Automatic parametrisations for adjoint-based shape optimisation

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Long Abstract

Introduction

Adjoint methods are the most efficient approach to compute the design sensitivities, as the entire gradient vector of a single objective function is obtained in a single adjoint system solve. This remarkable efficiency removes the stringent constraints on the size of the design space of stochastic methods and enables us to consider alternative approaches.

Our focus here will be on comparing two automatically derived parametrisations which provide rich design spaces without any additional user input. A first class uses the surface mesh nodes as design variables, representing the richest design space the CFD model can accept. A second class uses as design variables the control points of the NURBS patches of the surface representation (BRep), which is the finest design space that BRep of the CAD model can express.

1. Adjoint Surface Sensitivities

In this work, we use an in-house compressible discrete adjoint solver, mgopt, [1] derived from the flow solver using the automatic differentiation (AD) tool Tapenade. The primal flow solver of mgopt uses a standard node-centred, edge-based fully coupled compressible discretisation with implicit time-stepping. The time-stepping of the adjoint equations is a fixed-point method using the same assembly steps as the primal.

2. Automatic shape parametrisations

The adjoint approach allows us to consider automatic parametrisations that are derived without any additional user intervention, and typically are overly rich to contain all possible design modes, not just those that a designer thinks are important to this flow.

2.1 Node-based parametrisation

The node-based parametrisation (NBP) considers the surface-normal displacement of every design point to be a degree of freedom. This is design space is the richest space the CFD mesh can express, but is actually richer than what the CFD discretisation can resolve: the parametrisation allows odd-even oscillations in the shape which are not adequately recognised by the flow solver. Additional regularisation of the displacement field is required either by implicit smoothing [2] or explicit smoothing [1] of the initial displacement field δx^*,.

The advantage of the NBP is the extremely rich design space that is guaranteed to capture all shape modes that can be analysed on the CFD mesh. The main disadvantage is that the optimal shape exists only as a mesh, and needs to be translated back into a CAD format for further analysis or manufacturing, a process which may lose some of the fine detail of the mesh deformation can't be represented in the CAD description that it is mapped onto.

2.2 CAD-based parametrisation

Another automatic parametrisation can be derived directly from the boundary representation (BRep) of the CAD model. The BRep, in the typical the standardised STEP format, represents the shape in a number of NURBS surfaces. The richest design space this representation can express is spanned by the location and weights of the NURBS control points X_C, which are hence used as the design variables.

The NSPCC approach of Xu et al. [3] allows to impose geometric constraints $c = 0$ such as continuity of tangent or curvature across patch interfaces or box, radius and thickness constraints. The constraint derivatives are evaluated at a set of test-points X_T and assembled in a constraint matrix $\mathbf{C}$ for each constraint equation i and control point k. Using a projected gradient approach, the design space is then in the nullspace of $\mathbf{C}$, the design modes α hence are the N basis vectors of the nullspace and determined by an SVD.

3. Test case

Both parametrisations are applied to an internal turbine cooling channel, the VKI U-Bend [4]. This is a hairpin-shaped channel with a square cross-section and a circular-shaped return.

The flow-field and pressure drop of the simulation on the initial geometry will be validated against the experimental and computational benchmark results of Verstraete et al. [4].

4. Results

Optimisation results will be presented with both parametrisations, comparing the final pressure drop, flow fields and shape variations between the two automatic parametrisations presented here, as well as to optimisation with the 2-D spline-curve parametrisation of Verstraete [5].

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