Multidisciplinary Design Optimisation Research Contributions from the AMEDEO Marie Curie Initial Training Network

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This paper reviews the key research activities and results produced during the AMEDEO (Aerospace Multidisciplinarity-Enabling Design Optimisation) Marie Curie Initial Training Network (ITN). AMEDEO brought together optimisation researchers and practitioners from European universities, research organisations, multinationals and SMEs to develop innovative Multidisciplinary Design Optimisation (MDO) methods for the design of energy-efficient aircraft. A range of new results are presented in the areas of: 1) efficient High Performance Computing techniques for MDO, 2) efficient metamodel-based robust MDO frameworks, 3) the application of advanced MDO methods to aircraft engine design and 4) novel applications of MDO to the design of composite aeronautical structures. The future challenges that need to be overcome to embed MDO methods more effectively within commercial design cycles in the aerospace industry are also briefly discussed.

I. Introduction

Aviation is facing a critical challenge of meeting the growing demand for air travel while reducing significantly its impact on the environment. The future development of environment-friendly aircraft complying

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with recent European directives and research objectives (e.g. ACARE 2020 Vision [1]; ACARE Beyond 2020 Vision [2]) will be based on a systematic, model-based process where Multidisciplinary Design Optimisation (MDO) will be a key enabling technology. The recent EU document, *Flightpath 2050: Europe's Vision for Aviation* [3] predicts that by 2050 'multidisciplinary design and development tools are used routinely and co-operatively to support a high level of integrated system design'. The goal of MDO is to coordinate the individual disciplines affecting the design (e.g. aerodynamics, structural mechanics, acoustics, etc…) toward a system design that is optimal as a whole, taking into account the key interactions between disciplines as well as competing objectives. Unlike traditional sequential single discipline design optimisation approaches, MDO aims to avoid the generation of sub-optimal solutions due to poor balancing in the design process, which are too costly to remedy later in the design cycle.

Multidisciplinary analysis and optimisation methods were first used in the US to optimise complex aerospace systems and products [4] and are now a critical aerospace technology within Europe. Several MDO methodologies have been proposed, ranging from relatively straightforward (All-At-Once and Individual Discipline Feasible [5], Multiple-Discipline feasible [6]) to those aiming to partition large optimisation problems into a set of sub-problems where a coordination algorithm drives the sub-problem designs towards an optimal solution for the overall system. Promising decomposition methods include Bi-Level Integrated System Synthesis (BLISS) and its variants, Collaborative Optimisation and Analytical Target Cascading [7-9].

Since computational costs in MDO can be prohibitive, meta-models (also known as surrogate or response surface models) can reduce the computational effort. These replace the computationally expensive simulation model by an approximate one, which is then used in optimisation. Another challenging MDO problem, that is particularly relevant to energy efficient aerospace vehicles, arises in lightweight composite materials where the design variables describing the composite lay-up belong to discrete sets (integer number of plies, discrete set of ply orientations) where shape variables are continuous. Several requirements have to be satisfied, including ply continuity maximisation (also termed composite blending). Several bi-level strategies have been proposed [10] where the top level continuous optimisation is performed at the structure level by fast gradient-based techniques, and a stacking sequence optimisation at the local level is performed by evolutionary algorithms. It is also important to ensure that an aircraft performs consistently as desired [11], so that robust MDO frameworks are required. Some of the important approaches to such problems include metamodel-assisted stochastic optimisation and/or use of polynomial chaos expansions accompanied by advances in High Performance Computing [12]. The reader is referred for further details to the recent review of Martins & Lambe [13], which provides an introduction to MDO for non-specialists together with a description and classification of the most popular MDO architectures.

Over the last four years the AMEDEO (Aerospace Multidisciplinarity-Enabling DEsign Optimisation) Initial Training Network (ITN) [14] has brought together optimisation researchers and practitioners from European universities, research organisations, multinationals and SMEs to create a unique cohort of highly trained early stage researchers to develop innovative MDO methods for the design of energy-efficient aircraft. This paper reviews briefly some of the important scientific achievements of the AMEDEO ITN over the last four years and reflects on the future challenges that need to overcome to embed MDO methods more effectively within commercial design cycles in the aerospace industry.

II. The AMEDEO Research Projects

The AMEDEO network includes four universities (Technische Universität München, Germany (TUM); Technische Universiteit Delft, Netherlands (TUD); Koç University, Turkey (KU), and the University of Leeds, UK, (UoL, the Coordinator of AMEDEO)), five technology-focussed companies operating in the aerospace industry (Rolls Royce PLC, Derby, UK (RR); Airbus, France; Altair, UK; ALE Ltd, Netherlands; SFE GmbH, Germany) and two research and technology organisations (ONERA, France; Von Karman Institute, Belgium (VKI)). The scientific work was organised into four broad Scientific Work Packages (SWPs), which are described briefly below. The research collaborations and Early Stage Researcher (ESR) working on each project are highlighted in brackets after the project title.

SWP1: New computational and parametrisation methods for large-scale MDO problems

This Scientific Work Package addresses the need to improve the computational efficiency of optimisation methods in order that the largest possible design space can be explored in feasible timescales.

Project 1: Efficient High Performance Computing Techniques for Multi-disciplinary Optimisation (ESR: Mohammed Aissa, VKI; RR)

MDO methods require highly efficient computational methods so that several solutions of the governing discipline equations (fluids, solids, heat transfer etc) can be obtained in feasible timescales. This project explored the potential of GPU (Graphical Processing Unit) techniques for large-scale MDO problems since the computational costs associated with CPU-based solvers for MDO methods are currently prohibitive and form a bottleneck in the optimisation process. At the start of the project, an automated optimisation framework called

CADO, using Computational Fluid Dynamics (CFD) and Computational Stress Analysis (CSM), already existed at VKI and proved to be very efficient in compressor and turbine optimisation. The CSM evaluation was very computationally efficient, whereas the CFD evaluation was much slower. This project aimed to exploit the power of GPUs to accelerate the CFD evaluations and thus to accelerate the entire CADO procedure.

During the first half of the project the CADO software was examined in detail, together with the performance of the existing CPU-based CFD solver. Two main problems were identified, the first being slow convergence for complex test cases such as compressor blade cascades and turbine cascades. This was due to the pressure interpolation on the mesh boundaries of the blade surfaces, required to represent flow in the viscous boundary layer. A higher order interpolation and multi-grid acceleration acceleration techniques were used to improve convergence. These changes allowed the number of iterations to be reduced by between a factor of 2 and a factor of 3.

The next step was to port the CPU-based Euler CFD solver to the GPU. The Euler solver was chosen as a less complex alternative to Navier-Stokes solvers which would still enable the performance of the GPU to be tested. The results of this work were published as a VKI Symposium paper in 2014 [15]. The GPU-based Euler solver was then extended to solve the Navier-Stokes equations. At this stage, the GPU code had a speed up of only 1x to 2x.

Following a secondment to the University of Leeds, and following consultations with a PhD student, Nic Delbosc, significant speed ups of up to 28x faster than the CPU-based solver was achieved by optimising the number of user threads (computation units) increasing the active portion of the GPU card [16]. Since the GPU provides a limited number of registers for memory storing the code has been adapted to use less memory and sometimes it was found that it was faster to re-compute some variables than to store them, as is usual for CPU programming. Further speed up was achieved by examining the data exchange with the CPU. This exchange was minimised by running all the solver routines on the GPU, even the less adapted ones like the update of the mesh block interfaces. The GPU interface update does not rely on data stored on the CPU but instead made use of a lookup table sorting the cell face connections throughout the faces that are created only once, at the beginning of the simulation. The final GPU code optimisation considered the use of multi-streaming that allows many GPU functions to be run simultaneously. For a multi-block mesh, the multi-streaming feature allows the computation of all the mesh blocks at the same time. Without multi-streaming all GPU functions run on a standard single stream in a serial way, one function after another. Further details of the GPU RANS solver are available in the parCFD conference paper given in May 2015 in Montreal [17].

The final part of the project focussed on improving the efficiency of the CADO multi-disciplinary optimisation framework.CADO's modular design means that the CFD solver can be changed easily. The GPU-based CFD solver was implemented within the CADO framework and then tested on a transonic compressor cascade, which achieved a 25% reduction in entropy generation 23-times faster than when the CPU-based solver is used within CADO. This work is described in greater detail in a conference paper at the ICNAAM conference in Greece in September 2015 [17].

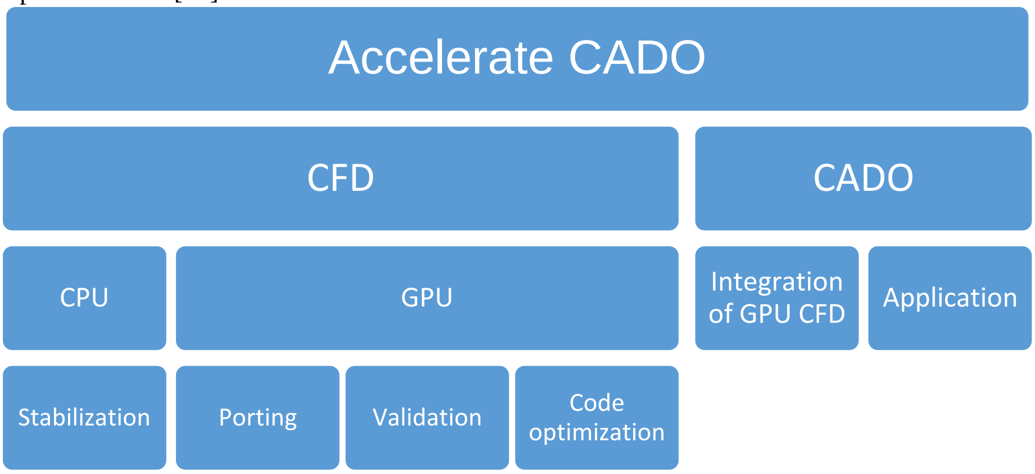


Figure 1.1: Chart of the strategy used to accelerate CADO showing tasks, subtasks and undertaken actions.

The application of the GPU-accelerated CFD codes for the aerodynamic performance evaluation of the annular stator geometry of the TurboLab Stator test case was reported at the 11th ASMO-UK/ISSMO/NOED2016 conference in Munich [17]. The TurboLab is a low Mach number compressor stator from the Technical University Berlin which is used to turn the inlet swirling flow into an axial outflow with a minimal total pressure loss. The stator was parametrized using common turbomachinery blade parameters such as chord length, chordwise blade metal angle distributions and thickness distributions on several spanwise blade sections. Lean and sweep are applied as three dimensional design features. The goal of the optimisation was to minimise the pressure loss and improve the axial outflow. 21 design variables were used for the optimisation namely: 9 for the metal angle distribution for the camberline, 2 for the thickness distribution, 6 for lean and sweep and 4 for the hub contouring.

The core components of the optimisation system were the multi-objective Differential Evolution algorithm, a database, several metamodels and a high fidelity evaluation chain. The evaluation chain comprised a fully automatic geometry and CAD generation, an automatic meshing and a high-fidelity performance evaluation using CFD. CFD evaluation was carried out using two solvers: FIME[TM] (http://www.numeca.com/product/fineturbo) a commercial RANS solver from Numeca with explicit time stepping and an in-house CFD solver with GPU acceleration and implicit time-stepping. The GPU accelerated steady RANS solver followed a special discretization based on Finite Volumes and convective fluxes were calculated using a Roe upwind approximation while second order accuracy was achieved through the MUSCL approach. Viscous fluxes were approximated following a central discretization scheme and the source term contained a contribution from the Spalart-Allmaras (SA) one-equation turbulence model. Time integration was performed using a 3 stages implicit Runge-Kutta first order scheme. The commercial solver has a similar space discretization with a low Mach number preconditioning of the right hand side. The time integration differs also since FINE[TM] uses the explicit time stepping multistage Runge-Kutta scheme. For both solvers total quantities are imposed at the inlet along with the flow direction and the mass flow is imposed at the outlet. The total pressure loss is calculated in terms of the Loss = $(p_{01}-p_{02})/(p_{01}-p_1)$. The area averaged axial deviation is also provided.

The first objective of the optimisation was to reduce the total pressure loss and the second objective was to reduce the deviation of the outflow as the integral of the whirl angle squared. Optimisation was carried out around 3 operating points with whirl angles of -47, -42 and -37 degrees. The first operating point with the nominal whirl angle had a weight of 0.5 for the optimisation objectives while both other operating points each had a weight of 0.25. The constraints were of two types: CFD and manufacturing constraints. The CFD constraint concerned the mass flow of the full annulus, which had to be 9 kg/s with a tolerance of 0.1kg/s, and this was imposed as an outlet boundary condition. The manufacturing constraint took the form of a geometry check which fixed the number of blades, axial chord length and requirements on the blade thickness. The blade was required to be thick enough to have sufficient space for 2 cylinders of material fixed onto the hub and a shroud with a radius of 5mm and 20mm depth. The distance between the two holes was fixed at 60mm. Another constraint concerned the hub contouring for which the radius change was limited by -5mm and +10mm. This limit was introduced in the hub parametrisation restricting the vertical translation of the control points.

The objective space was populated with 198 CFD evaluations. All plotted designs satisfied both the aerodynamic and manufacturing constraints. Different points from the Pareto Front dominated the baseline designs. A trade-off had to be made for the selection of a design from the Pareto front but the design that was non-dominated by any other design achieved relatively small improvements of 0.07% and 6% in total pressure drop and outflow angle respectively.

Publications [15-23] were produced from this project.

Project 2: Multidisciplinary node-based shape optimisation for composite wing preliminary design (ESR: Daniel Baumgärtner, ALE; TUM, ONERA)

Designing a wing to reduce the fuel consumption of an aircraft implies reducing drag while increasing structural performance. The latter typically corresponds to a minimization of the structural weight which in modern aircraft gives rise to the use of lightweight composite components. Lightweight composite wing designs, however, are susceptible to dynamic aeroelastic phenomena (e.g. flutter) which significantly influence their drag characteristics. Therefore, to effectively minimize the fuel consumption, an optimal trade-off between structural and aerodynamic performance must be found. This can be accomplished by means of a multidisciplinary shape optimisation approach in general or an aeroelastic shape optimisation approach in particular.

This project focusses on development of a new, flexible shape optimisation method for aeroelastic optimisation in the early phase of wing design. The aim is to provide more design freedom and greater optimisation potential than existing formulations. It used a consistent node-based formulation in which the optimisation directly operates on the numerical model rather than using a restrictive parametrisation approach. The node-based approach used is the Vertex Morphing Method (WMM) originally developed at TUM. Computational aerodynamic shape optimisation has become a standard process in the preliminary design of an aircraft's external shape, and is driven by the need for a trade-off between exploring the design space with a minimum number of constraints so as not to restrict the range of potential improvements, while introducing as much design knowledge as possible to avoid costly modifications later in the design process. This project developed the VMM for wing preliminary design in particular and for aircraft preliminary design in general.

The project began by testing whether the VMM can optimise a coupled, multi-disciplinary problem. An efficient coupled adjoint sensitivity analysis was derived and tested on a flexible cylinder shell immersed in a laminar incompressible fluid flow, Figure 2.1. The goal was to optimise the shape of the cylinder such that it generates maximum lift while minimising the drag. This showed that the optimal shape for this problem is a modified 'cylinder' which in its deformed shape turns into an airfoil, Figure 2.2.

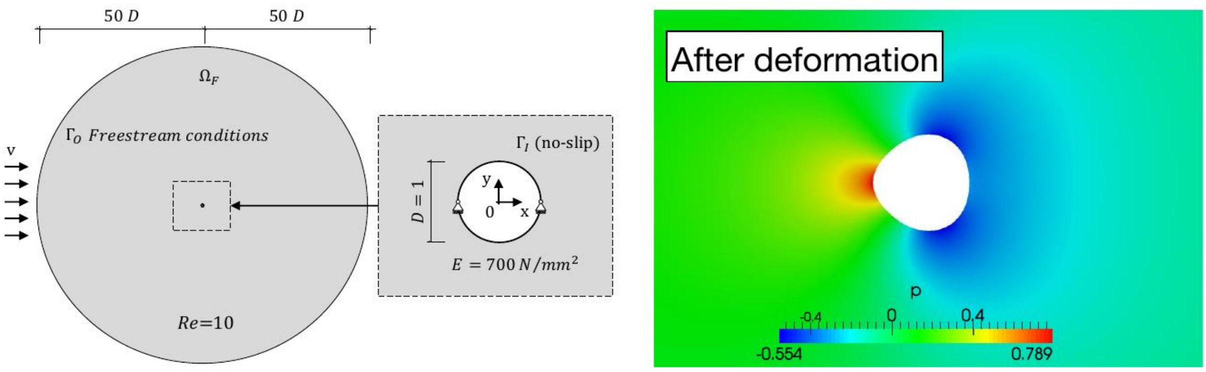


Figure 2.1: Node-based multidisciplinary shape optimisation– A generic test case

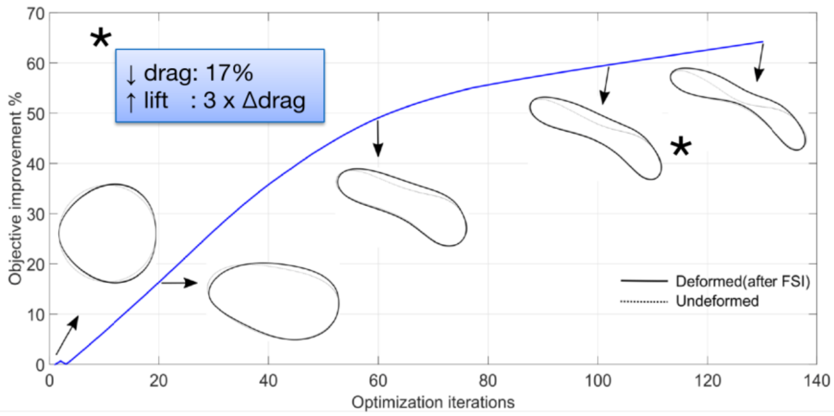


Figure 2.2: Shape evolution of flexible cylinder in laminar fluid flow during node-based multidisciplinary shape optimisation

This produced a new, more efficient and flexible but less accurate and more application dependent way of computing coupled sensitivities. It did, however, demonstrate that VMM showed good potential for both single disciplinary (aerodynamic) and multi-disciplinary (aeroelastic) problems.

