Multidisciplinary Optimization of a Transonic Fan Blade for High Bypass Ratio Turbofan Engines

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This paper presents the multidisciplinary and multiobjective optimization of a transonic fan blade for a high bypass ratio turbofan engine. Aerodynamic as well as static and dynamic structural performance criteria are considered in the optimization process. A two level optimization strategy is applied consisting of a Differential Evolution algorithm coupled to a Kriging surrogate model and high-fidelity Computational Fluid Dynamics and Computational Structural Mechanics analysis tools. The fan blade is designed for a long-range aircraft mission. The first objective in the optimization is therefore the maximization of the efficiency at cruise conditions. A second objective is defined in order to keep the vibration response of the fan as low as possible within its operating range. In addition several aerodynamic and structural constraints are imposed. An efficiency gain at the design point of 2.47% and an overall improvement of the vibration response of the fan blade prove the effectiveness of the optimization system.

Nomenclature

CFD	=	Computational Fluid Dynamics
CSM	=	Computational Structural Mechanics
DE	=	Differential Evolution
FEM	=	Finite Element Method
RANS	=	Reynolds-averaged Navier-Stokes

I. Introduction

High bypass ratio turbofan engines are nowadays the de-facto standard for powering medium and long range aircraft due to their high thrust and good fuel efficiency up to high subsonic aircraft speeds. One of the central components of the turbofan engine is the fan, which generates the majority of the engine's thrust and plays a key role for its fuel efficiency. Besides the apparent need to be aerodynamically efficient in order to reduce engine fuel consumption, the fan blades need to withstand considerable static and dynamic structural loads to which they are subjected to during operation. The design process of fan blades is therefore a multidisciplinary problem. Further complexity is added to the design problem by a high level of interaction between the different disciplines, which prevents one discipline to be optimized in isolation if a global optimal solution is sought. In this paper a multidisciplinary and multiobjective optimization system is presented and applied to the design of a transonic fan blade for a high bypass ratio turbofan engine. Structural and aerodynamic performances are treated concurrently in the optimization process, therefore allowing to find global optimal solutions in a limited design time.

II. Optimization System

The optimization system shown in Fig. 1 is the result of more than one and a half decades of research and development at the von Karman Institute[1,2]. Its core components are a multi-objective Differential Evolution algorithm [3], a database, several metamodels, including Radial Basis Functions, Artificial Neural Networks and Kriging, and a high-fidelity evaluation chain including a fully automatic geometry and CAD generation, automatic meshing and high-fidelity performance evaluations by Computational Fluid Dynamics (CFD) and Computational Structural Mechanics (CSM). The optimization system is based on a two-level approach with a Kriging metamodel being applied in the present application. An initial sampling of the design space is

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performed using a fractional factorial design containing 65 samples, whereas each sample is analyzed by the high-fidelity evaluation chain. The resulting relation between design parameters and performance is stored in the database which is used to generate a Kriging metamodel. Subsequently, the Differential Evolution algorithm is applied to find the best designs based on the metamodel predictions. A number of these designs are then re-evaluated by the high-fidelity evaluation chain and the results are added to the database, which is used to re-generate the metamodel. This process is expected to increase the prediction accuracy of the metamodel in the regions where it previously predicted optimal designs. In this paper, an entire loop consisting of metamodel generation, DE optimization, high-fidelity re-evaluation and storage of the results in the database is termed *iteration*.

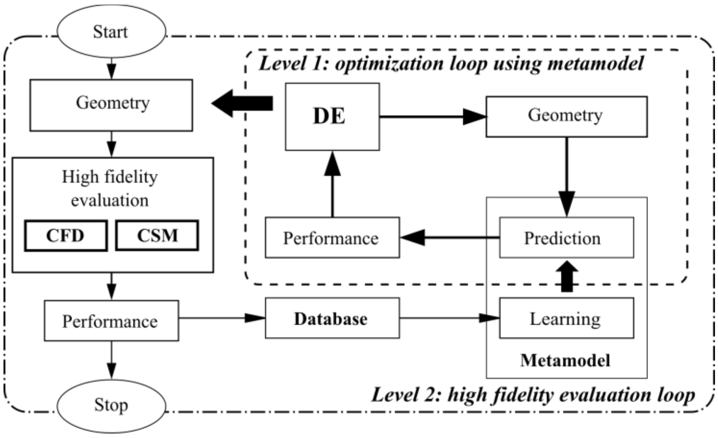

Figure 1. Flow chart of the optimization system.

