

A NOVEL IMPLEMENTATION OF COMPUTATIONAL AERODYNAMIC SHAPE OPTIMISATION APPLIED TO A RACE CAR DIFFUSER AND A JET INTAKE DUCT

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ABSTRACT

The development of an automated aerodynamic optimisation algorithm using a novel method of parameterising a computational mesh by employing userdefined control nodes will be presented. The shape boundary movement is coupled to the movement of the novel concept of control nodes via a quasi-1D-linear deformation. Additionally, a discrete third order smoothing step has been integrated to act on the boundary during the mesh movement based on the change in its second derivative. By implementing the discrete boundary smoothing both linear and non-linear shape deformation is achievable dependent on the preference of the user. The domain mesh movement is then coupled to the shape boundary movement via a Delaunay graph mapping. An optimisation algorithm called Modified Cuckoo Search (MCS) is used acting within the prescribed design space defined by the allowed range of control node displacement. In order to obtain the aerodynamic design fitness a finite volume compressible Navier-Stokes solver is utilized. The resulting coupled algorithm is applied to a range of case studies in two dimensional space including the design of a race car diffuser and a subsonic, transonic and supersonic intake.

Key Words: *mesh movement, aerodynamic shape optimization, cuckoo search, shape parameterisation, computational fluid dynamics*

1. Motivation

During the last 30 years, Computational Fluid Dynamics (CFD) has become a very mature field now being the primary tool for aerodynamic design [1]. In light of this, computational aerodynamic shape optimisation has emerged aiming to replace the resource intensive manual optimisation process based on human expertise and intuition.

Despite these advancements, significant challenges for the modelling community remain in the parameterisation approach, the efficient transfer between CAD and CFD systems and improvements in the computationally expensive mesh re-generation process and CFD evaluation during optimisation [2, 1].

Aerodynamic designers have a clear preference towards tools that are intuitive, efficient and allow a wide ranging applicability. This paper presents a novel implementation of computational aerodynamic shape optimisation in which the parameterisation approach makes use of user-defined ‘control nodes’ in the mesh as the method for both defining the geometry movements and as the design parameters for the optimisation process. The ‘control nodes’ are linked to the rest of the discrete shape boundary via a quasi-1D-linear boundary deformation. This is coupled to a ‘discrete boundary smoothing’. The Fast Dynamic Grid Deformation (FDGD) approach [24] has been applied to move the domain mesh and results in a self-contained algorithm formulated to propagate the effect of the ‘control node’ displacement throughout the discrete shape boundary and computational mesh making a mesh regeneration step redundant and allowing a flexible yet small design space. Also, there is no requirement to convert the geometry definition ‘stored’ in the mesh into any other format during the optimisation process.

2. Methodology

2.1. Geometry Shape Parameterisation

The developed approach is a discrete parameterisation acting directly on the boundary mesh. Once the initial computational mesh has been created (which could have originated as a CAD geometry), the geometry is then parameterised by choosing ‘control nodes’ at critical positions defined by the user on the geometry. An important feature of the parameterisation is the dimensionality of the explorable design space which can be adjusted through the number of control nodes and the designers settings. The number and position of these control nodes is crucial in the evolution of the geometry. The total degrees of freedom are defined as $d = \sum_{k=1}^{N_{CN}} f_{cn}$ with f_{CN} being the degrees of freedom on each ‘control node’ [3].

2.2. Mesh Movement

A methodology involving three steps has been defined starting with the displacement of the ‘control nodes’ based on the fitness that has been evaluated by the optimization algorithm. In a second step, the boundary of the geometry is deformed given the ‘control nodes’ displacement. A new scheme was developed to propagate the displacement of the ‘control nodes’ throughout the boundary and was termed ‘discrete boundary smoothing’. Finally, the domain nodes are moved utilizing the FDGD method [5].