The next stage was to apply the VMM to aircraft preliminary design. The first problem of interest was the aerodynamic shape optimization of a forward-swept wing aircraft. This required the development of a new algorithm for constrained optimisation and an extension of the surface sensitivity analysis. The new optimisation process was applied to find optimal shapes for the complete aircraft, including the wing, the fuselage and the attachment area of the wing to the fuselage. Generally, the optimal solutions represented 5-10% improvements compared to the previous state-of-the-art solutions. Figure 2.3 and Figure .4 show the design improvement for the wing and the inboard area around the wing attachment.

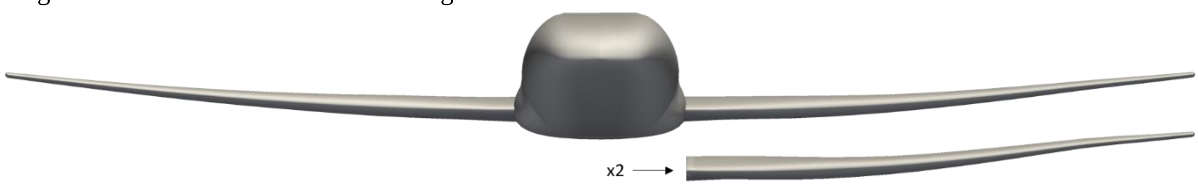


Figure 2.3: Comparison of baseline (left) and optimized (right) wing shape

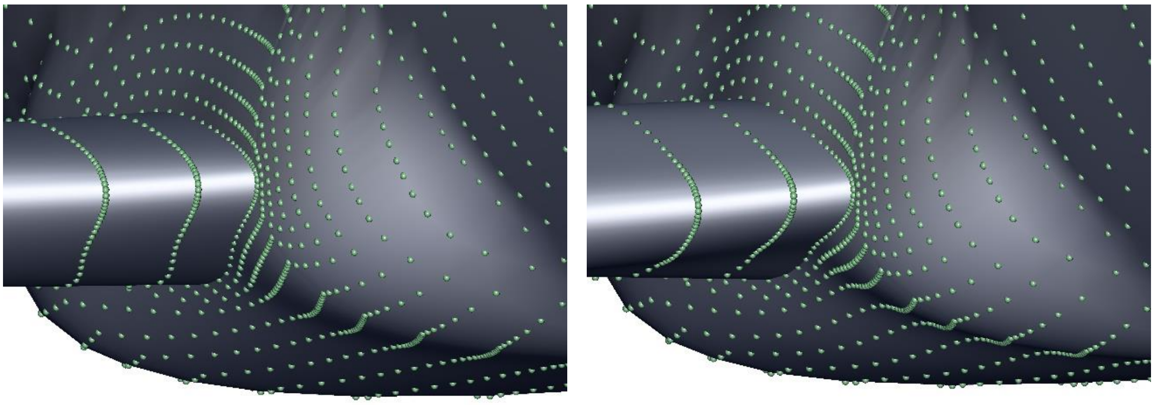


Figure 2.4: Inboard design before (left) and after optimization (right, design changes were scaled by x5). Points indicate surface nodes controlled during the optimization process.

Figure 2.5 shows the optimized surface pressure distribution. Significantly improved pressure gradients can be observed in particular inboard (reduced shocks). Overall, these results demonstrated that the VMM is a powerful alternative to traditional approaches in preliminary design.

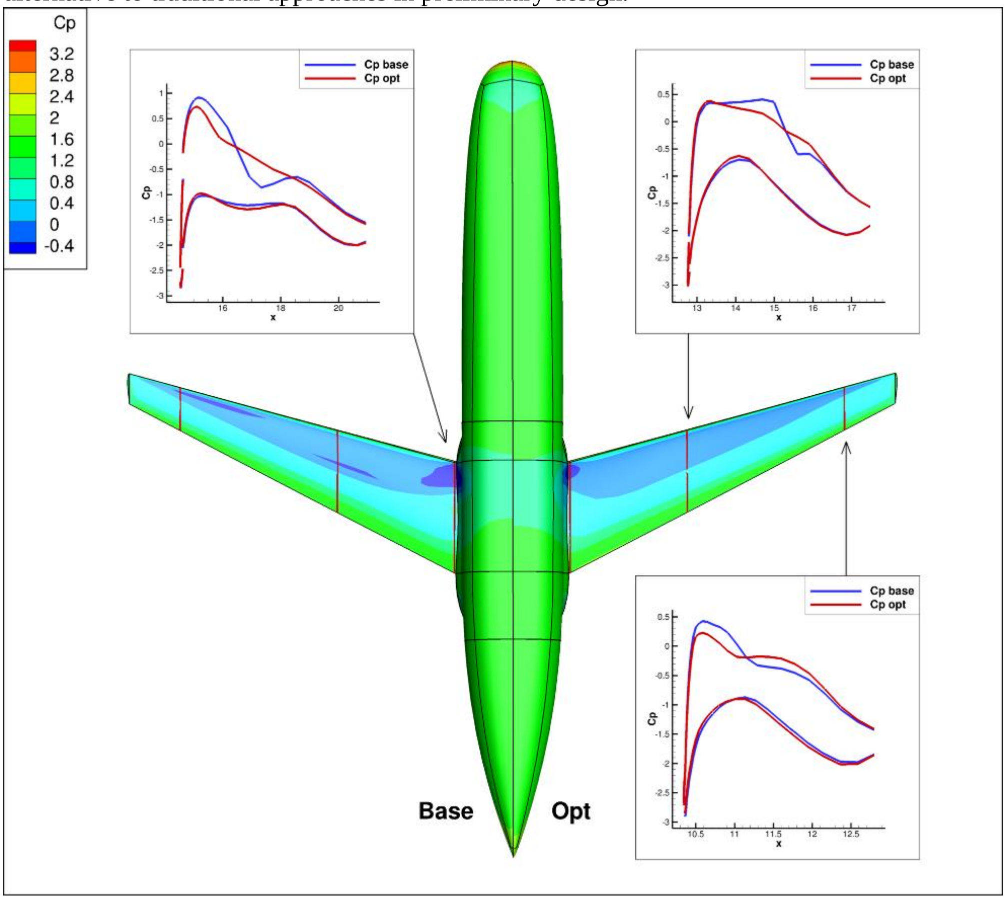


Figure 2.5: Pressure distribution at baseline (left) and optimized (right) design. Results correspond to some 21% improved drag at constant lift and constrained wing thickness.

In addition to being published in papers [24-27], all developments regarding the VMM were implemented in the open source multi-physics software, Kratos Multiphysics [28]. Any interested reader is able to test the process for their own applications.

The VMM-based optimisation method was then used to optimise the ONERA M6 benchmark wing at cruise conditions, where a flexible structure is considered. Correspondingly, the wing was modelled as a flexible shell whereas coupled sensitivities were neglected but a full fluid-structure interaction analysis was performed in every optimisation step. The optimised wing finally performed roughly 30% better than the baseline design, see Figures 2.6 and 2.7.

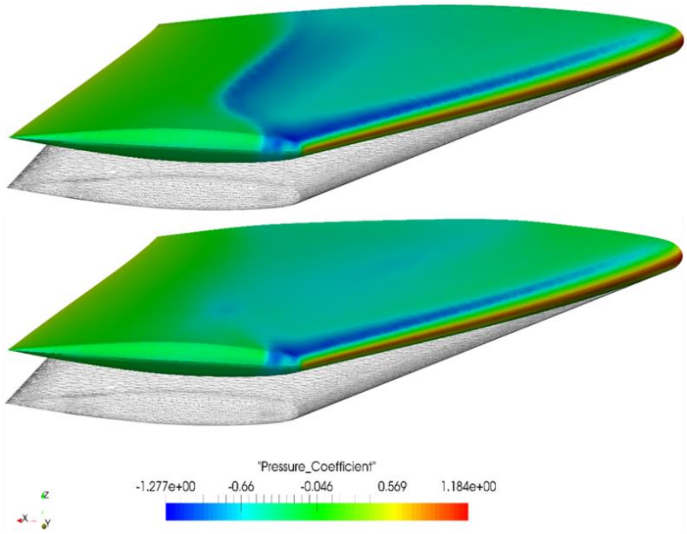


Figure 2.6: Initial (top) and optimized (bottom) pressure distribution at a flexible ONERA M6 wing. Black indicates the jig-shape. Results correspond to some 30% improved drag at constrained lift and thickness each in the deflected state.

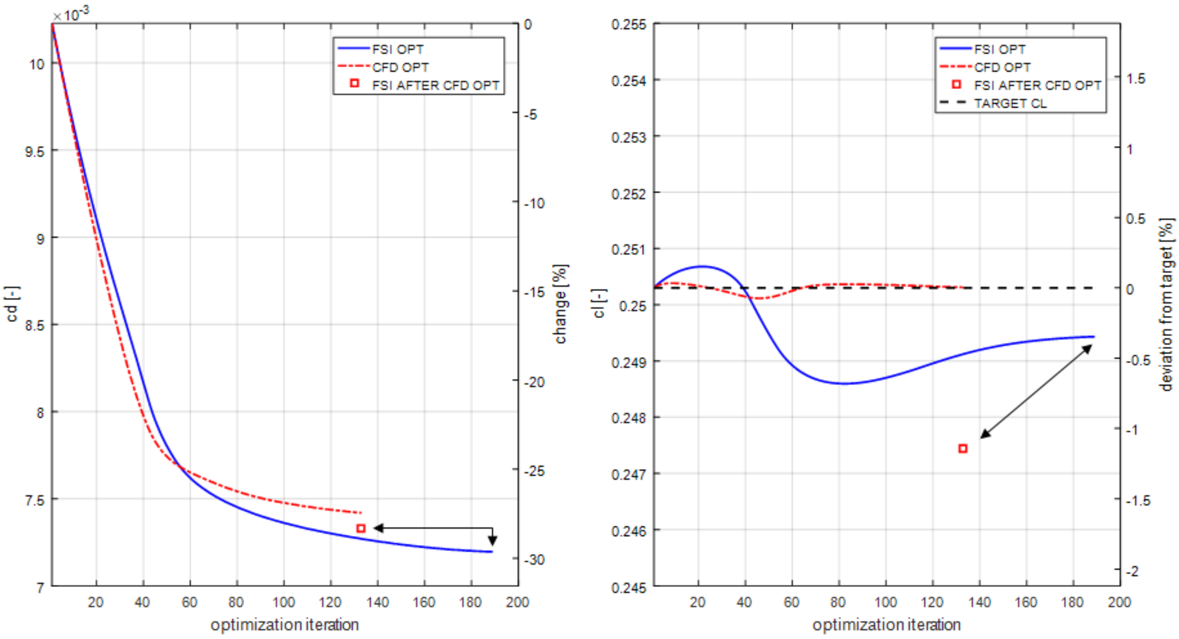


Figure 2.7: Comparison of a single disciplinary (CFD) and multidisciplinary (aeroelastic / FSI) node-based shape optimisation of the ONERA M6. Left diagram shows the drag coefficient as objective function and the right diagram shows the lift coefficient as constraint. Note that the FSI optimisation performs better in both cases.

In addition, the results demonstrated that this simplified aeroelastic optimisation without coupled sensitivities already outperforms a pure single disciplinary aerodynamic optimisation. Results regarding the node-based aeroelastic shape optimisation were published in [29]. This was the first published node-based aeroelastic (multi-disciplinary) shape optimisation of a wing.

Project 3: A Unified Multidisciplinary Shape Optimisation Methodology for Composite Aircraft Structures (ESR: Anna Arsenyeva, TUM; ALE, TUD, SFE)

The general goal in aviation is that fuel efficiency should increase by 1.5% per year, and this target has stimulated lots of effort to reduce the weight of aircraft. This project focusses on the multidisciplinary optimisation of composite aircraft structures, and the interplay between composite wing structural and aerodynamic optimisations. These consider shape and topology optimisation of the wing geometry and optimisation of the composite material structure. This means, for example, that the number of wing structure components (ribs, spars, etc.), as well as the number and orientation of the laminated composite layers can be changed during the optimisation, which leads to a mixed discrete-continuous design variables space. This requires special approaches to be employed for the optimisation.

The initial objectives of the project were as follows:

- To create an adaptive wing box model for an arbitrary outer shell
- To develop an implicit geometry parameterisation for topology/shape optimisation of internal wing box components
- To include steered fibre composite materials optimisation into wing box design
- Optimisation of the developed parametric wing model

A flexible wingbox model which can be easily adapted to a given outer wing shell was developed with an implicit geometry parametrisation for the further subcomponent optimisations, easy automatic sub-modelling and load extraction for different wing box components. A steered-fibre composite materials optimisation for designing optimal composite wing box components was also developed.

The wing outer shell was created by using a set of NACA-type airfoils, which enable automatic changes of the global wing architecture by specific positioning of 2D airfoils in the 3D space. This project focussed on the internal structure optimisation, for the given wing outer shape. Parameters of the wing box such as number and location of ribs/spars/stringers, their shape and thickness, which may linearly vary along the length for skin and spars components are considered as the optimisation variables, see Figure 3.1.

Several types of loads are considered, including acceleration load, engine loads and aero loads. The aero loads can be calculated using ANSYS Fluent CFD or simplified XFOIL 2D code. The flow simulation is calculated for a fixed external shape and obtained pressure distribution is mapped automatically to existing structural model in ANSYS Mechanical. (Figure 3.2).

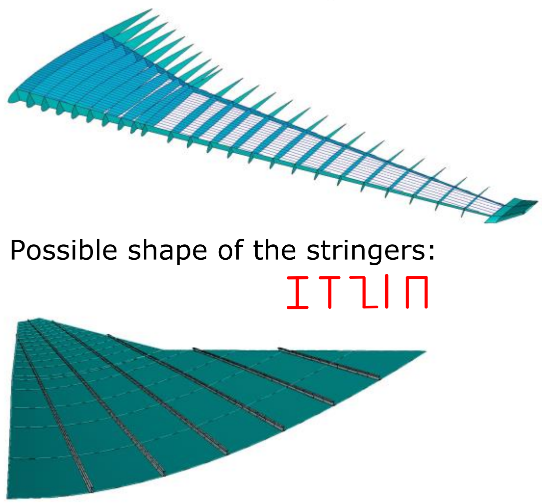
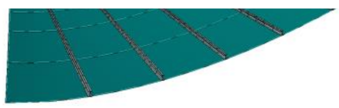


Figure 3.1: Ribs and spars definition (a), stringer components and its possible shape (b)



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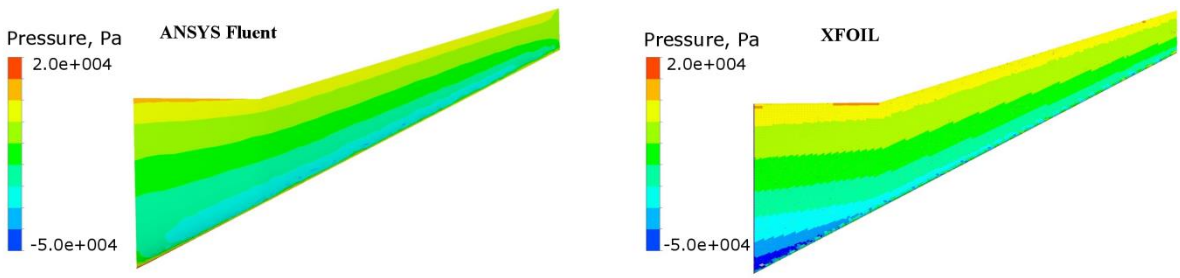

Figure 3.2: Pressure distribution for a wing obtained by ANSYS Fluent (left), XFOIL software (right).

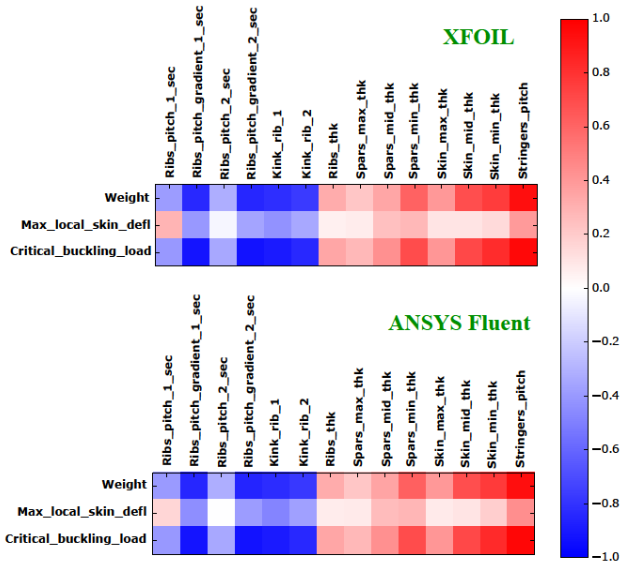

Figure 3.3: The resulting Spearman coefficient matrices: 300 designs

Spearman coefficient matrices for correlations between design parameters and resultants were obtained and good agreement with known wingbox design dependencies was achieved. Two numerical experiments, generated using Latin-Hypercube sampling within the coarse parameters, are performed for the models with XFOIL and ANSYS FLUENT. The resulting Spearman coefficient matrices for correlations between responses and the coarse design parameters are shown in Figure 3.3.

As can be seen XFOIL results give very similar correlations, compared to the results obtained for Fluent, meaning that it can at least capture general trends accurately. Considering that the XFOIL approach is much faster, compared to full CFD analysis, it can be used for the preliminary global optimization studies.

A two-stage approach for the wingbox parametrisation was used: at first, the spacing density of the ribs is described in each wing section as a linear function with two parameters. This helps to identify approximate ribs layout very fast (only 4 design parameters). At the second stage, the obtained rib positions can be varied, also allowing changing the rib angle individually, in order to refine to an optimal layout. The objective is to reduce the wing weight with constraints on maximum local skin deflection between each pair of ribs and also wing tip displacement, Figure 3.4.

For detailed optimisation of the ribs design, the special generic pattern model in the parametric space was created using the SFE CONCEPT software. Figure 3.5 shows an example of rib parametrisation and automatic connection to an external mesh. This pattern is capable of representing simplified topological optimal results for different ribs and can be automatically mapped to different rib shapes.