III. Fan Blade Parametrization

The geometry of the fan blade is defined by parametric Bézier and B-Spline curves which specify the blade chord, blade angles, the thickness distributions at hub and tip sections and the profile stacking axis by lean and sweep. The control points of the parametric curves are used as optimization parameters. A total of 31 optimization parameters are defined in this work, allowing all of the above mentioned quantities to change within specified limits during the optimization process.

IV. High-Fidelity Performance Evaluations

The commercial 3D Reynolds-averaged Navier-Stokes solver FINE^{TM}/Turbo is used for the aerodynamic performance evaluations of the fan blade. The fluid-domain is discretized with a multi-block structured mesh consisting of 1.8 million grid points. Five operating points on a constant speedline are computed by varying the outlet pressure. Turbulence effects are computed with the one-equation Spalart-Allmaras turbulence model.

The solid domain of the fan is discretized with an unstructured mesh consisting of quadratic tetrahedral elements. The open-source Finite Element Solver CalculiX[4] is used for the structural analyses which consist of static stress and vibration analyses. The static stresses are computed using non-linear geometric analyses. The blade is subjected to centrifugal loads at take-off conditions and pressure loads, which are obtained from the CFD computations and interpolated onto the FEM grid. The vibration of the fan blade is assessed by modal analyses whereas centrifugal stiffening of the structure is included in the computations. Blade vibrations are computed at three main operating points; take-off, top of climb and cruise. The Campbell diagram is used to compute the margin between excitation frequencies and blade natural frequencies at the rotational speeds associated with the aforementioned operating points. Excitations from one per revolution and two per revolution disturbances are considered covering possible sources like unbalance and cross-wind. Resonance is computed for the first ten harmonics of each excitation source and the first four Eigenmodes of the fan blade. The blade is modeled using material properties of Titanium. The computational domains for both fluid and solid are shown in Fig. 2. It should be noted that the solid domain includes the dovetail root of the fan blade for an accurate computation of stresses and vibrations.

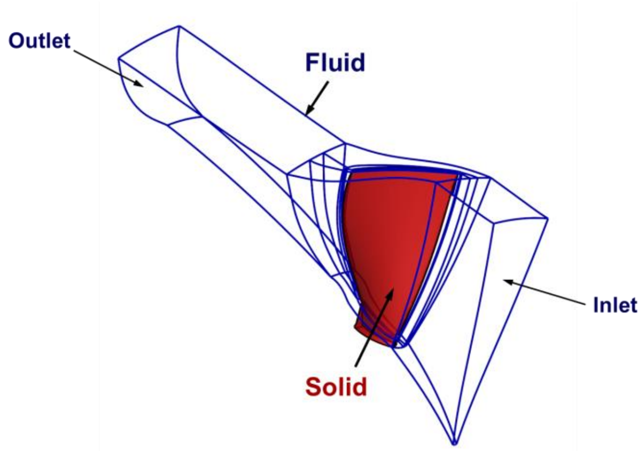

Figure 2. Computational Domains

V. Objectives and Constraints

Two objectives and five constraints are specified in this optimization. The first objective is the maximization of the isentropic total-to-total efficiency of the fan blade at the design point mass flow of 576 kg/s at cruise conditions. The second objective is the maximization of the margins between excitation and natural frequency of the fan blade for the three critical operating conditions take-off, top of climb and cruise.

As a first constraint, the minimal stall margin is specified. This margin specifies the mass flow difference between the design point and the point where the flow through the fan becomes unstable and stall or surge occurs. The second constraint is the design requirement that the total pressure ratio at the design point needs to be equal or bigger than 1.5. The third and fourth constraints are defined to ensure that the design point mass flow of 576kg/s is within the stable operating range of the fan. More specifically, the stall point (i.e. the last stable operating point towards low mass flows) needs to have a mass flow which is lower than the design point mass flow. Consequently, the choke point, which is the operating point with the highest mass flow in the fan's operating range, needs to be at a higher mass flow than the specified design mass flow. The fifth and last constraint is defined to ensure that the maximum von Mises stresses in the fan blade are lower than the yield strength of the titanium material.

VI. Optimization settings

The optimization is performed with a population size of 40 individuals per Differential Evolution generation. In each iteration 1000 generations are created based on the previously generated Kriging metamodel and 6 candidate individuals are chosen from the predicted Pareto-front for re-evaluation by the high-fidelity evaluation chain. The Differential Evolution cross-over constant is set to 0.8 and the mutation constant to 0.6.

