COUPLING OF PREDESIGN AND PERFORMANCE TOOLS FOR TRANSIENT AIRCRAFT ENGINE ANALYSES

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Abstract

Aero-engine performance is facing increasing demands with respect to thrust requirements, ratings and operational reliability. By that, it places a heavy burden especially on transient engine behavior. Evaluating this transient performance early in the design process of aero-engines aids to reduce the immense costs accompanied with engine development. For that purpose it is inevitable to integrate predesign and transient performance tools to give a more holistic view of tolerable new engine concepts.

In the present paper, a methodology for the direct coupling of preliminary engine design and transient performance via a central data model is presented. This methodology is explored at the example of a high-pressure compressor (HPC) similar to the one used in the IAE V2500 turbofan. Predominant transient performance phenomena such as rotor inertia, heat soakage and tip clearance changes in the turbo-components are captured in this process chain. Furthermore, effects of aerodynamic design changes of the HPC on engine's acceleration are investigated.

Nomenclature

A	Area
BC	Boundary Condition
c	Specific Heat Capacity
C	Tip clearance
d	Derivative
GTlab	Gas Turbine Laboratory
HPC	High-pressure compressor
HPT	High-pressure turbine
HTC	Heat Transfer Coefficient
IAE	International aero engines
J	Mass Moment of Inertia
M	Mass
N	Rotational Speed
NACA	National Advisory Committee for Aeronautics
P	Total Pressure
PW	Power
$\dot{Q}$	Heat Flow
t	Time, Time Step
T	Temperature
u	Circumferential velocity
v_{axial}	Axial velocity
W	Mass Flow
η	Isentropic efficiency
ϕ	Flow coefficient
ψ	Pressure coefficient

1 Introduction

Development of new aero-engines is - among others - dedicated to achieve high overall efficiency, in order to reduce fuel flow and thus alleviating CO2 emissions. The demand for high efficiency is also accompanied by the necessity of operational safety. This includes for instance the prohibition of compressor surge during transient maneuvers. Furthermore, aircraft authorities set demands on maximum engine's acceleration time for reaching specified thrust rates [1]. Therefore, it is inevitable to include transient aero-engine performance into the overall design process of new engine concepts to take operational safety and authorities' requirements into account. Eventually, this gives the engine developers a more holistic picture to identify tolerable or inacceptable design concepts. Applying this method in the early design stage of the engine helps to diminish engine development time and costs.

There are various researchers that devoted themselves to the coupling of performance and preliminary design. Bretschneider [2] presents a preliminary gas-generator design tool that is fed with performance data. Several studies are performed in which design parameters are varied to show the effect on overall engine layout including component's sizes and weights. However, the link to transient performance is not part of his work.

Schulte et al. [3] use a meanline calculation tool to predict the aerodynamics of a compressor resulting in characteristics in the conventional form of a compressor for each individual stage. The thermodynamic compressor model is split into its individual stages that use the provided characteristics. By that, the iteration scheme is increased by one entry per stage. Transient heat flows and their effect on tip clearance are examined to explore compressor stability. The mass moment of inertia is not regarded in this study. Kurzke [4] presents the preliminary engine design and transient simulation capabilities of GasTurb. The engine is designed to yield the mass moment of inertia of the spools. Then acceleration from idle to take-off power in conjunction with a re-slam maneuver is simulated. Stage-wise tip clearance variations of a physics-based approach due to heat soakage are incorporated in the model. The compressor characteristic is not regarded in this study. Nielsen [5] investigates the effect of heat soakage and the subsequent tip clearance changes on component performance and stability. Similar to [3] a state-space approach is used to determine tip clearance changes, which requires previously identified matrices. The varied tip clearance values during transients are translated into modulation parameters for efficiency and mass flow. The transient performance simulation results are compared to measurement data of the BR710 engine. Visser and Dountchev [6] develop a thermal heat soakage code, implemented in the Gas Turbine Simulation Program GSP. In the lumped parameter approach, heat transfer among the components is allowed for. In turbomachinery part of the heat transfer is assumed to take place before and part of the heat transfer after the compression/expansion process.

The key aspect of the present paper is the interconnection between preliminary design and transient performance tools to give a more comprehensive insight into new engine concepts. This coupling is performed within the DLR's in-house gas turbine simulation framework GTlab, ensuring data exchange via a central data model [7] [8] [9] [10]. The design of a compressor along with its blade attachments, disks and casing yields data (e.g. mass moment of inertia, radii) for the subsequent transient simulation. Furthermore, the provision of the compressor characteristic of the newly designed compressor replaces the generic component map and thus allows examining the current configuration. The limitation of this method is based on the accuracy of the underlying meanline calculation.