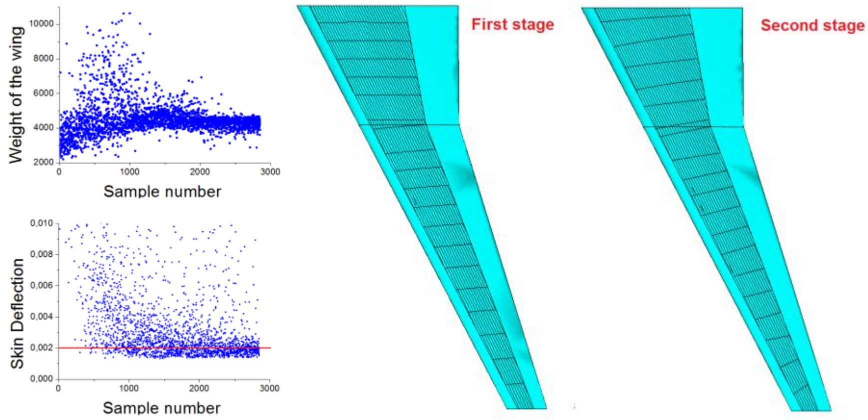

Figure 3.4. Convergence for skin deflection constraint (left), coarse model (middle) and refined optimization (right)

Another rib stiffeners parametrisation approach, well-suited for direct search methods (e.g. evolutionary algorithms), was proposed and implemented. It enabled topology-like shape optimisation to be performed, and to include various constraints within the optimisation (e.g. displacements, stresses, buckling, etc.), which is not possible in standard density-based topology optimisation. For similar optimisation tasks (stiffness maximization) this approach gives similar results to the topology optimisation, which was shown with various rib shape optimisations.

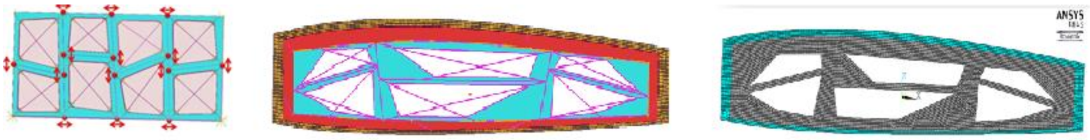

Figure 3.5: Generic parametric sub-model (left) SFE mapped geometry (middle) and mesh coupling with external mesh (right)

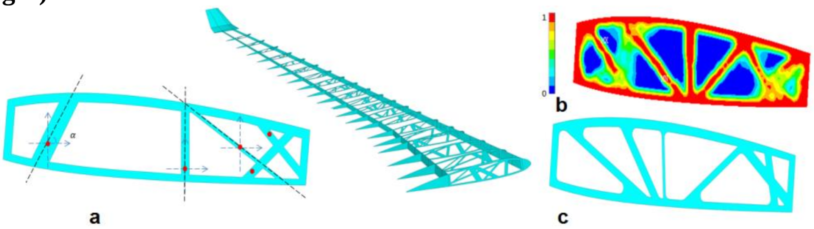

Figure 3.6: Example of Point-Angle-Width (a), Topology optimal result (b) and optimal result obtained by shape optimisation(c)

A new approach for fibre-steered composite optimisation was developed and evaluated. Here, the Maximum curvature constraint (MFCC) was added to the optimisation process and results were presented in a conference paper, where the method showed great capabilities of finding optimal fibre path. As an example, a 4-layer steered-fibre fuselage section with a window was optimised for higher buckling loads, see Figure 3.7.

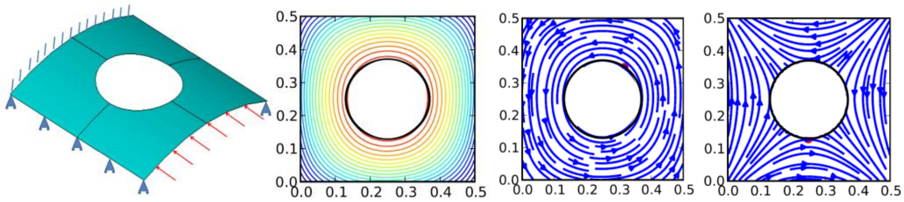

Figure 3.7: Problem example (left), optimal iso-lines obtained by 9 parameters (middle), optimal fibres placement for $[\pm\alpha]_s$ laminate with MFCC = 10 m^{-1} at each layer of laminate (right)

The method was applied successfully to fibre-steered rib optimisation. Results are compared with the topology optimisation in Figure 3.8.

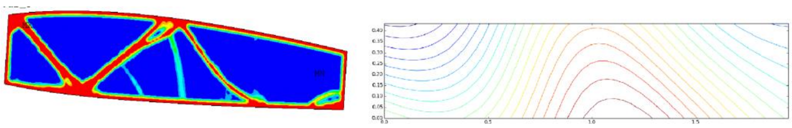

Figure 3.8: Results for two rib designs: topology optimisation (a), surface's iso-contour lines

Publications [30] and [31] resulted from this project. A journal paper on composite modelling and composite optimisation is now being prepared.

SWP2: Efficient metamodel-based robust MDO frameworks

Lightweight composite structures are making an increasingly important contribution to energy-efficient aircraft. This Scientific Work Package provides new approaches to complex composite optimisation problems where the design variables describing the composite lay-up belong to discrete sets (integer number of plies, discrete set of ply orientations) whereas shape variables are continuous.

<u>Project 4: Cohesive Zone Modelling of Thermo-Mechanical Delamination Propagation and MDO in the framework of Isogeometric analysis (ESR: Sam Duckitt, ALE; TUD, TUM, RR)</u>

A revised project description was accepted in February 2014; the new project aimed to model propagation of delamination in composite structures using Isogeometric Analysis (IGA), focussing on the optimal shape design of a composite fan blade subject to high velocity impact. It combines aspects of composite failure and isogeometric analysis within a complex MDO problem. The first objective was to link the SOPHY (SOFT+HYDRA+PADRAM) design system at Rolls Royce with LS-Dyna, as a means of including impact analysis and enable validation of the current design rules used at Rolls Royce for impact which could potentially lead to a lighter weight fan blade. The second objective was to ultilize the benefits of IGA, directly comparing the results with those obtained from objective 1. IGA can not only provide increased accuracy with fewer degrees of freedom, it has the potential to dramatically reduce the time spent setting up a suitable computational mesh, which can account for up to 80% of the analysis time in industrial problems.

The majority of the first 2 years of the project were spent gaining experience with Isogeometric Analysis (IGA). A library of NURBS scripts were written in Matlab and used to implement a new parameterisation method within an isogeometric cohesive element for the simulation of composite failure. A NURBS model defined the blade surface into 4 separate surfaces: 1 each for the pressure and suction sides, and 1 each for the leading and trailing edges. This technique enables the user to define the number of control points of each surface as a means of controlling the number of elements in the 3D IGA model. After ensuring the surfaces have matching parametrisations, a separate routine was created to automatically insert interior control points to create a valid solid NURBS model suitable for IGA. This process has been automated to also include the generation of LS-Dyna input files so that it can be used in an optimisation framework.

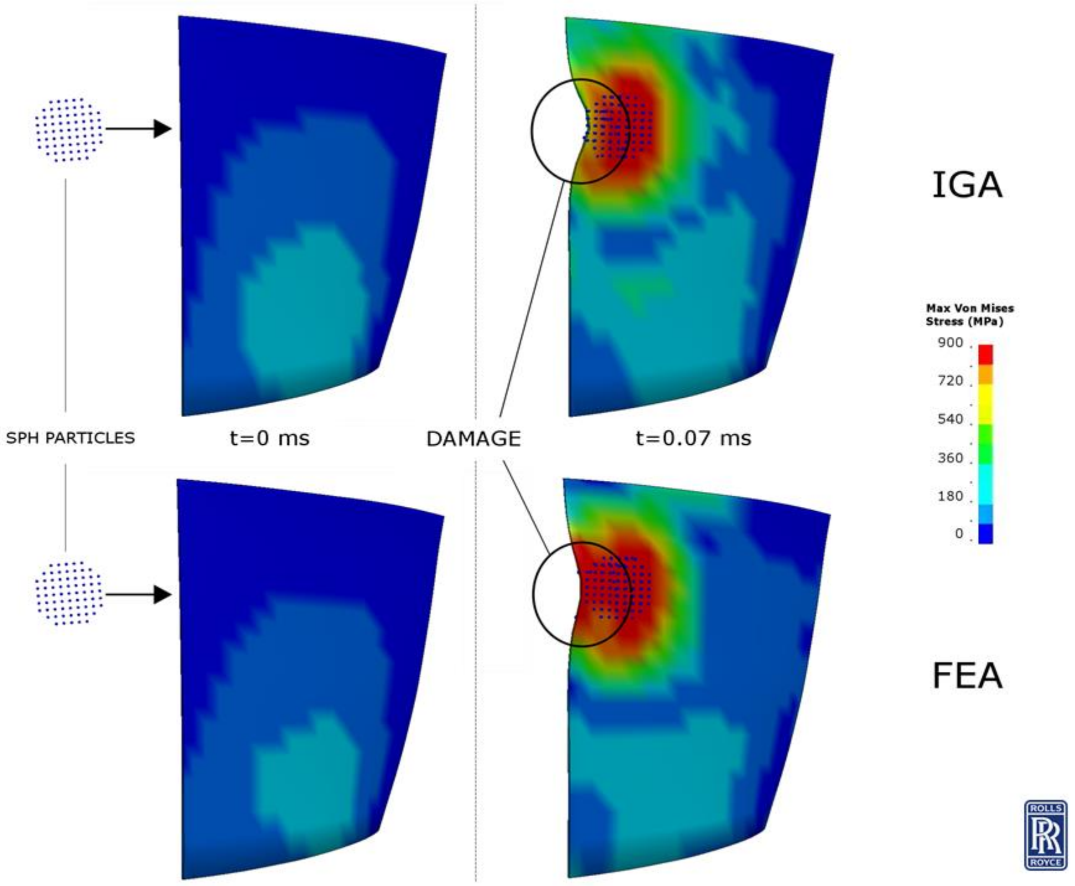

Figure 4.1: Maximum Von Mises Stress Plots for IGA (top) and FEA (bottom), (a) stress initialization before impact, (b) highest peak stresses after impact at t=0.07ms.

An investigation was performed to validate the IGA approach against finite elements. Initial results were obtained for a centrifugally loaded blade before moving on to impact simulations achieved using the Smoothed Particle Hydrodynamics (SPH) method. Bird strike simulations were performed on the NASA rotor 37 geometry and this was the first time that solid NURBS elements had been used to simulate high velocity impact. The results were presented at the 2016 ASME Turbo Expo conference and a paper was included in the proceeding (GT2016-567464) [32]. Figure 4.1 shows a comparison between the maximum Von Mises stress distributions obtained from IGA and finite element bird strike simulations. The method is now being validated against experimental impact data which has become available at Rolls-Royce. It is planned to re-run this approach and validate against experimental data. With this addition there are plans to publish a subsequent journal paper on the subject.

A detailed investigation into the use of NURBS control points as design variables to facilitate an IGA centred approach to optimisation was also carried out. This resulted in a more efficient approach which can dramatically reduce the number of design variables. The concept is to use a smaller set of control points to approximate the true geometry. These control points are then perturbed during the optimisation which generates a displacement field. This displacement field can then be mapped onto the true geometry to create new designs with a much smaller set of design variables hence speeding up the optimisation. This approach was implemented successfully for a simple 2D airfoil and a more complex 3D implementation on a stator blade surface. This approach is illustrated in Figure 4.2(a) for the simple 2D airfoil example.

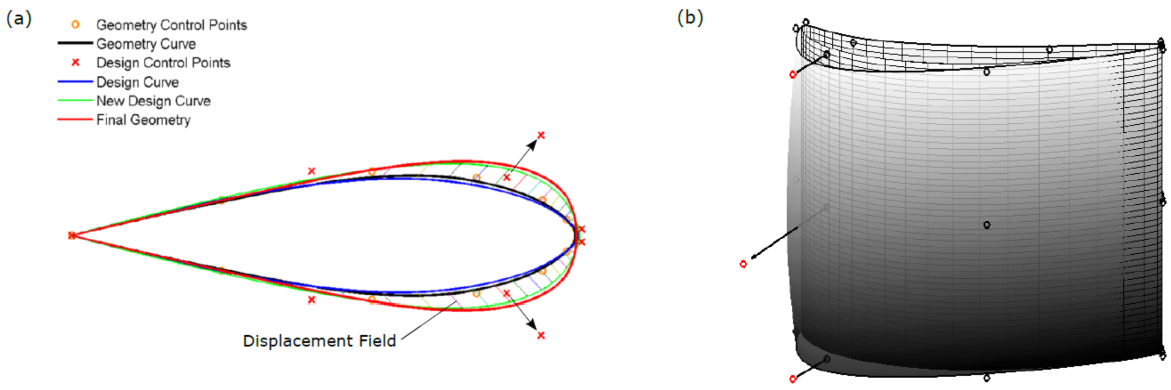

Figure 4.2: (a) 2D illustration of a B-spline parametrisation method and (b) perturbing a stator blade design by moving 3 control points (red).

The original airfoil geometry (black) is represented by 14 control points. This is then approximated by the blue curve which is defined with just 8 control points. Two of these 'design' control points are perturbed as indicated which generates the new green airfoil curve and an associated displacement field. This displacement field is then mapped and added to the original geometry which produces the final geometry (red). It can be seen that that this is a far more efficient approach to generate new designs as opposed to using all of the original geometry control points as design variables.

Figure 4.2(b) demonstrates the 3D implementation on a stator blade surface and shows the design changes which can be achieved by moving 3 of the control points (red) close to the leading edge of the blade. This approach has now been implemented to work with the Rolls-Royce SOPHY system.

The final part of the revised project was to combine the new B-spline parametrisation method together with the IGA approach for impact analysis into an automated multi-disciplinary design optimisation framework. Work was also carried out to automate the generation of finite element models from PADRAM. A routine was written to automatically create LS-Dyna input files for solid finite element models. Having both IGA and finite element optimisation frameworks, the methods can be compared to see which is most efficient in terms of computational time. This project produced publications [32-34].

Project 5: Aeroelastic Tailoring of Composite Wings using Mixed Fidelity Modelling (ESR: Kristofer Jovanov, TUD; ONERA, ALE)

The overarching aim of this project was to combine multi-fidelity models for design of composite wings in order to reduce overall computation time. Industry standard low-fidelity models used in the conceptual design stages neglect important physical effects that typically emerge in the transonic flight regime. With the inception of high-fidelity models in the conceptual design stages an optimal design tailored for transonic flight will outperform the design generated by the use of low-fidelity models. This will improve the aerodynamic efficiency, reduce the overall weight and consequently reduce the fuel emissions.

Generating responses and gradients for aero-structural optimisation is very computationally intensive. This project investigated if it is possible to alleviate the computational burden for high-fidelity aero-structural analysis and sensitivity analysis in a gradient-based optimisation framework by introducing low-fidelity aerodynamic models for the aeroelastic responses. The idea is to minimise the number of high-fidelity function evaluations and consequently reduce the overall computing time.

The performance of several aerodynamic models has been investigated. Three levels of fidelity were established, the lowest being a Vortex Lattice Model (VLM), which solves a set of linear potential equations, the second a panel code PANAIR A352 solving similar linear equations but on an arbitrary 3D wing model, and the third, highest level of fidelity where the high fidelity Euler equations were solved using the open source CFD code SU^2 and the in-house Computational Fluid Dynamics tool from ONERA, elsA. The VLM code solves the linear potential flow equations and is thus limited to the subsonic flow regime. Shock-induced flow in the transonic regime was modelled by the solution of the Euler equations. The vortex lattice code was modified to enable an explicit formulation of the aerodynamic stiffness matrix, which were then used in the solution of the nonlinear aeroelastic problems for their efficient convergence abilities. The structural governing equations are solved using the finite element method (FEM) and the wing is discretized by a combination of shell, shear and bar elements with multipoint constraint elements, see Figure 5.1.

Figure 5.1: Structured CFD model (left) and a structural Nastran-based model (right) of an ONERA M6 wing. Courtesy of ONERA.

Several techniques for solving the nonlinear aeroelastic equations together have been investigated. A nonlinear block Gauss-Seidel (NLBGS) method was implemented and augmented with a successive over-relaxation (SOR) scheme. The performance of the NLBGS method was enhanced by replacing the stationary relaxation factor with a dynamic relaxation factor, i.e. a relaxation factor that is updated for each iteration. This project used Aitken's delta method, which required only the displacement increments of previous iterations to update the relaxation factor.

The NLBGS scheme is one of the most popular methods for solving the high-fidelity steady-state aeroelastic problem. A major reason for this is its ability to preserve software modularity, i.e. it allows for established single-disciplinary solvers to be used in order to solve the coupled aeroelastic problem, however its performance is highly dependent on the value of the relaxation factor and has even been shown to diverge for problems with a strong fluid-structure coupling.

To further increase the convergence performance of the aeroelastic solver, Newton schemes were considered. These have second-order convergence rates and require inter-disciplinary gradient terms to form the aeroelastic Jacobian. These terms are not easy to acquire and can be prohibitively expensive for high-fidelity models. A multi-fidelity Newton (or quasi-Newton) scheme was therefore implemented where the low-fidelity aerodynamic model is used to form the interdisciplinary gradient terms. This methodology significantly increased the performance of the Newton schemes.

As mentioned above, the aeroelastic analysis is not sufficient for a gradient-based optimisation framework. Sensitivities need to be evaluated for the gradient-based optimizer to work properly. The methodology of computing gradients is analogous to the solution procedure of the static aeroelastic problem. The implementation costs are therefore minimal. A coupled link is established between the aerodynamic gradients in elsA and the structural gradients in Nastran. The sensitivities are then coupled using Matlab to solve the aero-structural sensitivity equations. Again, low-fidelity gradients from the VLM code are used to accelerate the solution of the high-fidelity sensitivity equations.

The goal of this project is to reduce the computational effort of high-fidelity aero-structural optimisation and make it an affordable instrument in the conceptual design stages. Industry standard low-fidelity models used in the conceptual design stages neglect important physical effects that typically emerge in the transonic flight regime. With the inception of high-fidelity models in the conceptual design stages an optimal design tailored for transonic flight will outperform the design generated by the use of low-fidelity models. This will improve the aerodynamic efficiency, reduce the overall weight and consequently reduce the fuel emissions.

At the end of this project, weight reduction optimisation was performed on a simplistic ONERA M6 wing model, where the objective was to reduce the weight during trimmed flight while not violating stress constraints. The design variables were the thicknesses of the structural members. This provides the groundwork for a later optimisation on a more realistic case, such as the NASA Common Research Model (CRM).
This project produced publications [35-38].