The ‘discrete boundary smoothing’ is inspired by the idea of artificial dissipation, a scheme applied to stabilize numerical solutions containing high gradients. The most common JST scheme applies a second and fourth order term for stabilisation. A modified approach applies a term $T\Omega = -(D^1 - D^3)\Omega$ exhibiting a third order and first order biharmonic and harmonic operator of the form $D^3\Omega = \nabla[\lambda\beta^{(3)}\nabla^2]\Omega$ and $D^1\Omega = \lambda\beta^{(1)}\nabla\Omega$ with λ and β being coefficients to scale and sense sharp gradients in the solution field [6]. This idea has been adapted. Let Ω be the discrete boundary so that $T\Omega$ may be discretized for a number of smoothing iterations $i = 2, 3, \dots, N_s$ and yields

$$\Omega^{i+1} = \Omega^i + \beta^i \lambda (\|\nabla^2 \Omega^i\| - \|\nabla^2 \Omega^{i=0}\|) \quad (1)$$

$\|\ \|$ is defining the norm operator in this paper. The smoothing iterations propagate the deformation of a boundary node and its respective change in $\nabla^2\Omega$ throughout the boundary. The first step $i = 1$ is reserved to perform an initial linear deformation step. β is applied to achieve mesh independence and is given as $\beta = \frac{\Delta s_{min}^2}{2}$.

A great advantage of the ‘discrete boundary smoothing’ is its flexible design space definition. This is greatly enhanced through the introduction of the scaling factor λ . In order to allow both linear and non-linear deformation along the same boundary, λ is set to be variable so equation 1 becomes

$$\Omega_j^{i+1} = \Omega_j^i + \beta^i \lambda_j (\|\nabla^2 \Omega_j^i\| - \|\nabla^2 \Omega_j^{i=0}\|) \quad (2)$$

with $j = 1, 2, \dots, N_B$ whereas λ is selected by the user individually for each ‘control node’ and then linearly interpolated for the remaining boundary nodes. For $\lambda = 0$ the smoothing is disabled and only the linear deformation step occurred, for $\lambda > 0$ smoothing is applied resulting in a non-linear deformation. It also allows great local control and shape preservation capabilities when used in conjunction with the range of motion defined per ‘control node’.

2.3. Computational Fluid Dynamics

The applied FLITE CFD system fluid solver is an edge-based, node-centred finite volume discretisation for solution of the compressible Reynolds Averaged Navier-Stokes equations [6]. All cases are fully viscous applying the Spallart-Allmaras turbulence model. In case of the jet intake case, the mass flow was fixed along the engine inlet face.

2.4. Modified Cuckoo Search

Modified Cuckoo Search [4] is an evolutionary algorithm applying the ‘survival of the fittest’ strategy to a given population. Each agent within the population exhibits a fitness value which is defined the objective function as for example Lift to Drag ratio. The population is separated into good and bad agents dictated by the fitness. All good agents are ‘cross-breed’ and the bad agents perform a random walk called Lévy flight in search of an improved agent. The process of replacing and creating eggs continues until a stopping criteria is met.

3. Case Studies

3.1. Intake Duct Optimisation

A common problem in aerodynamic design is the optimisation of an engine intake duct. In this case study a land-based supersonic vehicle has been optimised first for distortion and consequently for pressure recovery and distortion combined. Pressure recovery P_r measures the amount of restored total free stream pressure P_∞ $P_r = P_\infty/P_t$ to allow minimization of pressure losses. Distortion σ provides a measure of standard deviation of the total pressure P_t in relation to the mean total pressure \bar{P}_t across a plane or line of interest using the integral $\sigma = -\int_0^L \frac{|P_t - \bar{P}_t|}{\bar{P}_t L} dl$. Solutions to the fully viscous problem were sought at a range of Mach numbers $Ma = [0.5, 0.8, 1.1, 1.4]$. The applied mesh contains a total of 82868 mesh nodes and 163419 mesh elements including 7 boundary layers using four control nodes with a specified explorable design space of $x_C \in [-0.3, 0.3]$ and $y_C \in [-0.3, 0.3]$ for each control node C . The travel path as well as the fitness are illustrated in Figure 2. The utilized mesh as well as the initial and final pressure field for the case of $Ma = 0.5$ and optimization for Distortion only are visualized in Figure 1.