2 Methodology

In order to present the methodology of coupling performance and predesign disciplines, the predesign part is restricted to the high-pressure compressor (HPC) for brevity.

2.1 General Procedure

The very first step of this paper's methodology is a performance model of an engine based on generic turbomachinery maps. The steady-state performance model provides boundary conditions (BC), such as the mass flow, rotational speed and pressure ratio. These BC in conjunction with other compressor design parameters are required for the subsequent predesign calculation routines. At the beginning, the compressor is designed, and then the masses of the blades are calculated with the aid of a 3D CAD kernel, see Figure 1. Next, the blade foots, disks and the casing are designed, which allow the calculation of the corresponding weights and the sum of inertia. Finally the compressor characteristics are calculated by applying the off-design mode of the compressor tool. Eventually the relevant data (mass moment of inertia, efficiency and geometry) is exported.

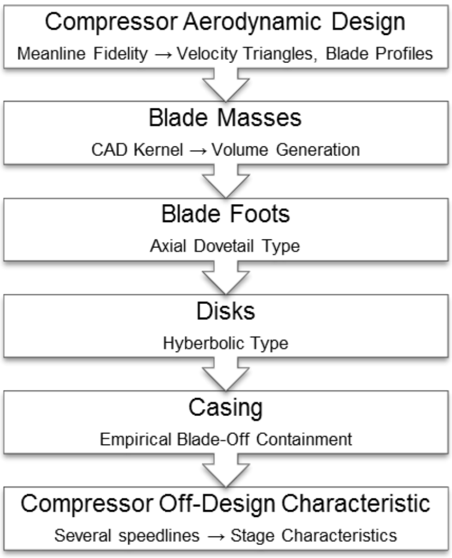

Figure 1 Predesign calculation routines

This exported data of the predesign workflow is applied to the performance model, as indicated in the flow chart in Figure 2. For the design point of the performance model only the efficiency of the compressor has changed by that. The design fuel flow is therefore adjusted to meet the design thrust requirement. This process is non-iterative, because the inlet conditions for the compressor do not change, since post combustion components are varied only. Therefore, the final engine design based on the designed meanline compressor is achieved. In the next step the fuel flow schedule for the transient maneuver is calculated and stored as an input for the following step.

Eventually, transient performance simulations are conducted. The mass moment of inertia for the high-pressure spool is retrieved from the predesign routine as well as some constant assumptions for the inertia of the HPT. Also, the newly generated stage maps are applied. The transient simulation yields performance quantities such as the thrust over time.
At this stage constant design parameters for the HPC are altered in the predesign calculation step and the subsequent process chain is repeated to investigate the effect on the transient behavior.

2.2 Thermodynamic Modeling

The thermodynamic steady-state performance calculation procedure of GTlab is described in detail in [8], [9] and [11]. In brief, a system of non-linear equations is solved in order to find a converged solution. That is due to the fact that for a fixed thrust demand the operating point in the component maps cannot be determined explicitly but must be guessed and then corrected based on the resulting offset.

