scheme used. A high fidelity numerical aerodynamic model with good capturing of the true physics is important in producing optimum aerodynamic designs, particularly at transonic conditions. The aerodynamic model also defines the parameter space of the problem, which is the definition of the aerodynamic outputs based on flow field inputs such as Mach number and angle of attack.

The quality of the optimization result obtained is driven primarily by the quality and type of numerical optimization algo-

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rithm used in the ASO framework. The two primary types of optimization algorithms are local methods and global methods. The local methods are usually built around the gradient-based approach, which uses the local gradient of the design space as a basis around which to construct a search direction. The optimization algorithm therefore traces a movement path through the design space until the gradient values become very small where the result has converged. These approaches are the most common methods used in the ASO framework ([5,13,14] for example), driven primarily by the low cost associated with them compared to global methods [15]. Global optimization algorithms, on the other hand, tend to be based around a swarm intelligence approach, where candidate solutions scattered throughout the design space cooperate together to locate the global optimum solution. Each candidate solution, of which there are typically around the order of 100, requires an objective function evaluation, which in ASO is a flow solution, and therefore are often considerably more expensive than the local algorithms. Furthermore, handling of constraints using global methods can be difficult and is often done on an *ad hoc* basis. The primary advantage, however, is that global algorithms are much less prone to converging in locally optimum solutions that are not necessarily close to the global optimum. Due to the high cost associated with such algorithms, and their issues in handling constraints (which is an important consideration for ASO), their use in ASO is more restricted than local methods but is becoming more common [16–18].

The aerodynamic model defines the parameter space of the problem, however, the problem design space, which the optimization algorithm interrogates, is constructed by the definition of a surface parameterization scheme. The ability of the optimizer to fully interrogate the true design space (which contains every possible design) is driven by the ability for the degrees of freedom of the parameterization scheme to represent any shape within the design space, and so this is a critical aspect of any optimization scheme. Furthermore, the use of a low number of design variables is highly advantageous, particularly if global optimization algorithms are used where the so-called ‘curse of dimensionality’ means that performance of global search algorithms deteriorates with increasing dimensions.

An important aspect of any parameterization scheme is orthogonality of the design variables. Orthogonal design variables means that a shape is represented by a unique set of inputs, often leading to a design space that is more efficient, meaning it can be represented with fewer design variables [19]. It also tends to simplify the design space against non-orthogonal design variables and leads to greater coverage of the design space, i.e. the design variables can represent a greater number of aerodynamic shapes; the design space of N design variables is always contained within the design space of $N + n$ design variables.

The work presented in this paper considers the optimization of aerofoils using a novel method of deriving design variables. Proper orthogonal decomposition (POD) is used on a training library of aerofoils, the selection of which can be considered a type of dimensional filtering, to mathematically extract optimum aerofoil shape modes, and these shape modes have the major advantage of being orthogonal. The method, which has recently been presented by the authors [20], was shown to be highly effective at representing the aerofoil design space often requiring less than a dozen variables to recovery aerofoil shapes. Furthermore, Masters et al. [21] demonstrated that for aerofoil design space representation, deriving aerofoil modes by SVD produced the most efficient and compact set of design variables, outperforming many other commonly used aerofoil parameterization schemes. The aim of the work presented here is to analyse the effectiveness of these novel orthogonal design variables when applied to aerodynamic optimization. Using POD means that advanced global search algorithms can be introduced into the ASO process; this has future implications on allowing investigations into aerodynamic multimodality. Hence, in this paper, an advanced constrained global search algorithm with an effective constraint handling framework is also employed to allow full design space exploration and exploitation. The use of a global search algorithm also means that any issue of multimodality in the design space can be effectively handled, thereby ensuring a true test of the design parameters.

2. Aerofoil parameterization and deformation approaches

A surface parameterization scheme defines a design space by a number of design variables. A separate problem to this, though often considered alongside, is the deformation of the subsequent surface during the optimization process, which is required to allow deformation of a body-fitted CFD mesh. The effectiveness of a parameterization method is i) being flexible and robust enough to cover the design space, and ii) efficient enough to represent a given shape with as few design variables as possible. Methods are classified as either constructive, deformative or unified. These are outlined below but more in-depth reviews have been presented by Samareh [22,23], Nadarajah et al. [19,24] and Masters et al. [25].

Constructive methods are those that consider the definition of the surface and the deformation of the surface separately. Examples of these methods are CST [26], PARSEC [27], PDEs [28] and splines [29]. Other approaches that combine various parameterizations in a hybrid approach, such as that of Zhu and Qin [30] can also be found. Due to the constructive nature of these approaches, perturbation of the base geometry through the optimization process therefore requires that the new surface be reconstructed which subsequently requires automatic mesh generation tools for production of a new surface and volume mesh. This extra difficulty can make it advantageous to consider approaches that manipulate an existing mesh.

An alternative to constructive are deformative methods which unify the geometry creation and perturbation. This tends to make them simpler to integrate with mesh deformation tools and allows the use of previously generated meshes – a considerably cheaper alternative to regeneration – though the mesh deformation is a separate algorithm. Analytic [1,31] and discrete [32] methods are examples of deformative approaches.

A further refinement of combining geometry creation and perturbation is the integration with a mesh deformation algorithm, and these types of methods are unified. Methods of this type typically have some interpolation that describes a link between the surface and volume, often via a set of control points that are independent of both, such that deformation of the control points results in deformation of the surface and CFD mesh. These are the most common approaches found in ASO, and the methods included in this unified category are free-form deformation [33], domain elements[11] and direct manipulation [34].

A novel method, recently developed by the authors, is to consider deriving aerofoil design variables using a matrix decomposition approach [20]. The approach utilises singular value decomposition (SVD) in a manner that analyses an initial library of aerofoils and decomposes that library into a set of optimum, reduced design variables that are geometrically orthogonal to each another. Masters et al. [25] has shown the method to be able to represent the boundary shape of a wide range of aerofoils using a small subset of design variables. It was also shown that for this inverse geometric design problem, that the modal design variables outperformed other commonly used aerofoil parameterization methods in terms of a minimum number of design parameters required to represent the boundary shape. This emphasises that having orthogonal design variables, which the SVD method provides, results in a more effective and efficient coverage of the aerofoil design space.