Project 6: Conceptual Multidisciplinary Aircraft Design using Aero-Structural Adjoint-based Method (ESR: A. Viti, ONERA; Airbus, ICL)

Airlines and aircraft manufacturers face the key challenge of keeping fuel consumption down, while achieving ever better performance. Fuel consumption can be reduced through improvements in engine efficiency, aerodynamic performance, lightweight materials, etc. however these cannot be considered in isolation. This project addresses one of the most important trade-offs: aerodynamic vs structural performance in the preliminary design phase and develops an adjoint-based optimisation method which can identify the best aero-structural trade-off for new aircraft configurations.

A forward swept wing (FSW) has been analysed in detail. The geometry was generated by using an airfoil for the wing-fuselage interaction and the Euler equations were solved for the flow analyses, using an in-house ONERA code. A structural analysis code was also developed in order to determine the stresses on the internal structure wing elements. These were then coupled successfully into a fluid-structure coupled analysis which was tested for shock-free and fully-shocked cruise conditions. A comprehensive investigation on the coupling was carried out by analysing the effect of all the different parameters that play a role in the interaction analysis. A shock-free and a fully shocked cruise condition have been taken into consideration and a range of parametrisations were tested in order to provide the fastest and most reliable optimisation for the two cruise conditions. This clearly demonstrated the need for aero-elastic coupling, which is much more important for FSWs compared to classical wings.

The wing-body geometry was then generated and a comparison between an isolated wing case and a wing-body configuration performed. This demonstrated the benefits of having a full wing-body configuration even in preliminary design. In parallel, the in-house ONERA code InAirSsi was developed to handle the unconventional FSW configuration and the structure of the wing was then optimized for a typical certification load. The project then focussed on the wing-body configuration, on which substantial progress was made. The main achievements with the wing-body configuration were:

Aerodynamic and aero-elastic optimisation comparison for the wing-body configuration. A rigid aerodynamic optimisation of the flight shape is not consistent since this would mean that whenever the load changes during the optimisation, the structure is not updated to achieve aero-elastic equilibrium. This inconsistency would be particularly serious for a Forward Swept Architecture, although it is less important for a classical wing, see Figure 6.1.

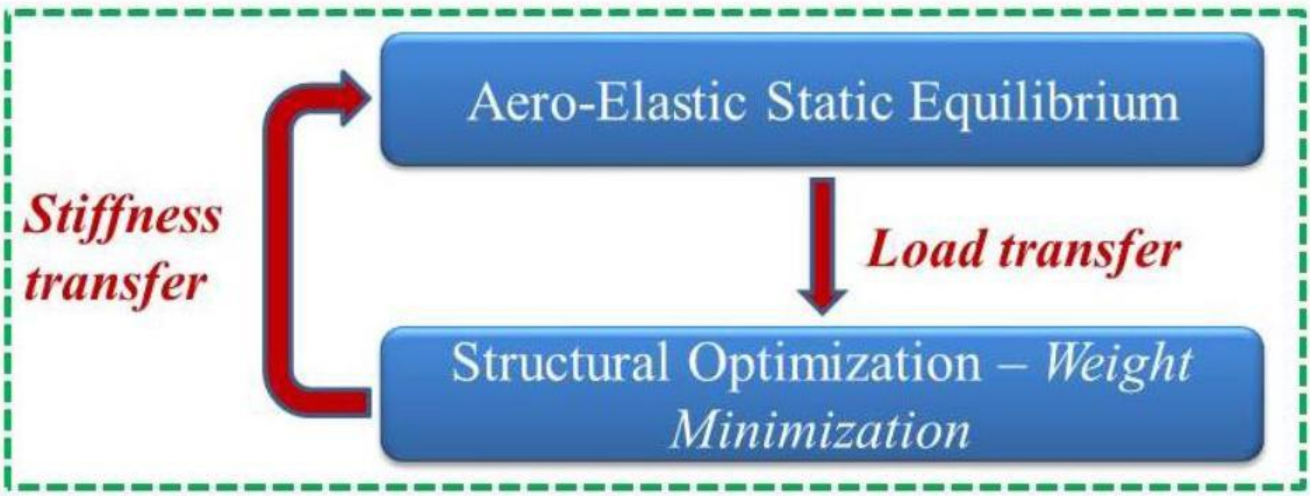

Figure 6.1: Structural optimisation at the aero-elastic equilibrium.

Development of consistent structural optimisation for the wing structure. Once the structural optimisation has been validated, a procedure for consistent structural optimisation was developed. The aerodynamic wing load was computed over time during the structural optimisation in order to have a load consistent with the new structural stiffness and wing deformation. This resulted in an iterative procedure that converges successfully to an optimized weight of the wing structure.

Mesh deformation procedure to handle wing planform change. A mesh deformation procedure to handle wing planform deformation has been developed. Starting from an in-house ONERA mesh deformation code, a procedure for global wing parameter mesh deformation was developed that is very useful for computing the sensitivity analysis of the configuration with respect to global wing shape parameters.

Sensitivity analysis for OAD top level optimisation. A procedure to compute the sensitivity of aerodynamic and structural wing characteristics with respect to top level global parameters that define the wing planform has been developed. Comparison between finite difference and adjoint method techniques for sensitivity analysis has been performed, the results of which have been used to improve the performance of the finite difference approach.

Collaborations with Airbus for OAD top level optimisation procedure. During a secondment in Airbus an Overall Aircraft Design procedure has been put in place. This has been completely developed and tested on conventional and unconventional aircraft architectures. The analysis was presented during the AIAA Aviation conference in Washington, June 2016 [39]. The procedure is summarised in Figure 6.2.

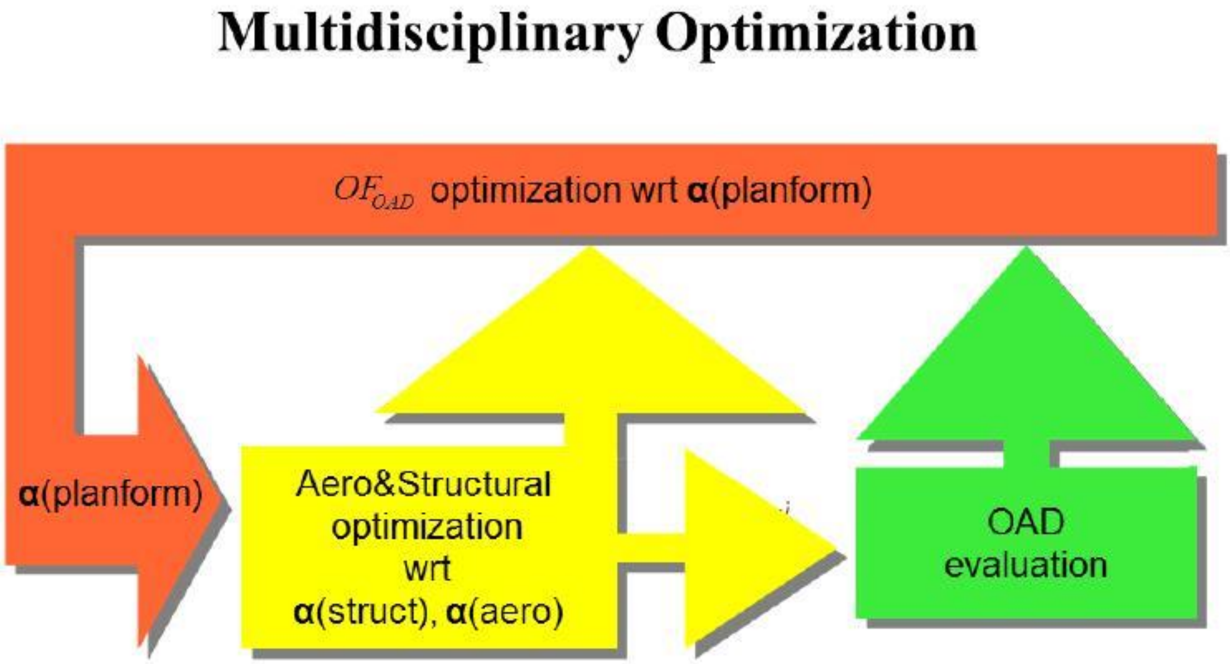

Figure 6.2: Overall Aircraft Design top level optimisation on top of the aero-elastic and structural ones; α(struct) and α(aero) are the structural and aerodynamic variables respectively.

*An investigation into parametrisation techniques for shape optimisation***.** Working with ESR2 in ONERA during a 3 months secondment, ESR2 and ESR6 collaborated to investigate parametrisation techniques for preliminary shape optimisation. The results of this were presented during the AIAA Aviation conference in Washington, June 2016 [41].

The project resulted in publications [39-42].

SWP3: Application of advanced MDO methods to aircraft engine design.

Highly energy-efficient aero engines will form an important component of any energy-efficient aircraft. This Scientific Work Package develops new MDO methods for important aspects of aero engine design affecting their overall fuel consumption including, cooling, fan and compressor geometries and materials, and high pressure turbines.

Project 7: Turbine Stator Well Heat Transfer and Design Optimisation using Numerical Methods (ESR: Julien Pohl, UoL; RR, VKI)

The requirement for ever more efficient gas turbine engines is leading to increased gas path temperatures, creating increasingly hostile environmental conditions for the adjacent turbomachinery and support structures. Cooling air systems are designed to protect vulnerable components from the hot gas that would otherwise be entrained into the cavities communicating with the gas path through the inevitable gaps between rotating and static parts. These cooling flows are bled from the compressor stages and reduce the engine efficiency, as they can represent around 20% of the total main gas path flow. The aim of this project was therefore to minimise the air cooling flows to levels consistent with maintaining the optimum component lives and the mechanical integrity of the engine. The project was carried out in three main steps to develop an automated MDO method. In the first step, a coupled method between a Computational Fluid Dynamics (CFD) solver and a Finite Element (FE) solver is validated against experimental data obtained on the MAGPI project [43]. The second step consisted of a flexible parametrisation of the cavity geometry, which is necessary for the third and final step, the application of a suitable optimisation technique to optimise the shape of the cavity.

The predictions are validated against the experimental data generated during the MAGPI project. In the latter project a two-stage turbine test rig was constructed with instrumentation for air and metal temperature measurements, as well as pressure taps, both in the main gas path and the adjacent cavity (turbine stator well). Two CFD solvers have been used: HYDRA (Rolls-Royce in-house) and ANSYS FLUENT (commercial). These CFD solutions have been coupled to the in-house FE solver SC03, which calculates the conjugate heat transfer thermal boundary conditions necessary to obtain the turbine assembly metal temperatures. The baseline and modified FE models are shown in Fig. 7.1.

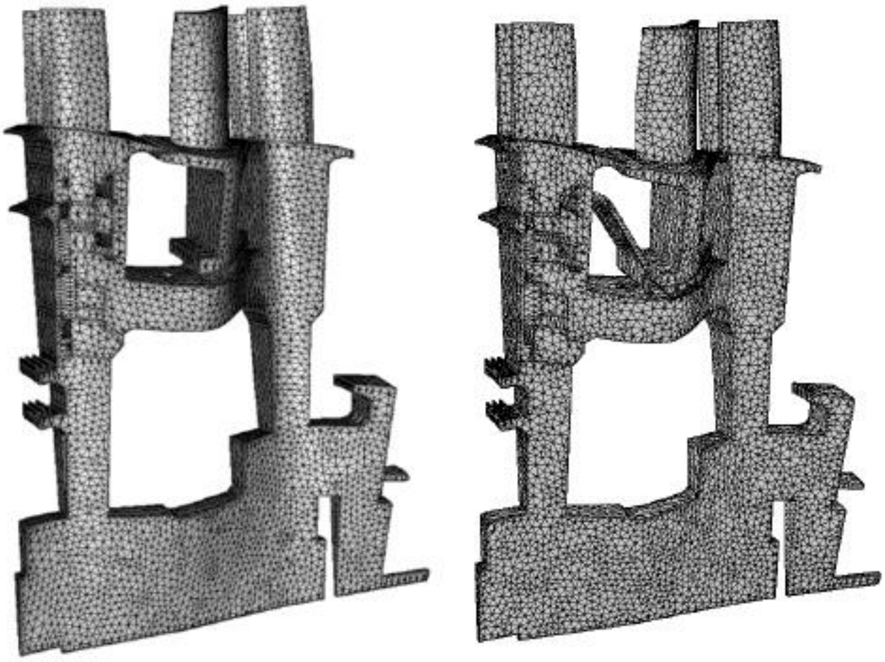

Figure 7.1: baseline FE model (left) and deflector FE model (right).

The CFD setup for the standard geometry is shown in Figure 7.2, where the main annulus and the cavity are meshed in a structured way and the stationary and rotating parts are connected by mixing planes for steady runs and by sliding planes for unsteady simulations. A second test case was also modelled for validation purposes. This contains an additional deflector plate inside the upstream cavity, which is attached to the stator foot. The additional deflector plate turns the cooling flow towards the rotor disc after entering the cavity, resulting in improved cooling. For this case, the main gas path has the same mesh as for the first test case, but the cavity is meshed separately: first in ICEM (structured mesh) and secondly in HYDRA (unstructured mesh). These meshes are then merged to the structured mesh of the main annulus, either non-conformally (with ICEM) or conformally (with HYDRA).

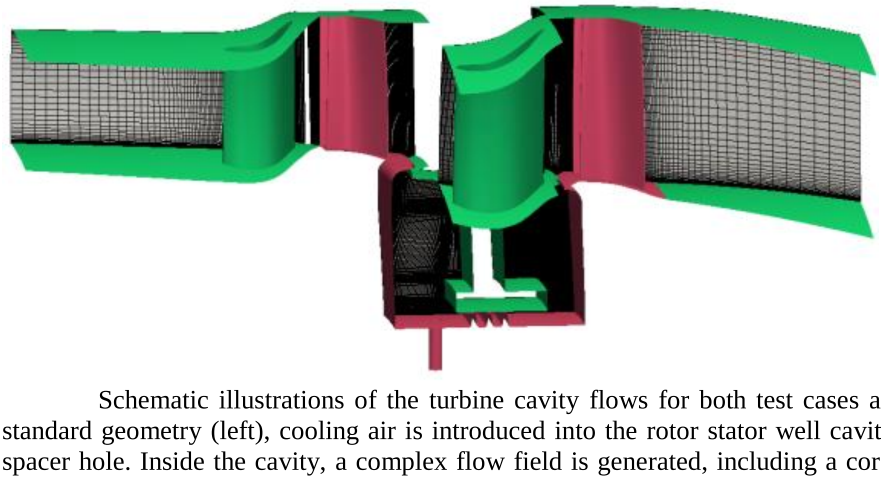

Figure 7.2: CFD model of the two-stage MAGPI test rig

Schematic illustrations of the turbine cavity flows for both test cases are given in Figure 7.3. In the standard geometry (left), cooling air is introduced into the rotor stator well cavity through a drive arm or disc spacer hole. Inside the cavity, a complex flow field is generated, including a core flow and a disc entrainment flow, induced by the rotating part of the turbine. The rim seal flow mixes the hot gas and cooling air, which has a significant effect on the temperature inside the cavity. In the deflector plate geometry, the cooling air does not penetrate the cavity to form a core flow, but instead impinges on the deflector plate and is turned towards the rotor disc, by forming a complex 3D vortex flow structure. The cooling air which reaches the disc is then entrained radially outwards by the rotating part of the turbine.

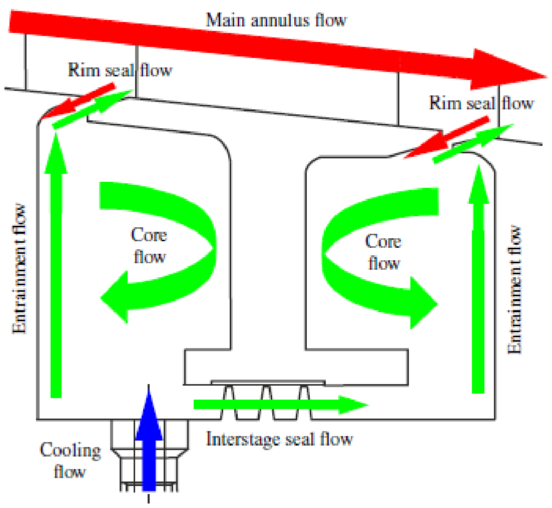

Figure 7.3: Turbine Stator well flow structure for standard geometry (left), with inserted deflector (right).

Earlier analyses showed good agreement between the CFD-FE temperature predictions and the experimental measurements along the cavity walls, for some flow conditions using the benchmark geometry without a deflector plate. In the rim seal region, however, larger discrepancies were observed. Further investigation showed that the thermal growth of the stator foot, (pulled radially outwards by the casing), is higher than the combined effects of the centrifugal forces and thermal loads induced in the rotor. This results in an increase of the inter-stage seal clearance by roughly one third. This increase in seal size has an effect on the flow field inside the cavity and also on hot gas ingestion from the main annulus, which explains why the experimental temperatures in the rim region are higher than predicted. In order to improve the temperature predictions, the geometry has been modified to account for the larger seal clearances. The modified geometry was then re-meshed and the new CFD results obtained. The resultant non-dimensional temperature predictions around the stator cavity wall are shown in Figure 7.4, where measurement points 14 and 24 are thermocouple positions near the up- and downstream rim, respectively.