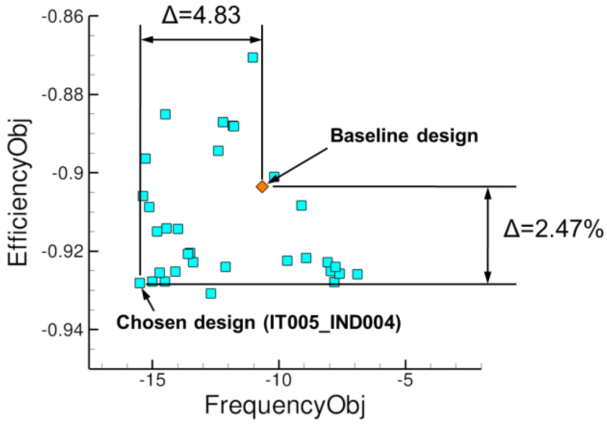

Figure 3. Objective space after 16 iterations. Only designs which are satisfying the constraints are shown.

VII. Results

In Fig. 3 the objective space after a total of 16 iterations is shown. All symbols in the figure indicate a design which is satisfying all of the above specified constraints. The orange diamond indicates the baseline design. It should be noted that the maximization problem was converted to a minimization problem; therefore improved performance is obtained towards the lower left corner of the objective space. As can be observed, a considerable performance gain of 2.47% in efficiency and 4.83 in frequency margin were obtained with respect to the baseline design after only five optimization iterations, which is equal to overall 95 high-fidelity performance evaluations. It is a quite remarkable result that the continuously updated Kriging metamodel is able to guide the optimization towards feasible regions in the design space and enables to find designs with improved performance within only a very limited number of iterations, although the optimization problem includes quite restrictive constraints. In total only 32 out of 161 designs that have been evaluated by the high-fidelity tools are actually satisfying all of the imposed constraints.

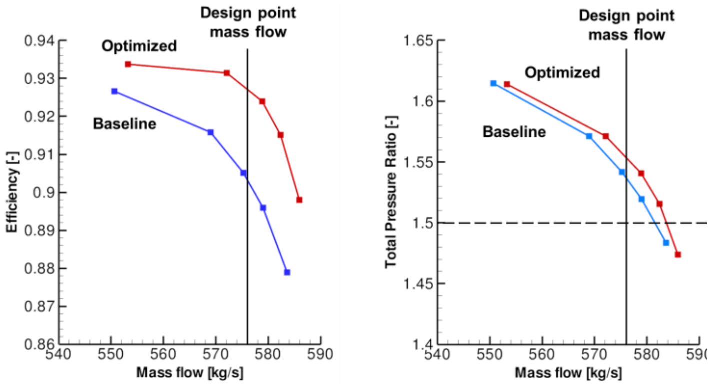

Figure 4. Performance curves of the baseline and the optimized designs.

As shown on the left hand side of Fig. 4, the optimized design shows a considerable efficiency improvement over the entire operating range. It is noticeable that the higher efficiency does not come at the cost of a narrower operating range compared to the baseline design. Solely a slight shift of the entire range towards higher mass flows is obtained. The pressure ratio has been slightly increased as well as shown on the right hand side of Fig. 4 and is well above the imposed constraint value of 1.5 (as indicated by the dashed line).

The origin of the frequency margin improvement shown in Fig. 3 can be best investigated by consulting the Campbell diagram for both baseline and optimized designs as shown in Fig. 5. For the baseline design two dangerous regions with particularly low margins between natural and excitation frequencies can be identified, which are indicated by the red ellipses in Fig. 5. The ellipse on the top right indicates the existence of a resonance point between the fourth blade eigenmode and the fifth engine order which is located in close proximity to take-off rotational speed. This resonance point has been successfully removed in the optimized design by stiffening the blade and therefore increasing the natural frequencies of the fourth eigenmode of the blade. A second and more severe situation exists between the first eigenmode of the baseline fan having a dangerously low margin to the first engine order which extends over the entire operating range and therefore posing a potential danger for excitation of the mode at all three key operating points. Also this situation was successfully resolved in the optimized design by increasing the natural frequencies of the mode, therefore increasing the margin towards the excitation frequencies at all three operating points.