2.3 Transient Modeling

The predominant influences for transient

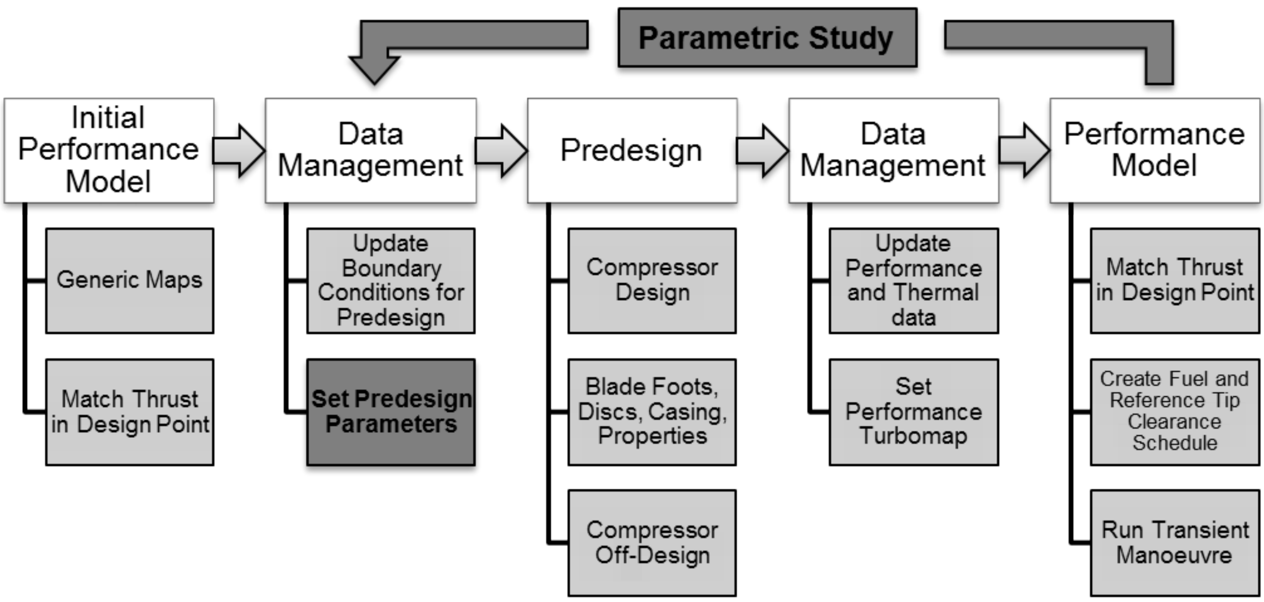

Figure 2 Process chain of coupling predesign and transient performance

performance are the rotor dynamics, heat soakage as well as the changes in tip clearance due to thermal expansion. Bauerfeind [12] was one of the first to outline the importance of heat soakage. Also Riegler [13] emphasized its importance to match transient experimental data. Among others, Khalid [14] modelled tip clearance changes during transients and proved a better agreement between measurements and simulation results by the inclusion of that. The compressor component is split into a front and an aft compressor, the tip clearance variations are averaged for both parts separately.

The basic transient thermodynamic simulation capabilities of GTlab for rotor dynamics as well as heat soakage are explained in [15]. In here, a brief summary as well as the extension of the heat soakage capabilities and the inclusion of tip clearance effects is elaborated on.

Owed the fact that the investigated transient maneuvers of this study comprise large time constants, volume packing effects are neglected. That is, because a fluid particle remains only about 1/100 seconds in the engine [16], whereas rotor acceleration falls in the range of seconds. Resolving mass storage effects becomes mandatory for compressor stability and reverse flow analysis but is not purposeful if large time scales such as rotor accelerations are investigated [17], [18].

2.3.1 Rotor Dynamics

In transient performance simulations the difference of the turbine power (PW_T) and the compressor power (PW_C) leads to an acceleration term.

$$PW_T - PW_C = \frac{dN}{dt} * J * N * \left(\frac{\pi}{30}\right)^2 \qquad (1)$$

With J being the mass moment of inertia and N being the rotational speed.

2.3.2 Heat Soakage

Compared to [15], the heat soakage calculation routines within GTlab were extended to allow for heat transfer among different components, bleed flows as well as the environment. More details can be found in Visser [6]. The so established thermal network is solved in every iteration of each time step in order to bring the components thermally to convergence. Another option to update the thermal network at the end of each time step only is implemented as well. The difference between the two options is negligible as long as the time step is kept small.

2.3.3 Tip Clearance

Secondary flow losses in turbomachinery are especially dependent upon tip clearance: If the gap is increased more flow can pass from the pressure side to the suction side degrading the lift of the airfoil, see Khalid [14]. Especially in the core turbo-components the tip clearance changes during transients must be considered due to the big clearance change to blade height ratio. For engine performance simulation quick calculation routines are favorable, especially considering the numerous time steps for transient simulations and the therewith associated computational cost. For that reason, a rather simple physics-based 1D approach for thermal expansion is developed similar to [4], as opposed to time-consuming higher-fidelity tools.

In here, the rotor blade row of a turbo-component is reduced to three different masses (case, blade and disk). Each of which contains geometric design data such as the inner and outer radius and the tip clearance as well as material data such as specific heat capacity and density. Furthermore, for the stress calculations a rim contribution for the radial stress at each inner and outer radius can be set. This is used for the transition between blade and disk, where the rotating blade causes a radial stress component at the rim.

In order to find the tip clearance C at a transient operating point the current tip clearance (C_{trans}, depending on the rotational speed N and the material temperature T) and the steady-state reference tip clearance (C_{ss}, depending on N only) of the current rotational speed have to be calculated, see Equation (2).