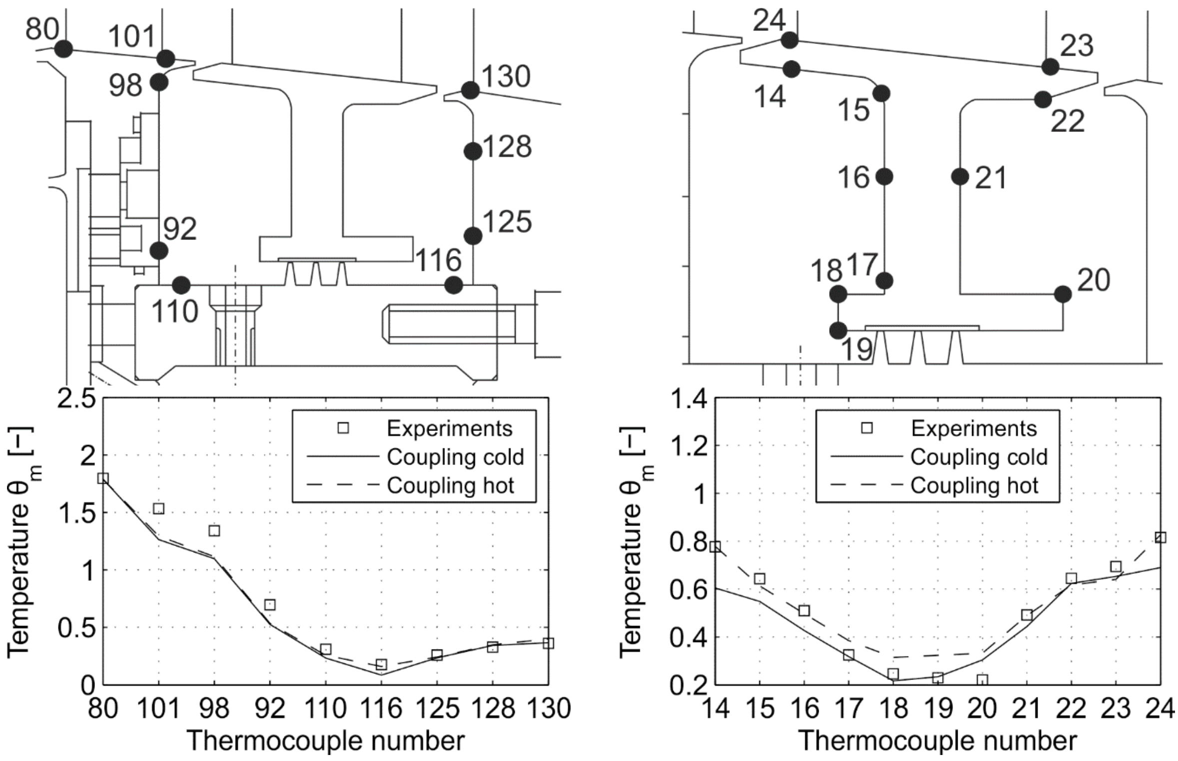

Figure 7.4: Rotor (left) and stator (right) disc.

The validation of the deflector plate geometry showed similar results. Both the cold and hot running clearances were modelled, in order to conduct a coupled FE-CFD simulation. Although the cold running model gave encouraging results, the hot running clearance improved the predictions significantly.

A flexible design parametrisation of the deflector plate has been developed (see Figure 7.5) in order to optimise the deflector geometry for rotor disc cooling. In total seven geometrical design variables were defined (Figure 7.5 (b)) plus one constraint ($\theta_{disc,ad}$). The objective function to be minimised was the mass flow rate of cooling air without penalising the constraint.

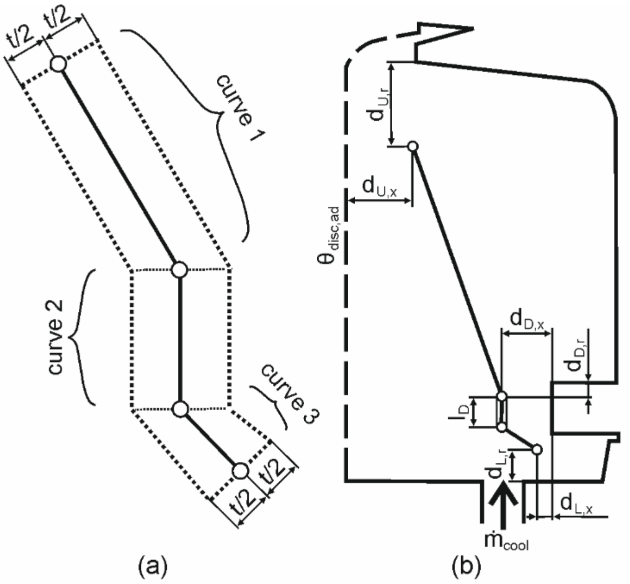

Figure 7.5: (a) parametrisation of the deflector plate and (b) its position inside the cavity.

The parametrised geometry is optimised using a meta-model assisted approach based on regressing Kriging in order to identify the optimum position and orientation of the deflector plate inside the cavity. The temperature distributions of the baseline and optimised deflector geometry cases are given in Figure 7.6. The optimised deflector plate geometry enabled the cooling air mass flow rate to be reduced by 70% compared to the baseline geometry without a deflector, while meeting critical cooling requirements.

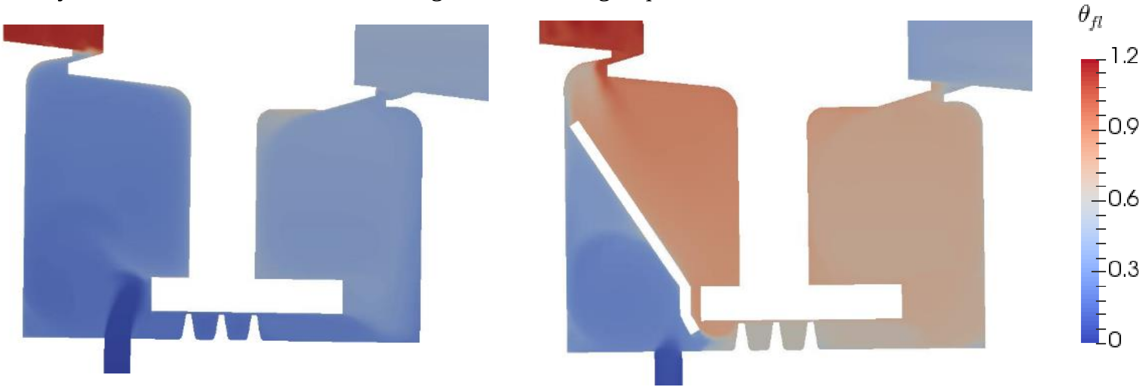

Figure 7.6 Temperature distribution in the baseline (left) and optimised deflector plate geometry (right).

The outcome of the optimisation was validated using the coupled CFD-FE methodology. This project produced publications [44-48].

Project 8: Novel 3D Shapes for MDO of Fans and Compressors (ESR: Ralf Schlaps, QMUL, RR)

Modern aero-engines are developed to reduce the specific fuel consumption to achieve the aim of reducing their global CO_2 emissions. The component efficiencies of components such as fans, compressors, turbines or combustors, therefore, need to be continuously increased. This becomes increasingly difficult since the component efficiencies are getting closer and closer to the physical limits. For instance, the efficiencies of compressor stages are already typically above 90%. Getting closer to 100% means minimising viscous effects without compromising the compressor performance at other engine speeds since an aero engine needs to operate efficiently at a wide range of operating conditions such as idle during approach and taxiing, and maximum thrust during take-off or cruise. Additionally, fan and compressor rotors are subjected to high mechanical demands since they need to resist high centrifugal forces as well as foreign object impact such as bird strike, ice impact or impact from debris.

In order to meet the structural requirements, the range of designs that can be considered in current design processes are somewhat limited, which usually hinders the goal of maximising the aerodynamic performance. A trade off must be found which satisfies the stability and efficiency requirements. Multidisciplinary Design Optimisation, where both the aerodynamic and structural aspects are considered simultaneously, has the potential to overcome the limitations of current design processes.

The goal of this project was to establish a multidisciplinary optimisation strategy enabling novel 3D aerofoil shapes for fans and compressors. These novel aerofoil shapes should meet all the requirements in terms of flow stability, structural stability, resistance against foreign object impacts, manufacturability and efficiency in order to reduce the fuel consumption of the aircraft. Furthermore, by improving these features aircraft would be safer, more environmental-friendly, quieter and more economical.

A number of essential steps were defined to achieve the goal of developing an automated multi-disciplinary optimisation process for compressor design. The first step included the development and validation of the methods in each discipline. In the second step the optimisation process was designed by choosing an appropriate parametrisation and selecting the optimisation technique suitable for the multi-disciplinary optimisation. In the third step, the optimisation process was applied to a compressor rotor to optimise its shape.

The validation of the Rolls-Royce in-house CFD code was carried out using the test data of a 4 stage high pressure compressor research rig. This is necessary since 3D design optimisation relies heavily on the predictions of Computational Fluid Dynamics (CFD) analyses, which must be reliable and accurate. The CFD validation work demonstrated that CFD was able to predict trends correctly, enabling designers to find tangible design improvements.

Furthermore, a parametrisation defining the compressor aerofoil was developed and two different optimisation processes were established. The first optimisation process uses a trust-based, automatic metamodelling method (known as MAM) and the other one used the Kriging (Gaussian Process Regression) technique. Both design processes have been tested, and they were both able to find significant design improvements. These successful optimisations demonstrated that the chosen parametrisation was appropriate for the compressor optimisations.

In addition, a framework to model impact of ice slabs onto compressor components has been developed, Figure 8.1. The consideration of FOD (foreign object damage) in the early design stage is a novel feature of this research.

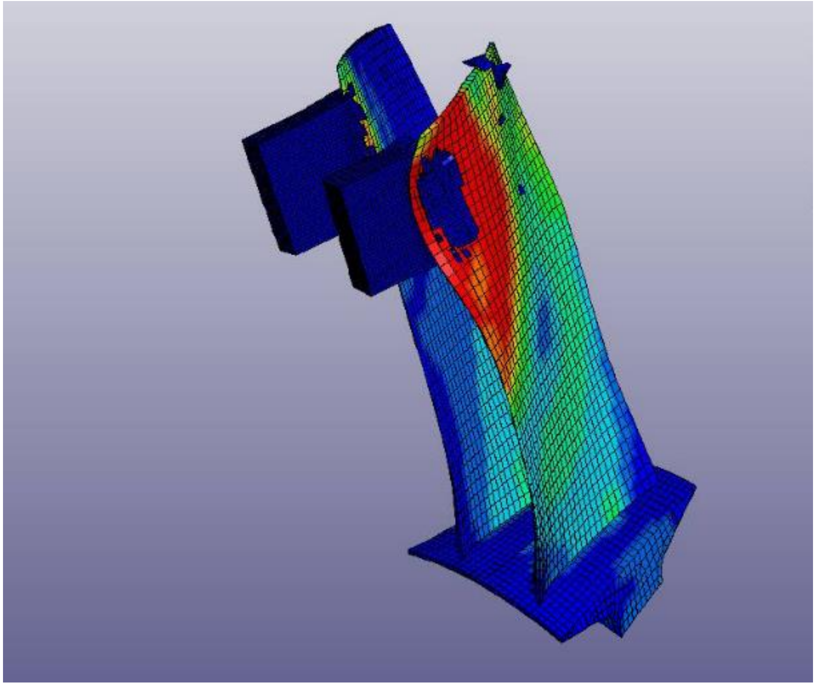

Figure 8.1: Ice impact model with two impacting ice slaps onto two disks.

It allows designers to take account of the requirements for impact-worthiness earlier in the design process, thereby reducing the risk of costly redesigns in a later design phase. This feature was also considered to provide the greatest benefit to the multi-disciplinary design process since it widens the design space for the optimiser.

The design processes developed during this project have a high potential to reduce costs, enhance efficiency and generally improve future designs. The final optimisation run showed that the compressor rotor can be further improved in terms of impact-worthiness and aerodynamic efficiency, even though the rotor had already been optimised by experienced designers, see Figure 8.2.

The project resulted in publications [49-51].

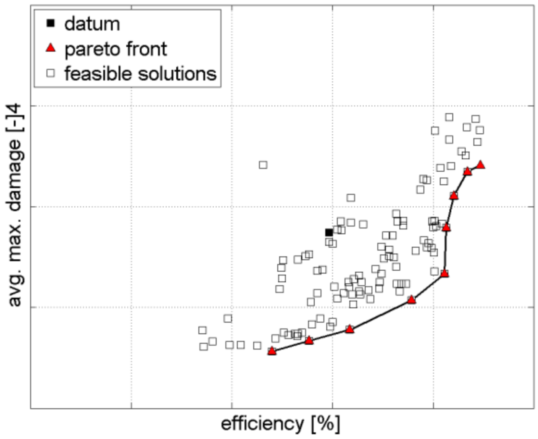

Figure 8.2: Pareto front showing possible trade-offs between efficiency and maximal damage.

Project 9: Multidisciplinary Design Optimisation of Aero-Engine Fan Blades (ESR: Christopher Chahine, VKI, RR, KU, University of Oxford)

Fan blades are central components of a modern aero-engine, are readily visible to the naked eye at the front face of an installed engine and produce more than 80% of total thrust for today's engines. This percentage can be expected to increase further for future high and ultra-high bypass ratio aero-engines.

Designing fan blades is a demanding task. Design considerations need to be driven by several disciplines including aerodynamics, structural mechanics, manufacturing and cost. In today's industrial design practice, blades are designed by a number of different departments, whereas each department is specialised in one particular discipline. The blade design progresses iteratively between the departments until a solution is found that satisfies all disciplinary requirements. This process, however, is very time and cost intensive. Moreover, it decouples the disciplines involved in the design process, which makes it difficult to reveal interactions between them. In view of the challenges that lie ahead of the aircraft industry in terms of the required reduction of fuel burn and exhaust emissions, increasing demands on reliability and increased competition, new, innovative design methods are required. These will need to be able to take full account of disciplinary interactions during the design process. Such methods are the subject of Multidisciplinary Design Optimisation (MDO). The goal of this project was the further development and application of these methods for the design of modern aero-engine fan blades.

A blade design resulting from a recent Multidisciplinary Design Optimisation study in this project is shown in Fig. 9.1. A CAD model of the blade is shown which is directly exported from the optimisation system, allowing the blade to be manufactured or, as shown, visualised in any standard CAD package.

Figure 9.1: Rendered CAD model of optimised fan blade

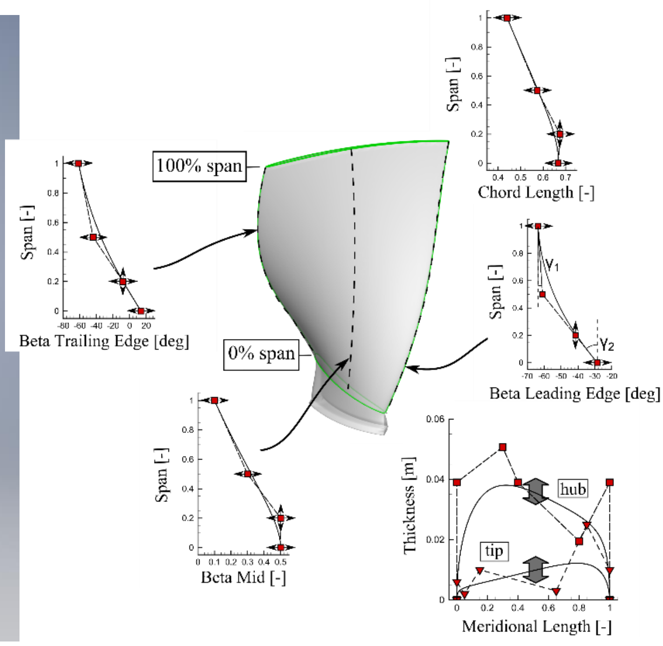

Figure 9.2: Fan blade parametrisation

The first part of the project aimed to establish a MDO framework for metallic aero-engine fan blades. A fan blade shape parametrisation based on parametric Bezier and B-Spline curves was developed allowing all design features of a modern fan blade, including three dimensional features like lean and sweep, to be represented, see Figure 9.2. Further, a comprehensive fully automated high-fidelity evaluation chain was established, consisting of the generation of the blade geometry and the associated fluid and solid domains, structured and unstructured meshing, as well as performance evaluations by Computational Fluid Dynamics (CFD) and Computational Structural Mechanics (CSM). An example of a resulting solid and fluid mesh is shown in Fig. 9.3. The evaluation chain was coupled to an Evolutionary Algorithm and accelerated by a Kriging metamodel. The successful application of the optimisation method was shown in a number of conference and symposium papers, including a paper that was presented at the 11th World Congress on Structural and Multidisciplinary Optimisation in Sydney, Australia [52].

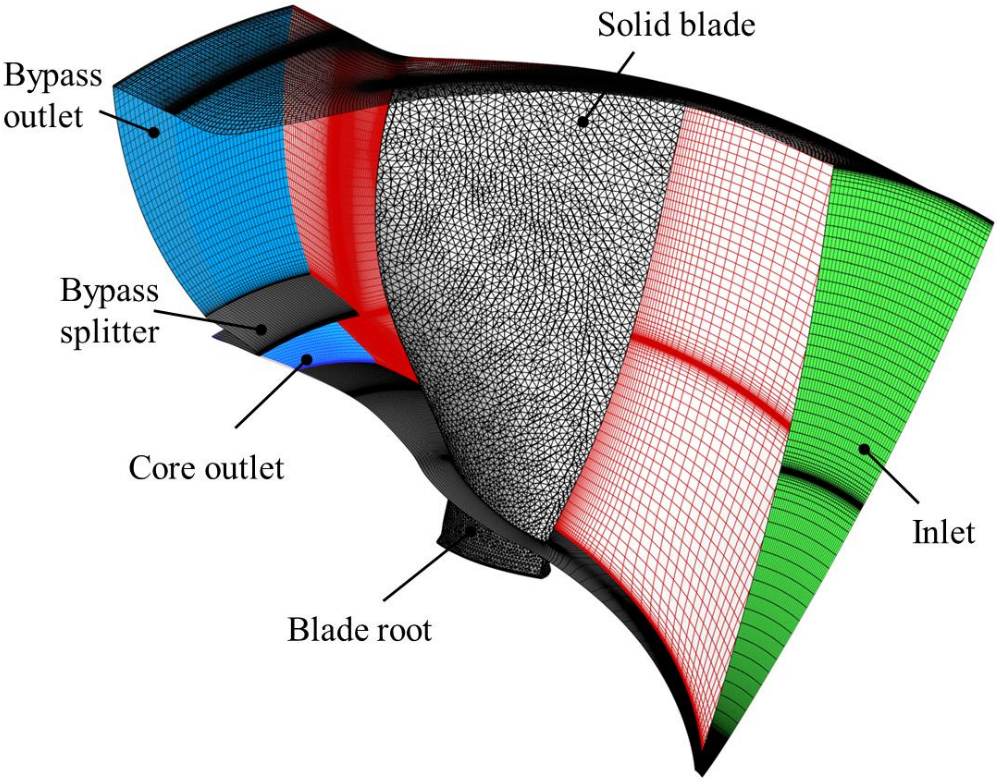

Figure 9.3: Meshed solid and fluid domain of the fan blade

Increased engine efficiency and an associated reduction in fuel consumption are currently the main targets in the development of new engines. To this end, jet engine manufacturers seek to increase the bypass ratio, which results in increased fan diameters. The weight of the fan blades and the fan section structure (disk, casing, outlet guide vanes and struts) are posing a limit on the potential efficiency gain associated with a larger bypass ratio, as improved aerodynamics is countered by the increase in engine weight. If the weight of the fan section can be decreased, engines with larger bypass ratios and in turn lower fuel burn can be realised. Lightweight materials are a key requirement for this purpose.

