AUTOMATION AND OPTIMISATION OF COMPRESSOR BLADE DESIGN WITH RESPECT TO MECHANICAL CRITERIA

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Abstract: In general, design of high pressure axial compressor blades involves several disciplines such as aerodynamics, CAD and stress analysis. Typically most of the design tools use graphical user interfaces (GUI) and only rarely they run in batch mode. However, for blade optimisation the whole design process must be automated and, therefore, has to be free from user interactions, especially the CAD part and FE-analysis.

This paper shows an example for process automation in the presence of such design tools and optimisation of an compressor blade regarding minimum mass and flutter sensitivity.

1 DESIGN PROCESS

Design of modern aero engines is typically split into component design tasks related to compressor, combustor and turbine, where each design task is split again into disciplinary subtasks regarding aerodynamic and mechanical aspects, respectively. Increased performance requirements and call for decreased development time and costs require new design concepts integrating analysis tools from different disciplines. In the following an investigation is shown where a typical part of the compressor blade design process at the Rolls-Royce company was analysed, automated and integrated in a common optimisation environment.

1.1 Current design process

Starting from one-dimensional meanline prediction, where global flow and geometry parameters are determined, the subsequent throughflow calculation provides radial parameter distributions. Based on these, blade-to-blade calculation is applied to design 2-dimensional blade geometries which fulfil the given flow angles and flow conditions on several radial stream surfaces. The final 3-dimensional blade geometry is generated by stacking the 2D blade profiles along a specific stacking line including additional design rules as bow and lean which define a spatial free-form surface tangential to all blade profile sections.

As soon as a 3D-aerofoil geometry is generated, it is transferred to a CAD-system as an unparametrised object where a standardised CAD interchange format like STEP203 is used. After the transfer the aerofoil is connected with a parametrised platform and root through a fillet radius. Finally, the blade is transferred to a FE-system for HCF (high cycle fatigue) and LCF (low cycle fatigue) analysis.

If the blade does not satisfy the stipulated mechanical criteria, the whole design process loop has to be restarted. A direct connection between the different disciplines does not exist yet. Each restart of this design process demands a considerable amount of work for the design engineers. Through the import of the aerofoil in the CAD-system as unparametrised object, all links between this unparametrised object and the platform are disconnected if the aerofoil is reimported. On this account the designer has to reassemble the aerofoil and platform each time.

The import of external geometry-data in CAD-systems has been simplified in the last years, but the programs still have to be guided manually by interactive user actions. A direct automation of this process as described is not possible but requires some modifications especially with respect to design parametrisation and data exchange.

1.2 A new approach for the design process

The new approach is based on data exchange of parametrised 2D-blade profiles where the same type of geometry description is used for aerodynamic design and assembly in the CAD system. Aerodynamic design is performed with the Rolls-Royce in-house tool *Parablading* parametrising the 2D blade sections in a length-preserving $(m-r-\theta)$ -coordinate system along the stream surfaces by cubic B-splines which are tangentially continuous at the B-spline crossover points [1]. The nodal and control points of the splines are then transferred to the *Unigraphics NX2* CAD system where the coordinates are transformed from the $(m-r-\theta)$ -coordinate system to the global $(x-y-z)$ -frame via

$$
\begin{aligned}
x &= x_0 + \int_{m_0}^{m} \sqrt{\left(1-(dr/dm)^2\right)}\,dm \\
y &= r\cos\theta \\
z &= r\sin\theta
\end{aligned}
\tag{1}
$$

The CAD-system is then able to automatically build up the spatial 3-dimensional aerofoil geometry by using knowledge based rules. The advantage of this procedure is that beside the geometry information the CAD system will also keep the necessary assembly information with the platform and the root. This results in a fully parametric CAD-model as shown in Figure 1 which allows design changes on both the aerofoil and the platform.

2 PROCESS AUTOMATION

The classical, human driven design process heavily relies on experience and intuition of the design engineer who automatically takes into account additional self-evident rules like smoothness of the aerofoil. Numerical optimisation, however, will accept any arbitrary shape with best performance while fulfilling given constraints only. Thus, setting up an automatic optimisation process requires more care about design parametrisation and formulation of design criteria and constraints.