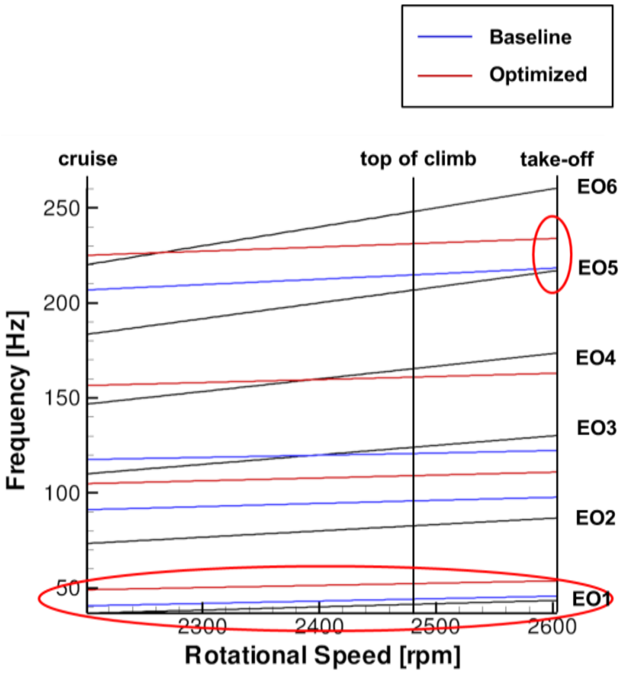

Figure 5. Campbell diagram of baseline and optimized designs.

The database which contains all designs that were analyzed by the high-fidelity evaluations provides a wealth of information for in depth analysis of the relationship between optimization parameters and objectives and constraints. Such an analysis provides essential information to the designer as it not only allows understanding the influence of single optimization parameters on the performance, but also the underlying physics that lead to improved designs. In this optimization, it was found that the gain in isentropic efficiency is strongly linked to sweep at the tip section of the blade. A plot of the isentropic efficiency versus the tip sweep is shown in Fig. 6. As indicated on the top part of Fig. 6, backward sweep of the tip section is defined as a translation of the blade profile at the tip along the chord line in the downstream direction. In contrast, forward sweep is defined as a translation in the opposite upstream direction. The red diamonds in Fig. 6 show the initial DOE samples, while each white square stands for a design that was evaluated during the optimization. The chosen design in turquoise is specially marked. The data shows that a correlation exists between increasing efficiency and forward sweep of the tip. The blue arrow shown in Fig. 6 was added to visualize this trend. This is not a new finding – forward sweep of the tip was already found to have a positive effect on efficiency and operating range of transonic fan blades in the mid-1990s[5] and has since then evolved to a standard design feature. It is however noteworthy, that this trend is confirmed in the optimization. However, despite the positive effects on aerodynamic performance, the best design chosen from this optimization does not have the highest possible amount of sweep, as can be seen in Fig. 6. The reason for this is that sweep strongly increases the stress levels due to increased bending moments in the blade. The designs that are exceeding the efficiency of the chosen design with higher amounts of forward sweep all show a violation of the stress constraint. Sweep is therefore a parameter which clearly

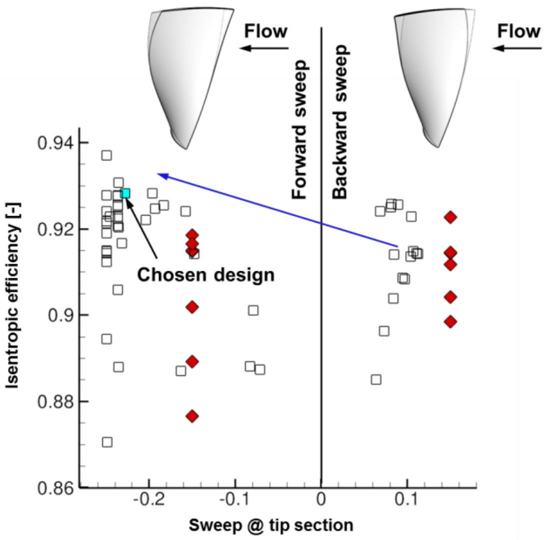

Figure 6. Efficiency versus sweep at the tip section.

demonstrates the need for multi-disciplinary optimization.

Another parameter with a strong influence on aerodynamic and structural performance is the thickness scaling factor at the hub section of the fan blade; see the right hand side of Fig. 7. The scaling factor was introduced as an optimization parameter in order to allow the entire thickness distribution at the hub profile section to be uniformly scaled without changing the shape of the distribution from the leading edge to the trailing edge. The effect of the hub thickness scaling factor on the isentropic efficiency is shown in the plot on the left hand side of Fig. 7. As can be seen, maximum efficiencies are obtained with small values of the scaling factor, i.e. a thin blade. This is reasonable from an aerodynamic point of view, since secondary flow losses near the hub are sensitive to the blade thickness. However, a certain thickness of the blade is needed in order to keep the stresses within acceptable limits and avoid blade failure. This is the reason why the chosen design has a relatively high thickness scaling factor. Similar to the previously discussed tip sweep, this parameter shows a tradeoff between aerodynamic performance and structural integrity. This is further exemplified in Fig. 8, where the maximum von Mises stresses in the blade are plotted over the hub thickness scaling factor. The red dashed line has been added to visualize the yield stress of the material which was added as a constraint in the optimization. An adverse trend with respect to Fig. 7 can be seen, with designs mainly being clustered above a scaling factor of 1.3. However, the other imposed constraints and vibration considerations eventually lead to a thickness scaling factor of about 1.7 of the chosen design.