Composite materials like Carbon-Fibre Reinforced-Plastics (CFRP) offer increased specific stiffness and strength compared to metallic alloys and therefore are attractive replacement materials for engine components. The first high bypass ratio aero-engine fan blades made of CFRP entered service in 1995. Since then, manufacturing techniques and design methods have advanced considerably, allowing blades to become thinner and lighter. This development introduces a number of challenges for design optimisation, including an increasing impact of aeroelastic effects on overall fan performance and a substantial increase in the complexity of the design problem. Both of these aspects were addressed in this project.

Aeroelasticity becomes an important consideration for composite fan blades due to lower mass densities and reduced out-of-plane stiffness compared to metallic blades. The correct prediction of the static aeroelastic equilibrium at different operating points, i.e. the determination of the correct running shape of the blade under centrifugal and aerodynamic loads, is an important requirement for accurate off-design performance analyses since the transonic flow field that spans much of the fluid domain has a dominant impact on overall performance and is sensitive to small changes in geometry. The impact of the aeroelastic blade deformation on fan performance has been reported in the open literature for titanium blades but is less well known for composite ones. Bigger deformations than are typical for titanium blades are to be expected which introduce various modelling challenges. Unlike traditional methods that are based on the deformation of the fluid mesh, the method followed here is based on a deformation of the CAD model and a re-meshing of the resulting fluid domain. This has several advantages, with the most important ones being: 1) re-meshing of the fluid domain retains high quality grids even in highly deformed regions of the domain which typically tend to produce highly skewed cells (e.g. in the tip clearance at high levels of untwist 2) a CAD model of the deformed blade is available. The method was implemented for titanium blades and allowed an assessment of the impact of the aeroelastic deformation on the aerodynamic design and off-design performance. This enabled the error that is introduced when excluding aeroelastic deformations from the design process to be quantified.

The second aeroelastic effect considered in this work was blade flutter. Flutter is a self-exited aeroelastic instability, which, if not properly damped, can rapidly lead to a failure of the component. Fan blades of large aero-engines are particularly prone to flutter. It is therefore important to take it into account in the design process. Flutter has been the subject of a large body of research in the past few decades. However, for some variants of flutter the underlying physical mechanisms are still not well understood. Hence, accurate flutter modelling and its prediction using computational tools is a demanding task. Various techniques have been proposed and are in use today by industry and academia which vary in the degree of coupling between structural and aerodynamic modelling. Their range of validity therefore equally depends on the degree of aeroelastic coupling present in the system. At the beginning of this project there was no clear indication in the literature on which methods would be the most suitable for the application to large composite fan blades in terms of validity and computational efficiency. Hence, this project also considered whether the most commonly applied technique today, i.e. the so-called energy method, could be applied to composite fan blades in order to produce sufficiently accurate results. Work in this direction was initiated and first results were published at the 14th International Symposium on Unsteady Aerodynamics, Aeroacoustics & Aeroelasticity of Turbomachines (ISUAAAT14) in Stockholm, Sweden [53]. The results indicated the existence of considerable aeroelastic coupling in the system.

Composite materials add an entirely new dimension to the design problem. Whereas with metallic materials, material properties are known at the outset of the design stage, the properties of a composite material are subject to design. The material design fundamentally impacts the stiffness of the blade which has important consequences for several performance parameters including structural performance like strength and natural frequencies, but also the static and dynamic aeroelastic response which in turn impacts aerodynamic performance. Design variables of a composite laminate include the choice of constituent materials, fibre orientations, ply stacking sequences and ply thicknesses. By locally adapting the design variables, the material can be tailored for improved fan blade performance. This, however, comes at the cost of an extensive expansion of the design space.

To circumvent some of this complexity, it is common practise to design composite components using a ply stacking sequence with a specific fibre orientation pattern which results in globally isotropic in-plane properties. These so-called quasi-isotropic laminates considerably facilitate design, analysis and manufacturing. They allow to design components with reduced mass compared to metals, but neglect the potential of optimally adapting the material for the application at hand. Particularly for applications where weight is of critical concern, like in the aerospace industry, there is a considerable interest in using the material more efficiently.

Fan blades present a particularly demanding application because of the inherent multidisciplinary nature of the design problem. Besides the fact that the material design affects overall blade performance as described above, it also determines the best possible blade shape. The same is true in the other direction, as the blade shape predetermines the best possible material distribution. Hence, in order to generate an optimal blade design, shape and material parameters should be treated in unison in the design process.

The final goal in this work was therefore the introduction of composite material optimisation into the already established shape optimisation framework, enabling for the first time a multidisciplinary fan blade optimisation with a concurrent consideration of blade shape and material parameters. A key challenge for the completion of this task was met with the development of a composite material parametrisation method that enables the material to be characterised with a small number of continuous design variables while maintaining the most influential parameters for the blade design. The implementation of this method is almost finalised and details of the method are planned to be published after testing and validation have been completed.

The publications [52-54] resulted from this project. ESR9 also won the 'Best Presentation Award' for his talk at the '10th ASMO-UK/ISSMO Conference on Engineering Design Optimisation'.

Project 10: Multidisciplinary design optimisation of winglet and squealer for high pressure turbine applications (ESR: Stefano Caloni, RR, QMUL,UoL)

The design of a turbine blade is a complex task involving several disciplines with competing requirements. The use of shroudless high pressure turbines emphasises the importance of these competing disciplines. On the one hand the component has to be as aerodynamically efficient as possible whilst on the other hand it has to satisfy given temperature requirements that limit the ability to achieve very efficient tip designs.

Currently, such components are designed jointly by several departments addressing one discipline at the time. Usually the design is achieved in a sequential work-flow where the outcome of a department becomes the input for the next. If the requirements are not met, the current design is revised and iterated in the design chain. The design process iterates between departments till the final design is obtained or the project runs out of time. Therefore, through experience, a set of design rules are used to guide the design process avoiding the need of additional iterations between departments. However, this reduces the likelihood of achieving a true global optimum design during the design process. This project aimed to develop more effective design processes for improving the performance of turbine blades. Multi-disciplinary techniques were used to analyse the component from different perspectives simultaneously and Multidisciplinary Design Optimisation techniques used to carry out a detailed exploration of the design space, to identify new, high performance designs.

At the beginning of the project, the research focussed on three main configurations, those with flat tips, winglets and squealers and shapes with combinations of winglet and squealer shapes. A multi-disciplinary analysis methodology for turbine blade design was developed during the project. Initially, a simple single discipline analysis was used and subsequently the complexity of the system was increased by adding other disciplines. Every time a new discipline was involved the design space was modified accordingly. An automatic work flow was progressively updated to handle the different disciplines and different tools required.

At the start of the project, the geometry of the tip was parametrised and the parametrisation was then used by the different analyses; a single geometry definition shared between disciplines was found to simplify the process of exchanging information between simulations. The aerodynamic performance was analysed first by using Computational Fluid Dynamics (CFD) to predict the flow behaviour. Key performance attributes were determined and automatically extracted for different designs, together with preliminary information about the cooling requirements. Experimental data has been provided by the Rolls Royce Osney Lab, University Technical Centre, to validate the simulations and good agreement between the numerical simulations and experimental results was achieved. This agreement provided confidence that the simulations can be used within a meaningful optimisation analysis.

Optimisation techniques were then used to increase the aerodynamic efficiency of the component whilst reducing the cooling requirements. The optimisation was successful and demonstrated the trade-off between cooling requirements and efficiency. A number of interesting configurations were found and analysed, the results of which were presented at the European Turbomachinery Conference (2015) held in Madrid [55]. Following this optimisation, the fidelity of the model was increased. The internal cooling passages and the cooling holes near the tip area were fully modelled by using an internal parametrisation in conjunction with scripts for generating the geometry. In order to comply with the requirements for an automatic design optimisation, this geometry generation was fully automated.

The performance analysis considered not only the flow behaviour around the aerofoil but also the temperature distribution achieved inside the blade due to the cooling. This was achieved using three steps, the first involving the setup of a Finite Element (FE) model for solving the solid domain, the second the implementation of interpolation techniques for exchanging information between the two disciplines, then finally the development of coupling techniques. During a secondment at the Von Karman Institute in Brussels, the coupling techniques were further developed and tested successfully. The performance of the coupled techniques was compared with those of an uncoupled analysis and the results were presented at the ASME TurboExpo 2015 conference held in Montreal [56].

Further development of the coupled analysis was accomplished successfully. The Rolls Royce CFD solver was modified to enable conjugate analyses of the turbine blade using a single solver. This was found to significantly reduce the computational time and increase the quality of the results by avoiding the numerical noise caused by FE-CFD interpolations. The CFD conjugate solver was validated and new boundary conditions successfully implemented. The conjugate method was then applied to different squealer tip configurations (one closed and three opened). An opened squealer was found to show particular promise and was identified as being worthy of further investigation. These results were positively received by the audience during the ASME TurboExpo 2016 conference in Seoul where the findings were presented [57].

Finally, stress considerations were included in the design optimisation. The optimisation focused on the geometries that had showed most promise in previous studies. The analysis involved conjugate CFD simulations for understanding the aerodynamic performance, the behaviour of the cooling system and thermal effects on the blade. Moreover, a FE analysis was conducted to understand the stress state imposed to the blade. A multi-objective optimiser (MAM) recently developed at QMUL was used in the optimisation, which used surrogate models to increase the performance of the tip addressing both the fluid and solid performance simultaneously. A journal article on the optimisation work is currently being prepared [58].

Publications [55-60] have arisen from this project.

SWP4: Novel applications of MDO to the design of composite aeronautical structures.

Lightweight composites are now widespread in aircraft design and will be vital in enabling the industry to meet ever increasing targets for aircraft efficiency and sustainability. This Scientific Work Package develops novel MDO methods that can address key challenges in modelling composite damage, crashworthiness and acoustic performance and exploring the potential of forward swept composite wings.

<u>Project 11: Incorporation of Bird Strike Requirements in MDO of an Aircraft Wing using Sub-Space Metamodels (ESR: Jonathan Ollar, Altair; QMUL, UoL)</u>

This project aimed to transfer existing knowledge about crashworthiness optimisation from the automotive sector to the aerospace sector. In the automotive industry crashworthiness requirements often require analysis time measured in days rather than hours and results that are noisy and need to be filtered before assessment. This project explored techniques for handling the disparity in execution time between static and crashworthiness analyses.

An optimisation architecture, the Multi-Point Approximation Method (MAM) was identified as a suitable starting point for the project. The architecture was initially extended to handle MDO more efficiently by introducing the concept of disciplines within the optimiser. This allows for separate attributes (e.g. number of points per iteration, whether gradients should be used, etc.) to be handled for each discipline individually. Following this, a method was developed within the project, the sub-space approximation method, which takes advantage of any disparities in design variable dependence between the disciplines and reduces the computational budget needed to solve the optimisation problem.

To overcome identified limitations in terms of variable dependence, which can spoil the optimisation process as a whole, resulting in constraint violations in the final solution, the sub-space approximation method was extended into two, more robust methods. The first method is less sensitive to erroneous assumptions by adaptively accounting for incorrect assumptions by updating the values of eliminated variables in each iteration of a trust region-based optimisation process. The second method is a fully automatic approach, without any need for assumptions to be made, which makes use of a variable screening approach. In each iteration of a trust-region based optimisation, the previously evaluated designs are used to determine the dimensionality of the response produced by each model, and eliminate insignificant variables. Both methods have been tested on analytical examples and on simple finite element models successfully.

Furthermore, the pool of available approximation methods in the MAM was extended to include Kriging and gradient-enhanced Kriging, a method which is computationally expensive for large problems, especially when enhanced by design sensitivities. This led to a novel method being developed in collaboration with Swansea University, for reducing the computational budget needed.

The final part of the project was dedicated for testing of the developed MDO framework on an aircraft example. A wing model was devised and an optimisation was carried out considering both static stiffness of the wing as well as bird strike at several locations along the leading edge. The wing structure was a 3m long aluminium structure with a root chord of 830mm and a tip chord of 670mm. It had two longitudinal spars and 11 ribs as shown in Figure 11.1: the complete structure is shown on the left and the internal structure on the right. The material is precipitation-hardened aluminimum (6061-T6).

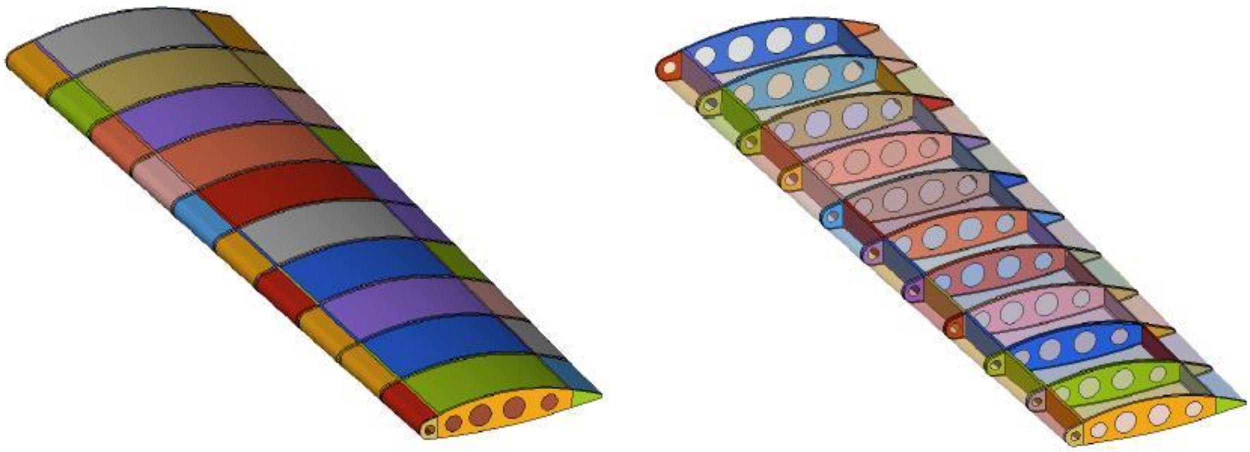

Figure 11.1: The wing model: complete structure (left) and internal structure (right).

The objective of the optimisation was to minimise the weight of the structure subject to meeting the structural requirements. The design variables were the thicknesses of the 100 components. The starting thickness for all components was 3mm with a lower bound of 2mm and upper bound of 5mm. The leftmost rib was not designable as in this study it was constrained by boundary conditions. The final thickness distribution is shown in Figure 11.2. None of the panels have gone to the upper thickness of 5mm, but some are lower than 2mm. Many of the ribs have resulting thicknesses which are in the thinner part of the thickness range. This may be due to the very simplistic set of static requirements for the optimisation. All leading edge skins have high thickness whilst leading edge ribs are thinner. This is probably because the leading edge skin is more likely to rupture if the leading edge rib is less compliant.

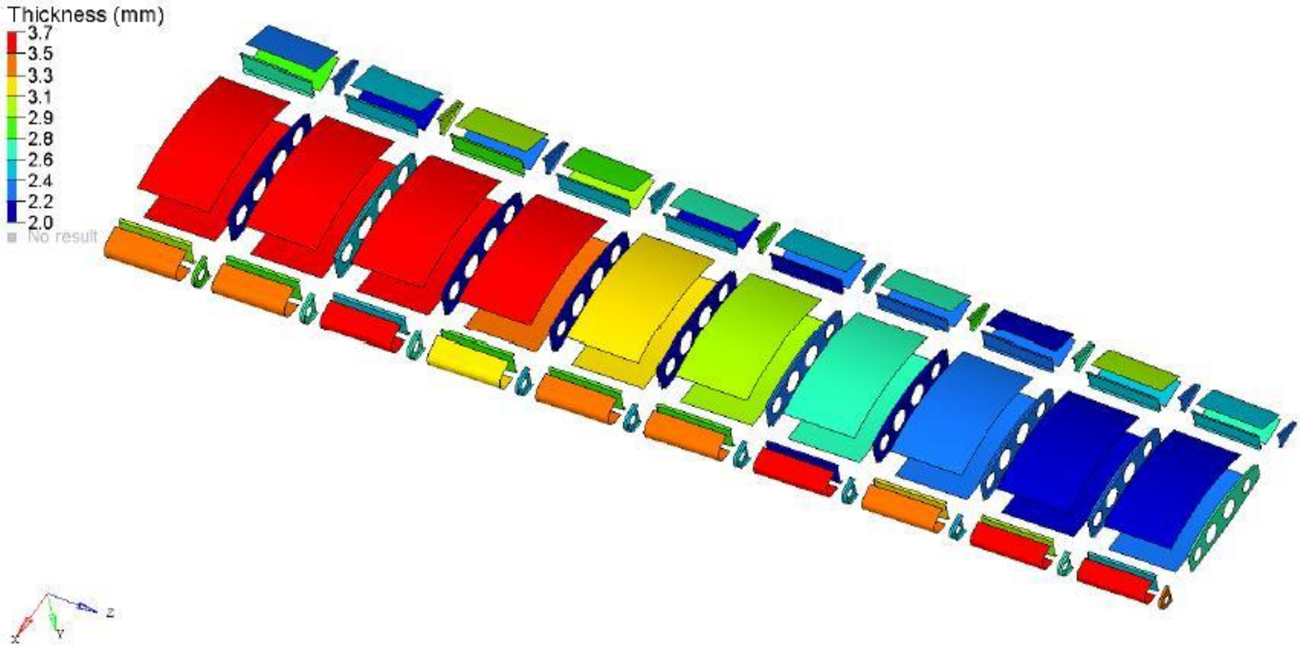

Figure 11.2: Final thickness for each of the considered components.

It was shown that by using the sub-space approximations proposed as part of the newly developed MDO framework, the computational effort needed to solve the optimisation problem was far lower than what would otherwise be possible. The optimisation finished in 8 iterations having evaluated 139 stiffness simulations and 1276 bird strike simulations in total, less than would have been required per iteration had sub-space metamodels not been used. The final result is a mass saving of 4.7% and a reduction of all previously violated constraints to less than 1%.

Publications [61-67] resulted from this project.