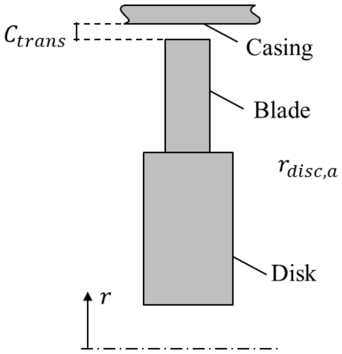

Figure 3: Rotor blade row replacement geometry in the performance

$$C = C_{trans}(N,T) - C_{ss}(N) \qquad (2)$$

The elongations of the case, blade and disk have to be determined using the general stress equation, taken from [19] to determine the tip clearance. Employing the superposition principle, the general stress equations are split to yield the contributions for temperature, spinning and rim individually. Thus, the stress calculation for the case is simplified because the spinning contribution is zero. Moreover, if one neglects the pressure of the working fluid, the rim contribution diminishes to zero as well. From the stresses the displacement can be determined. The temperatures of the case, blade and disk are regarded as time dependent only and independent of the radial position. This simplifies the equations in that thermal stresses can be neglected [4]. The steady-state reference tip clearance C_{SS} is determined prior to the transient calculation from the pre-determined working line and is retrieved from a schedule. This tip clearance effect is already incorporated in the steady-state component characteristic.

From the tip clearance C the efficiency and flow of the turbo-component are modulated. That is to take into account the increase of the swirl and its corresponding secondary flow losses when the tip clearance is increased for instance. For the constant modulation parameters, values similar to the ones used in [5] are employed.

2.4 Multi-Stage Compressor Modeling

The multi-stage compressor modeling is introduced into the steady-state and transient performance code by splitting the original compressor component (HPC) into its individual stages. This improves especially the dynamic modeling capabilities, since heat soakage effects can be resolved in the stages individually. By that, the transient matching of the subsequent stage is taken into account as opposed to the overall compressor model, where the applied characteristic is based on steady-state thermal and fluid effects only [20].

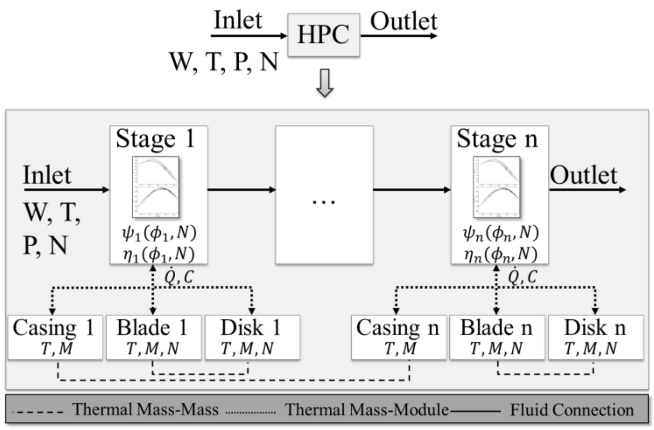

Figure 4: Multi-stage compressor model embedded in performance synthesis

The stage characteristics are employed in the conventional form of isentropic stage loading coefficient, also known as pressure coefficient (ψ) and isentropic efficiency (η) over flow coefficient ($\phi = \frac{v_{axial}}{u}$) [21]. Furthermore, it was found that providing the rotational speed as a scharparameter in the stage characteristics guarantees a better agreement to the aerodynamic meanline tool. Employing the rotational speed parameter ensures to take into account Mach number effects, which become important for relative inlet values greater than 0.75 [22].

Casing, blade and disk masses are defined for each stage to allow for heat soakage and tip clearance calculation. The individual casing masses are thermally connected as well as each blade mass with the stage's disk mass, see Figure 4. The heat flow ($\dot{Q}$) and tip clearance variation (C) from the solution of the thermal network affect the stage's performance and by that the entrance conditions for the subsequent stage. Eventually, stacking the stages together delivers the overall compressor performance.