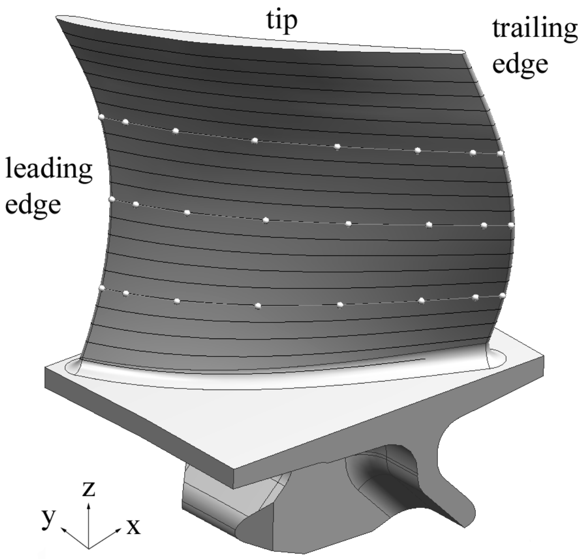

FIGURE 1: 3D rotor blade model with parametrised aerofoil

2.1 Design parametrisation

In *Parablading* the shape of the aerofoil can be controlled via parameters like the coordinates of the control points of leading and trailing edges as well as pressure and suction sides. Alternatively, more descriptive parameters like the maximum thickness, chord length, theta-shift, axial shift and stagger angle for each section, respectively, can be modified. A direct modification of selected profile parameters, however, would lead to undesired leaps and non-smooth transitions between sections. For this reason, radial distributions of such parameters are used which are described as parametric curves in 2-dimensional spaces spanned by section number and corresponding parameter.

In the following investigation, the maximum thickness of the sections is used as design quantity where the correlation between section number and thickness of an individual section is described by a B-spline with five control points, Figure 2. Design changes can then be performed by moving the control points and extracting the thickness of a specific section from the B-spline.

The advantages of this parametrisation are

- parameter reduction, since the number of control points is less then the number of blade sections,
- any design change on control points will result in smooth distributions for the blade thickness, and
- the characteristics can be adapted to both rotor and stator thickness distributions.

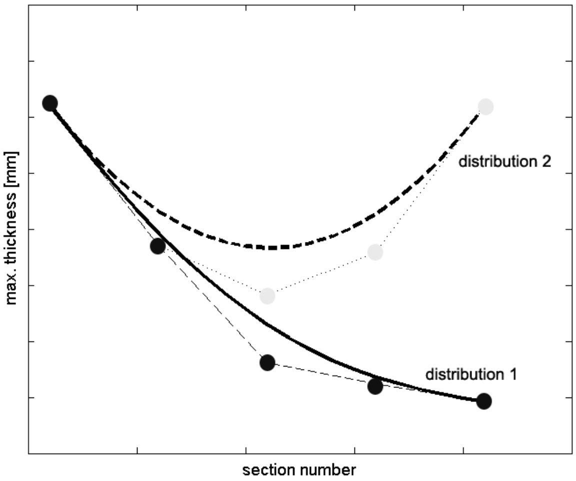

FIGURE 2: Radial blade thickness distributions

2.2 Design criteria

One of the design goals is to find blades with minimum mass which has major influence on disk loading, and thus on the sizing of the rotor disk. The latter is strongly correlated to disk weight and finally to the whole engine weight.

A second design goal is durability with respect to dynamic loading which can be measured according to the Goodman diagram by

$$(2) \quad AF = \frac{\hat{\sigma}_a}{\sigma_a}\left(1 - \frac{\sigma_s}{R_m}\right) .$$

This factor relates the alternating stress amplitude σ_a for a given mean stress σ_s to the resistance $\hat{\sigma}_a$ against dynamic bending and the ultimate tensile strength R_m .

The stresses have to be taken from a FE-analysis based on the 3-dimensional blade model provided by the CAD system. Therefore, the blade geometry is transferred as native format to the FE-system and meshed. After defining boundary conditions, gas loads and rotor speed, the FE system gives the necessary information on low and high cycle fatigue as well as frequency information.

Forced blade vibrations result from flow disturbances acting periodically on the blades. To identify forced response regions, the Campbell diagram may be used, Figure 3. Especially crossings of the eigenfrequencies $f_i(n)$ of the blades depending on rotor speed n with multiples of the rotor speed jn according to the engine orders j are identified and labelled as $f_{i,j}$.

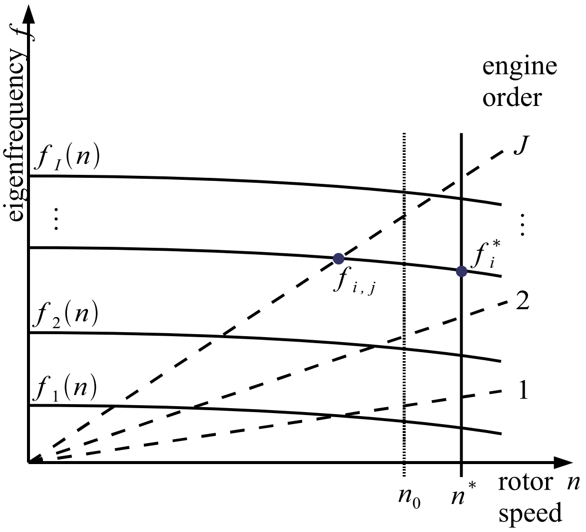

FIGURE 3: Campbell diagram

A major part of mechanical criteria deals with avoidance of dangerous resonances due to circumferential variations in the steady state aerodynamic loading associated with engine orders. For maximum rotor speed n^* this can be expressed by the relative distances of the eigenfrequencies $f_i^* = f_i(n^*)$ from the excitation frequencies $j\ n^*$:

$$(3) \quad \nu_{i,j} = \frac{|f_i^* - j\ n^*|}{j\ n^*} \cdot 100\% .$$

Beside resonance self-exiting flutter is one of the most critical reasons for failure. Without sufficient damping any small initial vibration can lead to increasing amplitudes. According to [2] and [3] the reduced frequency

$$(4) \quad \omega_i^* = \frac{2\pi f_i^* C}{U_{rel}}$$

may be taken as characteristic value evaluated for maximum rotor speed n^* with the chord length C as characteristic length and the downstream inlet velocity U_{rel} as characteristic velocity.

2.3 Process integration and control

The integrated design process is shown in Figure 4 consisting of three columns summarising modules for process flow control, design evaluation procedures and external programs, respectively, which are embedded in the automation and optimisation environment *iSight* [4]. The process flow involves initialisation of design conditions and initial design, design exploration or optimisation methods, and post processing of the optimisation results.

The optimisation algorithm interacts with the design evaluation flow which is also defined in *iSight*. For given parameters like the thickness distribution, the integration program firstly calls *MATLAB* as an external procedure to perform adequate modification on the B-spline described in section 2.1 and extract the desired discrete thickness values for the various blade sections.

These values are written to the input file of *Parablading* which modifies the aerofoil and creates an output file with all control points and knots of the 2-dimensional blade section profiles. Together with a modified parameter file, this dfa-file contains all information necessary to create the 3-dimensional blade including platform and root in the CAD-system *Unigraphics NX2*. The resulting geometry is transferred to the FE-system *ANSYS10* via a prt-file. After meshing the FE-program performs static and dynamic analyses and returns stresses and eigenfrequencies to *iSight* via file parsing. Based on these values, *Excel* sheets are used to evaluate objective and constraint functions.

3 OPTIMISATION

As seen in the previous chapter, realistic design tasks typically result in optimisation problems with several conflicting objectives and constraints. The multi-criterion optimisation approach offers an adequate mathematical concept to deal with such conflicting design goals. As a result one obtains a set of non-dominated compromise solutions, also called Pareto optima, which means that no objective value can be improved without worsening at least one other objective.

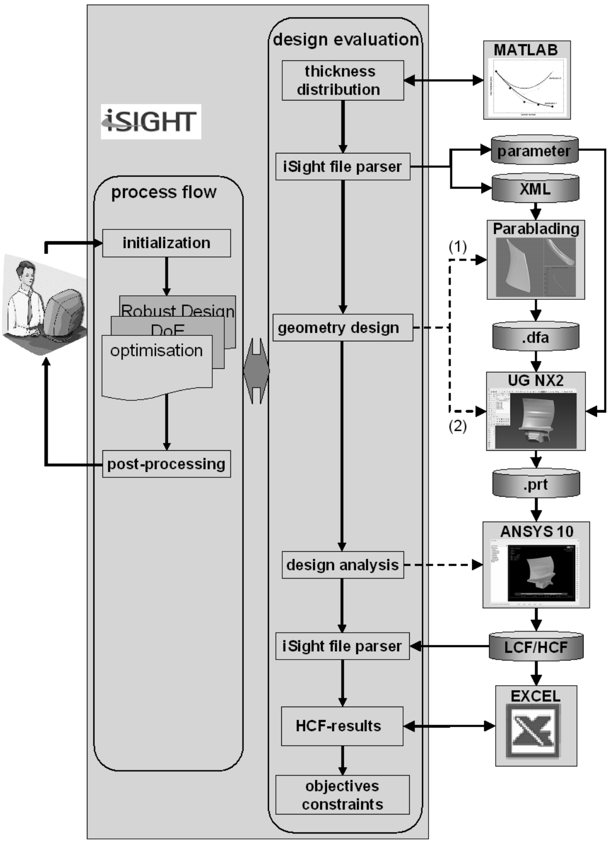

FIGURE 4: Integrated mechanical blade design process

3.1 Problem formulation

In the following investigation the control points of the thickness distribution described in section 2.1 serve as design variables. Additionally the fillet radius between aerofoil and platform is used as a design variable and summarised together with the control point coordinates in the design vector $\boldsymbol{p}$.