Project 12: Multi-disciplinary Analysis and Optimisation of Composite Forward Swept Wings (ONERA,TUD, Altair)

Due to recruitment difficulties, this project was split into two complementary projects. The first project was carried out by ESR12a, Marco Tito Bordogna, and aimed to develop a new strategy for composites tailoring which can account for aeroelastic phenomena.

An important aspect of the strategy was that it included high-fidelity CFD-CSM loads computation and their associated sensitivities with respect to the design parameters. A detailed comparison between two different composite parametrisation methods (lamination parameters and polar invariants) for a composite forward swept wing was performed. This demonstrated that both methods are capable of modelling composites in a continuous fashion; this makes them suitable for composite optimisation. For both methods the feasible design space was introduced according to the latest literature and their spaces have been explored with respect to manufacturable stacking sequence. The goal of the comparison was to find the most suitable method for optimising a real case aerospace structure. Buckling, strength, manufacturing and aeroelastic constraints were all taken into account in the comparison. The comparison concluded that lamination parameter approach is the most suitable for the optimisation of an aerospace composite structure.

The strategy was applied to the test case of a composite forward swept wing short-range civil aircraft to evaluate whether or not the use of unconventional laminates improves the overall structural weight. In collaboration with ESR12b, blending constraints to be implemented during gradient based structural optimisation were derived and applied. The outcome of the cooperation was a paper in the Journal of Composite Structures [68]. The focus then moved to identifying the recommended fidelity level to be used in the wing optimisation strategy. A backward swept wing model (“Acquill wing model”) was used to set up a preliminary optimisation via MSC Nastran SOL 200, see Figure 12.1.

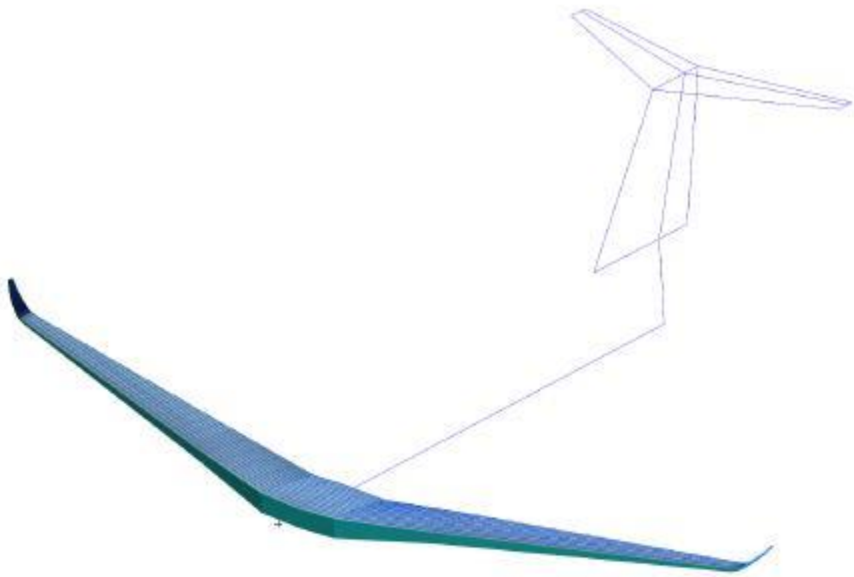

Figure 12.1: Aircraft wing model used in the optimisation.

The goal was to start treating large scale structural optimisation with important constraints on buckling, strength, aeroelasticity, manufacturing and perhaps winglet efficiency. This work is currently ongoing. It will create the basis for performing a fidelity level analysis where DLM loads will be compared those generated from the ONERA elsA/AEL module. The optimisation was carried out with MSC Nastran SOL 200 demonstrating that the constraints can be implemented using commercial optimisation software. This project produced publication [68].

Project 12a was supplemented by project 12b, carried out by Paul Lancelot, entitled **Investigation of stacking sequence parametrisation options for aeroelastic tailoring.** This project investigated the different methods available for composite structure optimisation under aeroelastic loads.

The use of composite materials to build large structures is one of the main challenges facing the aircraft industry. While in general they offer improved mechanical performance with higher strength and lower weight compared to their more conventional aluminium counterparts, they are more difficult to design due to the increased number of design variables that need to be correctly chosen. These methods are based on different types of parametrisation for the stacking sequence, like for instance the lamination parameters or the polar form. Several ways of optimizing these parameters for given constraints were compared and a number of techniques for retrieving a feasible stacking sequence from the optimal set of parameters, taking into account the blending and manufacturing constraints, were analysed.

Whilst most simulations used lamination parameters to formulate the stiffness properties of the laminates, the performance of polar invariants were also considered. On this type of problem, both lamination parameters and polar invariants were found to give similar outputs. A simplified version of NASA's Common Research Model (CRM) wingbox was used as a test case for strength optimisation under gust loads. Gust load computations require nonlinear dynamic solutions for which NASTRAN cannot compute derivatives for the gradient-based optimisation. This issue was overcome by implementing the equivalent static load technique using Matlab. A number of different strategies to ensure that the optimisation performs optimally for both thickness and stiffness were considered. Results showed a good improvement in term of weight between the quasi-isotropic solution (black aluminium) and the anisotropic solution.

This project collaborated with ESR12a on the definition of blending constraints. Blending is one of the most important manufacturing issues for variable stiffness composites. When the structure which has to be optimised is composed of several panels, it requires ply continuity throughout the structure. In the continuous optimisation level, this requirement is usually not applied since the stacking sequence is unknown. However this leads to a gap in terms of performance between the continuous optimum solution and the retrieved feasible stacking sequence (using a genetic algorithm optimisation procedure). Defining maximum allowable gradients between panels during the continuous optimisation allows a reduction of this gap, and aids the stacking sequence retrieval algorithm. This innovative method was successfully applied on the classical 18 panels horseshoe problem, and to a gust load benchmark problem. The latter considered a transport aircraft wing that can freely move in plunge and was hit by a *1-cosine gust*. The objective function is the structural mass and only the strength constraints were applied. The loads are extracted from NASTRAN Solution and the optimisation performed within Nastran Solution 200. A matlab script was used for the data transfer between the two solvers. Thicknesses of several panels over the wing box are used as design variables, and the convergence was reached after 25 iterations, providing a significant reduction in mass and root bending moment, see Figure 12.2.

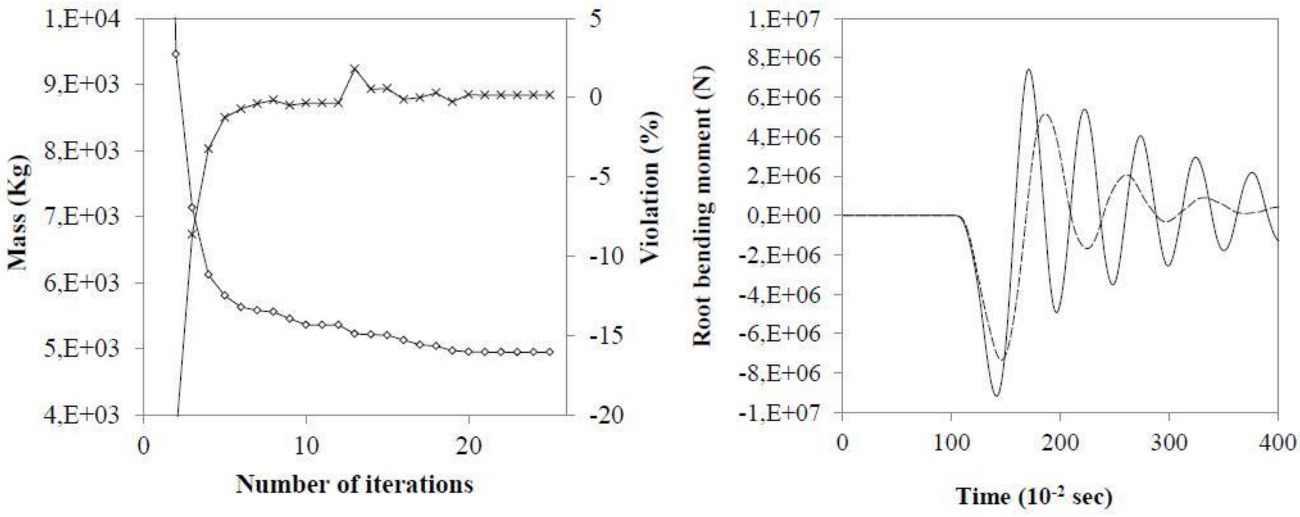

Figure 12.2: Optimisation results of a wing hit by a 1-cos gust.

Finally, the well-known problem of non-continuity of flutter and divergence inside the lamination parameters design space, which makes gradient-based optimisation difficult, was considered. This project considered a two-step strategy to reduce the number of design variables in aeroelastic tailoring problems, combining the lamination parameters (or polar invariants) with the kick angle definition. This showed promising results for future application.

This project produced publications [68] and [69].

Project 13: MDO of composite fuselage structure with vibro-acoustic requirements (ESR: Gokhan Serhat, KU,TUD, Altair,UoL)

This project aimed to provide a methodology for the early design stages of the development of modern composite fuselages to satisfy the competing objectives of high strength, low weight and low inner cabin sound pressure level.

During the optimisation of the fuselage section with respect to structural and acoustic requirements, a large range of different designs have to be generated and evaluated. In order to automatize the entire optimisation process an Automatic Optimisation Engine (AOE) was developed. This links together all of the numerical tools and automates each different task. In order to have a modular structure, the facilities of AOE were grouped under several subroutines. For each subroutine the user is allowed to choose between available options or specify the values of the parameters. The working principle of AOE is presented in Figure 13.1.

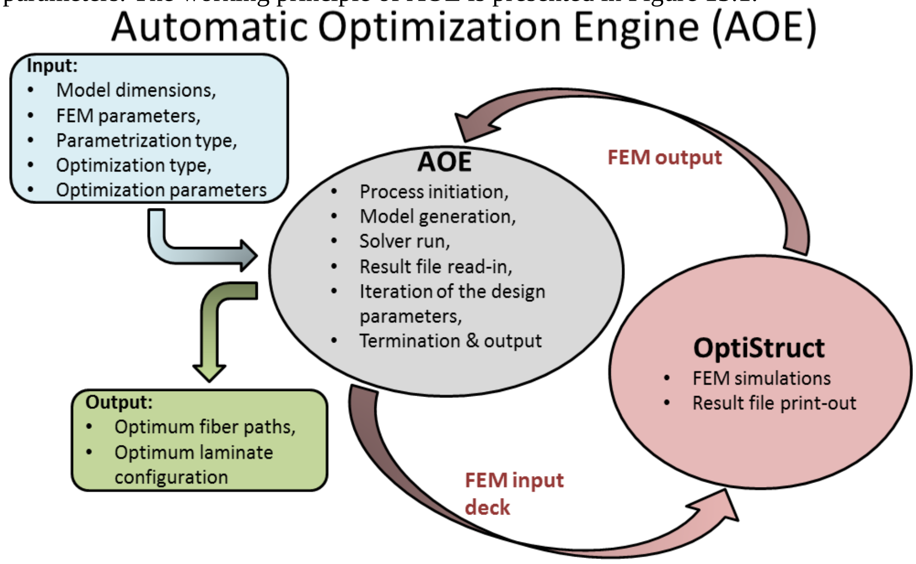

Figure 13.1: A schematic diagram showing the working principle of AOE.

Since Multi-disciplinary design of complex products using MDO requires rapid generation of computational models for multiple disciplines, an automatic Model Generator that generates mechanical, acoustical models for subsequent FE analyses has been built. Figure 13.2 shows a sample finite element model of the fuselage section and an acoustic cavity.

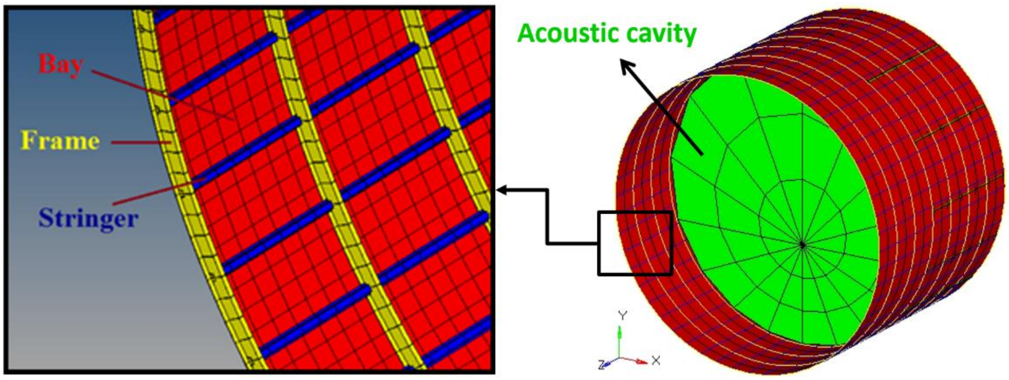

Figure 13.2: Sample finite element model of the fuselage section and acoustic cavity generated by Model Generator module.

An optimizer module is used to carry out a laminate optimisation process. It contains optimisation algorithms including Full-Factorial DoE, 0th Order (Derivative-Free) Local Search and 1st-order Gradient-Based Local Search. Low frequency sound transmission properties of the shell structures can be altered by varying the stiffness properties. Numerical simulations were carried out to observe the effects of fibre orientations and laminate stacking sequence on the sound absorption capabilities as well as structural strength. This favoured the development of different parametrisation approaches for the vibro-acoustic analysis of a fuselage made of composite laminates. Three different parametrisation approaches were developed based on panel, bay-based fuselage and continuous fuselage optimisation.

The most important functions of an aircraft fuselage are to enclose the passenger cabin, hold the aircraft structure together and withstand forces and bending moments to ensure flight safety. It is also necessary to ensure adequate vibro-acoustic performance in order to provide the passengers with a comfortable environment. Therefore, a multi-objective optimisation study is required. Figure 13.3 depicts the response surfaces and optimum points for maximum longitudinal stiffness and maximum panel natural frequency which are mechanical and vibro-acoustic performance metrics, respectively. The lower axes of the diagrams stand for the lamination parameters V_1 and V_3 which are the design variables while vertical axes are the responses.

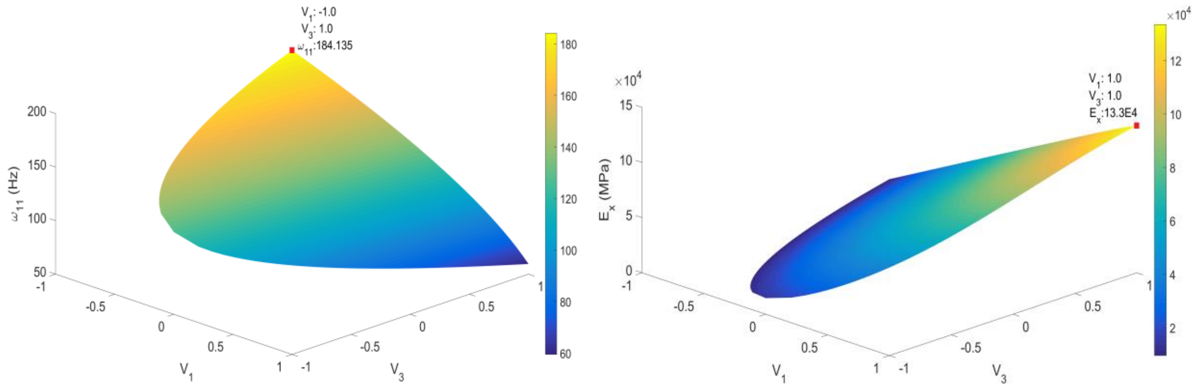

Figure 13.3: The response surfaces and optimum points for maximum panel natural frequency (left) and maximum longitudinal stiffness (right).

A comparison of preliminary design methodologies for the optimisation of stiffened, fibre-reinforced composite fuselages for vibro-acoustic requirements was carried out. The effect of fuselage stiffness properties on the vibro-acoustic performance was investigated using two different approaches. The first method only considered the structural model in order to explore the effect of design variables on fuselage vibrations. The simplified estimation of the acoustic behaviour without considering fluid-structure interaction brings certain advantages such as reduced modelling effort and computational complexity. The second method utilized coupled vibro-acoustic simulations and provided more accurate results at the expense of increased computational cost. The vibro-acoustic performance metrics used in the research included: maximum panel fundamental frequency, minimum equivalent radiated power (ERP) from the panels or fuselage section, and the minimum average sound pressure level (SPL) in the acoustic cavity.

For ERP calculations, bay panel and fuselage section models were used, whereas for the SPL calculations the fuselage section model with acoustic cavity was used. The structures were excited by uniform outer harmonic pressure which is a simple representation of turbulent boundary layer noise outside the aircraft. Both ERP and SPL are averaged in the excitation frequency range: 1-250 Hz. The values of the design variables at minima and maxima have been observed to be similar for the bay ERP, fuselage section ERP and SPL. However, the general trend of fuselage section ERP has been found to be considerably closer to the SPL than the bay ERP and its overall accuracy is therefore superior. This is very important in multi-objective optimisation, as the optimum might be located in the middle regions of the design space.

In order to quantify the total conformity of the two different metrics, the error was defined by: $|\{\overline{SPL}\} - \{\overline{ERP}\}|$. The optimisations have shown the ERP to be a useful performance metric in early-stage vibro-acoustic design optimisation.

The project produced publications [70-72].

III. Conclusions

Collectively, the AMEDEO research projects have developed new and/or improved MDO methods for a number of strategically-important aspects of aerospace design. For example, ESR2's development of a powerful new node-based shape optimisation method, which has been adopted by ONERA and its wider dissemination throughout industry has been facilitated by its implementation into the well-established open-source Multiphysics framework KRATOS Multiphysics. The methodology and corresponding source tools are now publicly available so anyone from industry or academia may use the tools to perform node-based single and multi-disciplinary shape optimisation with their own designs.

Other examples include the new advanced MDO method for preliminary aircraft design (developed by ESR 6) which enables Direct Operative Costs to be modelled accurately in the early stages of aircraft design, the MDO methodologies of ESRs 7, 8 and 10 for improving aero-engine design and ESR 11's powerful new sub-space optimisation method for crash and safety investigations. These outcomes and those from the other projects are already providing important benefits for key EU aerospace manufacturing and supply chain companies.

However, although the improvements in automated design optimisation processes achieved in AMEDEO are indeed substantial it is important to recognise that, as identified recently by Shahpar [73], the impact of MDO anticipated in ACARE 2020 Vision [1] and ACARE Beyond Vision 2020 [2] will depend on overcoming deeply entrenched human factors and organisational issues. It is therefore likely that the greatest long-term impact of AMEDEO on the wider adoption of MDO throughout the aerospace industry will be through the future careers and achievements of its highly-trained ESRs.