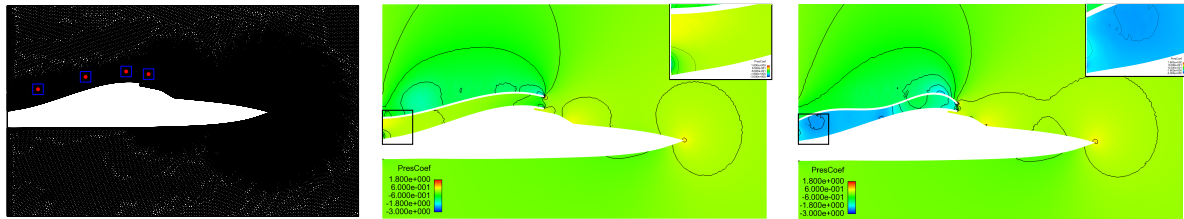


Figure 1: A supersonic vehicle with engine intake duct showing (a) detailed mesh including the control node locations and their range of motion (b) the pressure field of the initial geometry (c) the pressure field of the optimised geometry for Ma 0.5

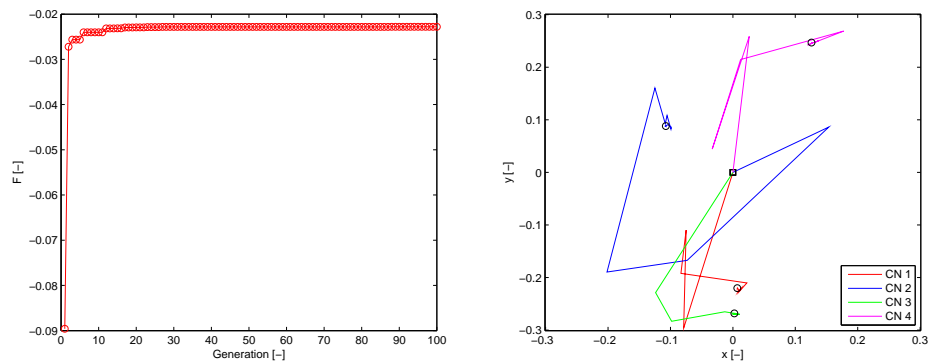


Figure 2: (a) The development of the fitness with increasing generations only considering distortion (b) Control node movements of best egg starting from their initial position \square - start point \circ - end point

3.2. Race Car Diffuser

A 2D diffuser shape of a race car was optimised for down-force to drag ratio. Downforce has been measured as the negative lift according to $F = - \oint p(\mathbf{n} \bullet \mathbf{j}) dB$ and drag was determined by $D = \oint p(\mathbf{n} \bullet \mathbf{i}) dB$ with p is the non-dimensionalized static pressure, \mathbf{n} is the normal unit vector directing into the surface and \mathbf{i} and \mathbf{j} are the parallel and vertical unit vectors in relation to the freestream velocity direction. Up to four control nodes were selected to determine a solution at a Mach number of $Ma = 0.1$ on a mesh with 41324 mesh nodes and 93564 mesh elements.

4. Conclusions

An automated aerodynamic shape optimisation algorithm has been developed making use of the concept of ‘control nodes’ in the mesh. The approach was coupled to the ‘discrete boundary smoothing’ technique allowing both linear and non-linear deformation along the same boundary. The approach is complemented with the FDGD domain mesh movement allowing to cut the mesh regeneration step and reduce the problem inherent in translating geometries from CAD-based geometry definitions to CFD meshes. Modified Cuckoo Search (MCS), an evolutionary optimisation approach, has been implemented to find the global optimum. The resulting algorithm is self-sufficient during the entire optimisation cycle and has been successfully applied to various different aerodynamic problems including a race car and subsonic, transonic and supersonic engine intake duct optimisation. It demonstrated to be robust in terms of the diverse applicability as well as its ease of implementation for all test cases and improvements in the fitness were achieved with a fast convergence in terms of number of generations. It has also demonstrated to be intuitive to use being able to include human expertise and allowing a flexible yet small design space.

For future work, the authors aim to extend the code into 3D. Additionally, ‘dynamic’ control nodes will be tested with the position being an optimisation by itself in order to increase the explorable design space whilst maintaining the rapid convergence. Also, enhancing the optimisation methodology may be exploited by implementing hybrid schemes combining this evolutionary approach with local gradient-based searching.

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