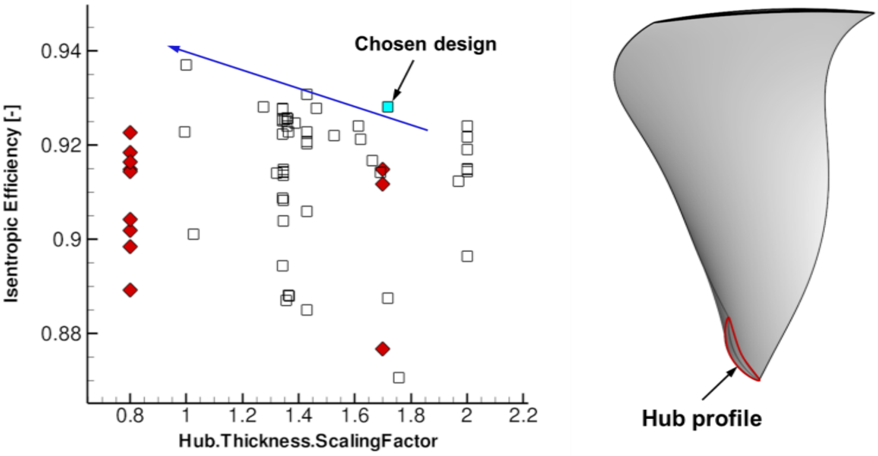

Figure 7. Efficiency versus thickness scaling factor at the hub section.

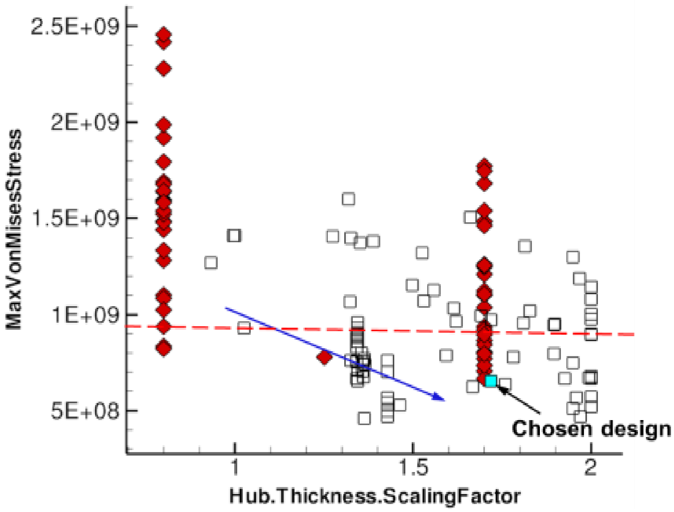

Figure 8. Maximum von Mises stresses versus thickness scaling factor at the hub section.

VIII. Conclusions

This paper presents the application of a two-level optimization system based on a Differential Evolution algorithm and a continuously updated Kriging metamodel to the multidisciplinary and multiobjective optimization of a transonic fan blade for a high bypass ratio turbofan engine. Aerodynamic as well as structural static and dynamic performance criteria were considered in the optimization process by using high-fidelity CFD and CSM computations for the design evaluations. Improved designs were found after only a very limited number of function evaluations with the best design found after 5 iterations (95 high fidelity design evaluations).

An efficiency improvement of 2.47% at the design point with no penalty in operating range and a considerable improvement in the vibration response were obtained.

A detailed analysis of the influence of single optimization parameters on the aerodynamic and structural performances allowed identifying the most important parameters that contributed to the improved design. From an aerodynamic point of view, forward sweep at the tip section was found to have a dominant impact on the efficiency improvement. An overall increase of blade stiffness with respect to the baseline design was necessary in order to avoid dangerous vibration excitations within the operating range of the fan blade. Tip section sweep and thickness at the hub section were discussed as two examples which showed a tradeoff characteristic between aerodynamic performance and structural integrity, therefore underlining why a multidisciplinary optimization framework needs to be applied for such design problems.

Acknowledgments

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