Acknowledgements

The financial support for AMEDEO through EU grant reference 316394 is gratefully acknowledged.

References

1. European Aeronautics: A vision for 2020. Meeting society's needs and winning global leadership. *Advisory Council for Aeronautics Research in Europe (ACARE),* http://www.acare4europe.com, (2001).
2. Aeronautics and Air Transport: Beyond Vision 2020 (Towards 2050). Background Document. *Advisory Council for Aeronautics Research in Europe (ACARE),* http://www.acare4europe.com, (2010).
3. Flightpath 2050. Europe's vision for aviation. Report of the high level group on aviation research. European Commission, http://ec.europa.eu/transport/air/hlg_aviation_aeronautics_en.htm, (2011).
4. J. Sobieszczanski-Sobieski, R.T. Haftka. Multidisciplinary aerospace design optimization: survey of recent developments, *Struct. Opt*., **14**, 1-23, (1997).
5. E.J. Cramer, P.D. Frank, G.R. Shubin, J.E. Dennis and R.M. Lewis. On alternative problem formulation for multidisciplinary optimization. *Proc. 4th AIAA/USAF/NASA/OAI Symp. on Multidisciplinary Analysis and Optimization,* Cleveland, OH, AIAA 92 – 4752 (1992).
6. S. Kodiyalam and J Sobieszczanski-Sobieski. Multidisciplinary design optimization: some formal methods, framework requirements and application to vehicle design. *Int. J. Vehicle Design,* **25**, 3-32 (2001).
7. R.D. Braun, P. Gage, I.M. Kroo, I. Sobieski. Implementation and performance issues in CO. *Proc. 6th AIAA Symp. MDAO, Bellevue, WA,* (1996).
8. H.M. Kim, D.G. Rideout, P.Y. Papalambros, J.L. Stein. ATC in automotive vehicle design, *J. Mech. Des.*, **125**, 481-489, (2003).
9. S. Tosserams. Distributed Optimization for System Design – an augmented Lagrangian coordination approach, *PhD thesis, University of Eindhoven,* (2008).
10. D. Liu, V.V. Toropov, O.M. Querin and D.C. Barton. Bilevel optimization of blended composite wing panels. *AIAA Journal of Aircraft*, **125**-1, 107-118 (2011).
11. P.N. Koch, R.-J. Yang and L. Gu. Design for six sigma through robust optimization. *Structural and Multidisciplinary Optimization*, 26 (2004), 235–248.

12. D. M. Frangopol, K. Maute. Life-cycle reliability-based optimization of civil and aerospace structures (Review article), *Computers and Structures*, 81 (2003) 397–410.
13. J.R.R.A. Martins, A.B. Lambe. Multidisciplinary Design Optimisation: A Survey of Architectures. AIAA Journal, 51(9), 2049-2075, 2013.
14. AMEDEO ITN (EU FP7-PEOPLE-2012-ITN, project no. 316394). http://www.amedeo-itn.eu/
15. Aissa, M.H.; Verstraete, T. (2014) "Efficient high Performance Computing Techniques for Multi-disciplinary Optimisation", 5th Symposium of VKI PhD research, March 10-12th 2014, von Karman Insitute for Fluid Dynamics, Rhode-Saint-Genese, Belgium.
16. Aissa, M.H., Verstraete, T. and Cornelis, V. "Aerodynamic optimization of supersonic compressor cascade using differential evolution on GPU." *INTERNATIONAL CONFERENCE OF NUMERICAL ANALYSIS AND APPLIED MATHEMATICS 2015 (ICNAAM 2015)*. Vol. 1738. No. 1. AIP Publishing, 2016.
17. Aissa, M.H., Verstraete, T. and Vuik, V. (2016). "A GPU-Accelerated Steady CFD Solver for Turbomachinery Optimization" 28th International Conference on Parallel Computational Fluid Dynamics (ParCFD 2016), May 9-12st 2016, Kobe, Japan (extended abstract).
18. Aissa, M.H., Chahine, C. and Verstraete, T. (2016). "Surrogate-Model Assisted Evolutionary Optimization of an Axial Compressor Stator" 11th ASMO UK/ISSMO/NOED2016: International Conference on Numerical Optimisation Methods for Engineering Design, July 18th-20th 2016, Munich Germany. (extended abstract).
19. Aissa, M.H. , Mueller, L., Verstraete, T. and Vuik, C. (2016). "Acceleration of Turbomachinery Steady Simulations on GPU" Euro-Par 2016 WS, 22nd International European Conference on Parallel and Distributed Computing, 22th-26th of August, Grenoble France (in publication: Lecture Notes in Computer Science)
20. Aissa, M.H., Verstraete, T. and Vuik., C. (2016). "How GPU Computational Power Can Alter the Established Comparison of Explicit to Implicit CFD Simulations?" abstract at 5th European Seminar on Computing June 5 - 10, 2016 Pilsen, Czech Republic (abstract).
21. Aissa, M.H. (2015) "A GPU-Accelerated Navier-Stokes Solver for Multidisciplinary Design Optimization". 27th International Conference on Parallel Computational Fluid Dynamics (ParCFD 2015), May 17-21st 2015, Montreal, Canada (extended abstract).
22. Aissa, M.H. (2015) "A GPU-accelerated Navier-Stokes solver for steady turbomachinery simulations". 6th VKI PhD symposium, March 11-13th 2015, von Karman Institute for Fluid Dynamics, Rhode-Saint-Genèse, Belgium.
23. Aissa, M.H.; Verstraete, T.; Vuik, C. (2014) "Use of modern GPUs in Design Optimization", 10th ASMO-UK/ISSMO conference on Engineering Design Optimization, June 30th - July 1st 2014, Delft University of Technology, Delft, The Netherlands.
24. Najian Asl, R.; Baumgärtner, D.; Bletzinger, K.-U. (2015) "Towards shape optimization of steady-state fluid-structure interaction problems using vertex morphing". 16th AIAA ISSMO Multidisciplinary Analysis and Optimization Conference, June 22-26th 2015, Dallas USA. doi: 10.2514/6.2015-3356.
25. Baumgärtner, D.; Najian, R.; Bletzinger, K.-U. (2015) "Potential and difficulties of node-based shape optimization taking into account fluid-structure interaction". 3rd ECCOMAS Young Investigators Conference, July 20-23rd 2015, Aachen Germany. (Abstract)
26. Baumgärtner, D.; Wolf, J.; Rossi, R.; Wüchner, R.; Dadvand, P. (2015) Contribution to the Fluid-Structure Interaction Analysis of Ultra-Lightweight Structures using an Embedded Approach. CIMNE Monograph (ISBN: 978-84-943307-6-6)
27. Baumgärtner, D.; Viti, A.; Dumont, A.; Carrier, G.; Bletzinger, K.-U. (2016) "Comparison and combination of experience-based parametrization with Vertex Morphing in aerodynamic shape optimization of a forward-swept wing aircraft". 17th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, June 13-17th 2016, Washington D.C. USA. doi:10.2514/6.2016-3368.
28. http://kratos-wiki.cimne.upc.edu.
29. Baumgärtner, D.; Bletzinger, K.-U; Viti, A; Dumont, A. (2016) Node-based shape optimization in aircraft preliminary design. 11th ASMO UK/ISSMO/NOED2016: International Conference on Numerical Optimisation Methods for Engineering Design, Munich, Germany.
30. A.L. Arsenyeva, F. Duddeck, Optimization of fiber-steered composites by using Iso-contour method with maximum curvature constraint, ECCM17, Munich, Germany, July 2016.
31. A. Arsenyeva, F. Duddeck, "Efficient and adaptive parametric modeling for shape optimization of a wingbox", In: 3rd ECCOMAS Young Investigators Conference, Aachen, Germany, 2015.
32. Duckitt, S. J.; Shahpar, S.; Bisagni, C. (2016) "Parametric Bird Strike Study of a Transonic Rotor Using Isogeometric Analysis", Proceedings of ASME Turbo Expo, GT2016-567464, June 13-17th, 2016, Seoul, South Korea.
33. Duckitt, S. J.; Guo, Y.; Ruess, M. (2014) "Isogeometric modelling of composite delamination", Proceedings of NSCM-27: the 27th Nordic Seminar on Computational Mechanics, October 22-24th, 2014, Stockholm, Sweden. (TRITA-MEK Technical Report 2014:24, KTH Mechanics, Stockholm, Sweden, 2014).
34. Duckitt, S. J.; Shahpar, S.; Bisagni, C.; (2016) "Multiobjective Optimisation of a Compressor Stator using a 3D B-Spline Parameterisation", Proceedings of 11th ASMO UK / ISSMO / NOED2016: International Conference on Numerical Optimisation Methods for Engineering Design, July 15-18th, 2016, Munich, Germany.
35. Jovanov K.; De Breuker, R.; Abdalla, M.M.; Blondeau, C. (2016) "Multi-fidelity aeroelastic analysis and sensitivity analysis for gradient-based structural optimization", 11th ASMO UK/ISSMO/NOED2016, July 18 – 20th 2016, Münich, Germany.
36. Jovanov K.; De Breuker, R.; Abdalla, M.M.; Blondeau, C. (2016) "A Linear Aerodynamics-based Preconditioner for High-Fidelity Aeroelastic Analysis and Sensitivity Analysis". 17th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, AIAA Aviation 2016, June 13 – 17th 2016, Washington, USA.
37. Jovanov K.; De Breuker, R. (2015) "Accelerated Convergence of High-Fidelity Aeroelasticity Using Low-Fidelity Aerodynamics". International Forum on Aeroelasticity and Structural Dynamics June 28th - July 2nd 2015, Saint Petersburg, Russia.
38. Jovanov, K.; De Breuker, R.; Abdalla, M.M. (2015) "Accelerated convergence of static aeroelasticity using low-fidelity aerodynamics", 56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, SCITECH 2015, January 5 - 9th 2015, Kissimmee, Florida.
39. Viti A., Druot T., Dumont A. (2016) "Aero-structural approach coupled with direct operative cost optimization for new aircraft concept in preliminary design", AIAA/ISSMO-MOA conference, June 2016, Washington.
40. Viti A., Dumont A., Carrier G., Hewson R. (2015) "Innovative Aero-Structural Design Process for a Forward-Swept Wing in Preliminary Design", 3AF 50th International Applied Aerodynamics Conference, March 2015, Toulouse.
41. Baumgaertner D., Viti A. (2016) "Comparison and combination of experience-based parameterization with vertex-morphing in aerodynamic shape optimization of a forward-swept wing aircraft", AIAA/ISSMO-MOA conference, June 2016, Washington.
42. Bach C., Jebari R., Viti A., Hewson R. (2016) "Composite stacking sequence optimization for aeroelastically tailored forward-swept wings", Structural and Multidisciplinary Optimization, Springer Edition, pp. 1-15.

43. MAGPI. ‘Main Annulus Gas Path Interaction – Specific Targeted Research Project’. EU contract no. 30874, 2006.
44. J. Pohl, H.M. Thompson, R.C. Schlaps, S. Shahpar, V. Fico, G.A. Clayton, ‘Innovative turbine stator well design using a kriging assisted optimization method’ to appear in *Journal of Engineering for Gas Turbines and Power*, 2017.
45. J. Pohl, H. Thompson, A. Guijarro Valencia, G. Lopez Juste, V. Fico, G. A. Clayton, ‘Structural Deflection’s Impact in Turbine Stator Well Heat Transfer', *Journal of Engineering for Gas Turbines and Power*, **139**, 041901-1, 2017.
46. Pohl, J.; Thompson, H.; Schlaps, R.; Shahpar, S.; Fico, V.; Clayton, G. (2016) "Innovative Turbine Stator Well Design Using Design Optimisation" 16th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery (ISROMAC 2016), April 10-16th 2016, Honolulu, Hawaii
47. Pohl, J.; Fico, V.; Dixon, J. (2015) "Turbine Stator Well Cooling - Improved Geometry Benefits" Proceedings of ASME Turbo Expo 2015: Turbine Technical Conference and Exposition, June 15-19th 2015, GT2015-42658, Montreal, Canada.
48. Pohl, J, Thompson, H.M., Fico, V., Clayton, G.A. (2016), Turbine stator well geometry benefits – method validation and design optimisation. 11th ASMO UK/ISSMO/NOED2016: International Conference on Numerical Optimisation Methods for Engineering Design, Munich, Germany.
49. Schlaps, R.; Shahpar, S.; Toropov, V.V. (2015) "Multi-fidelity optimisation of compressors". 3rd ECCOMAS Young Investigators Conference, July 20-23rd 2015, Aachen Germany.
50. Schlaps, R. C.; Shahpar, S.; Guemmer, V. (2014): “Automatic Three-Dimensional Optimisation of a Modern Tandem Compressor Vane”, In Proceedings of the ASME Turbo Expo 2014, GT2014-26762, 16th-20th June 2014, Duesseldorf, Germany
51. Pohl, J.; Thompson, H.; Schlaps, R.; Shahpar, S.; Fico, V.; Clayton, G. (2016) "Innovative Turbine Stator Well Design Using Design Optimisation" 16th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery (ISROMAC 2016), April 10-16th 2016, Honolulu, Hawaii
52. Chahine, C. Verstraete, T., He, L.: “Multidisciplinary Design Optimization of an Aero-Engine Fan Blade with Consideration of Bypass and Core Performance”, June 8th-12th 2015, Sydney, Australia.
53. Chahine, C., Verstraete, T., He, L.: “On the Validity of Decoupled Flutter Prediction Methods for Composite Fan Blades”, 14th International Symposium on Unsteady Aerodynamics, Aeroacoustics and Aeroelasticity of Turbomachines, September 7th-11th 2015, Stockholm, Sweden.
54. Chahine, C., Verstraete, T., He, L.: “Multidisciplinary Optimization of Aero-Engine Fan Blades”, 6th Symposium of VKI PhD research, March 11th-13th 2015, Von Karman Institute for Fluid Dynamics, Rhode-Saint-Genese, Belgium.
55. Caloni, S.; Shahpar, S.; Coull, J. D. (2015) “Numerical investigations of different tip designs for shroudless turbine blades”, 11th European Turbomachinery Conference, ETC11, March 23-27th 2015, Madrid, Spain.
56. Caloni, S.; Shahpar, S. (2015) “Investigation into coupling techniques for a high pressure turbine blade tip” ASME Turbo Expo 2015, June 15-17th 2015, Montreal, Canada.
57. Caloni, S., Shahpar, S. (2016) “Multi-Disciplinary Analyses for the Design of a High Pressure Turbine Blade Tip” ASME Turbo Expo 2016, June 13-17th 2016, Seoul, South Korea
58. Caloni, S.; Shahpar, S.; Coull, J. D. (2016) “Numerical investigations of different tip designs for shroudless turbine blades” IMechE part A “Journal of Power and Energy” (accepted for publication, the publisher is finalising the article).
59. Caloni, S., Shahpar, S. (2016) “Multi-Disciplinary Analyses for the Design of a High Pressure Turbine Blade Tip” ASME Journal of Turbomachinery (submitted).
60. Caloni, S., Shahpar, S., Kovoloev, Y., Toropov, V. (2016) “Multi-Disciplinary Optimisation of the shroudless turbine tip” under preparation, 2017.
61. Ollar, J., Toropov, V., and Jones, R. (2016) Sub-space approximations for MDO problems with disparate disciplinary variable dependence. Structural and multidisciplinary Optimization, DOI: 10.1007/s00158-016-1496-0.
62. Ollar, J., Mortished, C., Jones, R., Sienz, Johann., Toropov, V. (2016) Gradient based hyper-parameter optimisation for well conditioned kriging metamodels. Submitted to structural and multidisciplinary optimization.
63. Schlaps, R., Ollar, J., Shahpar, S., and Toropov,. V. (2016) Multi-disciplinary optimization of compressor rotor subjected to ice impact. 11th ASMO-UK/ISSMO International Conference on Engineering Design Optimisation, Munich, Germany, July 18-20, 2016.
64. Ollar, J., Jones, R., and Toropov, V. (2016) Incorporation of bird strike requirements in MDO of an aircraft wing using subspace approximations. 11th ASMOUK / ISSMO International Conference on Engineering Design Optimisation, Munich, Germany, July 18-20, 2016.
65. Mortished C, Ollar, J., Jones R, Benzie P, Toropov V, Sienz J (2016) Aircraft wing optimisation based on computationally efficient gradient-enhanced kriging. 57th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Kissimmee, FL, USA, January 4-8, 2016
66. Ollar, J., Toropov V, Jones R (2015) Adaptive sub-space approximations in trust regions for large scale MDO problems. 56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, FL, USA, January 5-9, 2015.
67. Ollar, J., Toropov V, Jones R (2014) Mid-range approximations in sub-spaces for MDO problems with disparate discipline attributes. 15th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, GA, USA, June 16-20, 2014.
68. Terence Macquart, Marco T. Bordogna, Paul Lancelot, Roeland De Breuker (2015) Derivation and application of blending constraints in lamination parameter space for composite optimisation. Composite Structures, Volume 135, January 2016, Pages 224–235.
69. Lancelot, P.M.G.J., de Breuker, R. (2016). Aeroelastic tailoring for gust load alleviation. Proceedings of the 11th ASMO UK / ISSMO / NOED2016 Conference on Numerical Optimisation Methods for Engineering Design, July 18-20th 2016, Munich, Germany
70. Serhat, G., Faria, T.G., and Basdogan, I. "Multi-Objective Optimization of Stiffened, Fiber-Reinforced Composite Fuselages for Mechanical and Vibro-Acoustic Requirements," 17th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, (AIAA 2016-3509), Washington, D.C., 2016.
71. Serhat, G., and Basdogan, I. "Effect of Several Modelling Techniques and Parameters on the Optimization of Composite Laminates for Vibro-Acoustic Requirements," 11th ASMO UK/ISSMO/NOED2016: International Conference on Numerical Optimisation Methods for Engineering Design, Munich, Germany, 2016.
72. Serhat, G., and Basdogan, I. "Comparison of vibro-acoustic performance metrics in the design and optimization of stiffened composite fuselages," 45th International Congress and Exposition on Noise.
73. S. Shahpar (2011). Challenges to overcome for routine usage of automatic optimisation in the propulsion industry, The Aeronautical Journal, 115, paper no. 3637.