As described in section 2.2, one of the design goals is to minimise the mass m of the blade. Another design goal is to keep away the first bending mode from flutter instability. This may be expressed by maximising the reduced frequency ω^*_{1B} according to definition (4) where f_i^* has to be substituted by the first bending eigenfrequency at maximum speed. Since maximisation of a function yields the same result as minimising of its negative, the design problem can be formulated as

$$(5) \quad \min_{p\in P}\begin{pmatrix} m \\ -\omega^*_{1\mathrm{B}} \end{pmatrix}$$

where P denotes the set of admissible designs. This subset is given by design constraints on stresses and eigenfrequencies where the hat quantities are user-defined constants according to Rolls-Royce design guidelines:

$$(6) \quad \min_{i\in[1,I]} \nu^*_{i,j} \geq \hat{\nu}_j, \quad j=1(1)J$$

$$(7) \quad AF \geq \widehat{AF}$$

$$(8) \quad \begin{array}{l} \omega^*_{1\mathrm{B}} \geq \hat{\omega}_{1\mathrm{B}} \\ \omega^*_{1\mathrm{T}} \geq \hat{\omega}_{1\mathrm{T}} \end{array}$$

$$(9) \quad f_{1,j} \geq \hat{\gamma}_j \, n_0, \quad j=1(1)J$$

$$(10) \quad \frac{f^*_{k+1}-f^*_k}{f^*_k} \geq \hat{\nu}_{k,k+1}, \quad k=1(1)K$$

The inequality constraints (6) enforce a minimum distance between the first I eigenfrequencies of the blade and the excitation frequencies resulting from the first J engine orders at the maximum rotor speed. Condition (7) constrains the dynamic stress amplitude for a given mean stress according to equation (2). In order to avoid flutter, the first bending and torsion eigenfrequencies have to lie above prescribed values which is expressed by inequalities (8), respectively. Resonance avoidance is achieved by lower limits (9) on the eigenfrequencies compared to the excitations by the first J engine orders where n_0 denotes the design rotor speed and $\hat{\gamma}_j \in (0,1)$ are user-defined constants. Finally, constraints (10) enforce frequency separation of the first $K+1$ vibration modes.

3.2 Optimisation results

The multi-objective optimisation problem (5)-(10) is solved with the neighbourhood cultivation genetic algorithm (NCGA). This algorithm introduced by Watanabe [5] is an advancement of the SPEA2 algorithm developed by Zitzler [6]. In addition to the SPEA2 algorithm, NCGA implies the mechanism of neighbourhood crossover. Twenty individuals are chosen as members of the starting population, which are then carried forward for 40 generations, summing up to a total of 800 design evaluations. About 90% of the runs have been feasible.

Figure 5 shows a comparison of the optimisation results with a reference design. Both goals are improved where the mass can be reduced by approximately 5% for identical flutter safety and the reduced frequency may be increased by about 9% for identical mass.

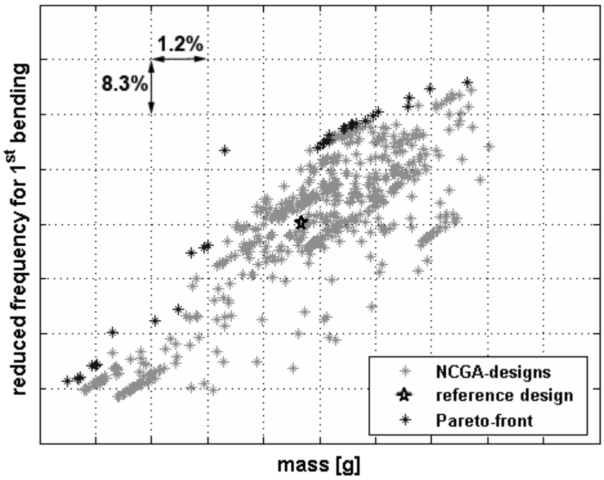

FIGURE 5: Optimisation results with NCGA

4 CONCLUSIONS AND OUTLOOK

The paper presents an example of a multi-disciplinary optimisation process applied to mechanical blading design for an axial compressor. The two important steps are automation of originally GUI-based design tools with automatic data transfer between the different analysis programs and proper parametrisation for smooth geometry modification. All subtasks are integrated in the process automation software *iSight* offering various optimisation algorithms like the NCGA. The goal to automate a realistic technical design process in a common optimisation environment could be achieved and better designs then the human benchmark reference design could be obtained.

Based on these promising results, future investigations will have to extent the present process with respect to additional aerodynamic design criteria resulting in a more rigorous multi-disciplinary optimisation chain. A key element for this extended process will be to adapt gas loads according to aerofoil modifications during the design process.

5 ACKNOWLEDGE

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