2.5 Predesign Modeling

2.5.1 Compressor

The compressor modeling is based on a DLR in-house mean line methodology. The applied meanline algorithm is part of a GTlab internal library which provides various simple methods for initial component design [7]. The mean line tool can be used for geometry generation based on a set of user defined input variables. In addition to thermodynamic design parameters such as mass flow, target pressure ratio, inlet conditions and spool speed, compressor specific parameters are required. These include important stage parameters like the De-Haller number and the diffusion factor in the design point as well as a series of parameters required for profile loss calculation. The profile loss calculation is based on the experimental data determined for the NACA profile family [23]. Furthermore, the meanline tool can also be used for the calculation of compressor off-design performance based on existing geometries. One can calculate individual operating points, a speedline or multiple speedlines. By that, either a single map for the whole component or stage specific characteristics can be calculated and subsequently used within the performance model. The data exchange is performed via the central data model integrated in GTlab.

2.5.2 Blade Masses

The blade geometry is parameterized using the BladeGenerator parameterization. This parameterization is developed at DLR to support automated 3D-CFD blade optimization processes and features a high degree of freedom in the design of fan, compressor and turbine blades [23]. In addition, GTlab integrates the open source computer aided design (CAD) kernel Open Cascade which allows a complete three dimensional mathematical description of the engine parts and enables benefits like dimensional visualization and accurate estimation of important physical properties like mass, center of gravity and moments of inertia. Based on the blade data stored in the central data model and the CAD kernel, GTlab automatically generates the required 3D blade row models. By specifying a material, the mass of the blades is automatically calculated and is available in the subsequent process.

2.5.3 Blade Attachments, Disks, Casing

In addition to the blading, the total weight of the compressor mainly consists of blade attachments, disks and the compressor casing.
The geometries and masses of these structural-mechanical components are computed via calculation routines of the conceptual design toolset GTlab-Sketchpad [7]. The required boundary conditions and input values are derived from the thermodynamic data and the results of the compressor meanline tool. The calculation is carried out in case of any relevant changes in the design process and leads to a precise determination of the overall compressor weight.

3 Application

The methodology is applied to a performance model of a two-spool turbofan. This engine setup and the investigated variations are described briefly in the following.

3.1 Engine Setup

The engine model (Figure 5) used in this study offers a sea-level take-off thrust of 120 kN and is similar to the IAE V2500, installed on the A320 aircraft family.

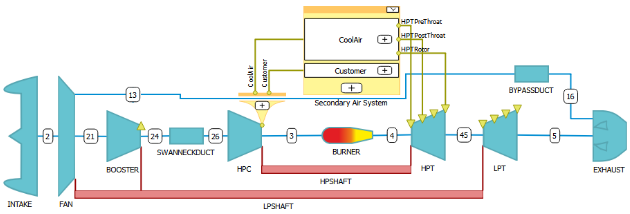

Figure 5: Turbofan Performance model

The fuel flow schedule for the transient simulation is retrieved from steady-state performance simulations of the engine at sea-level static conditions with 60 kN thrust for the starting point and 120 kN for the end point.

3.2 Case Study

The compressor tip radius is among the design input parameters of the applied meanline algorithm. The variation of this parameter with fixed remaining design conditions is investigated in this study. Each compressor design has an effect upon the performance results due to different mass moment of inertia, stage maps and geometric data (for thermal effects). For each compressor design the transient fuel flow schedule is determined in the performance model, starting with the required fuel flow for 60 kN of net thrust at 0 seconds and leveling off at the fuel flow for 120 kN of net thrust at 4 seconds. Eventually the transient maneuver is simulated.

Table 1 lists the variations of the compressor's tip radius along with the cases' names to be able to refer to them in the results section.

	Radius [mm]	Setup	Maps	Inertia	Geometry
Case01	270	A	✓	✓	✓
Case02	280	A	✓	✓	✓
Case03	290	A	✓	✓	✓
Case04	300	A	✓	✓	✓
Case05	310	A	✓	✓	✓
Case06 – Case10	270 - 310	B	✓	✓	×
Case11 – Case15	270 - 310	C	✓	×	×

Table 1: Overview of the investigated cases along with the effects taken into account

In general, the contributions of a different compressor design to the performance results can be divided into the following:

1) Stage maps
2) Mass moment of inertia
3) Geometric data.

In order to evaluate the different effects in more detail, further studies were conducted by employing the same radii (Case06 – Case15, see Table 1). From Case01 to Case05 all three contributions are considered. From Case06 to Case10 the thermal effects are switched off, thus the variation of geometric data for tip clearance corrections or for time constants of thermal masses is neglected. Therefore, only contribution 1 and 2 are considered. From case 11 to 15 only the different stage characteristics are employed to the performance model for different radii.

4 Results and Discussion

The results of the compressor tip radius variation are presented in the following. Two different compressor designs are shown in the cross-section in Figure 6.

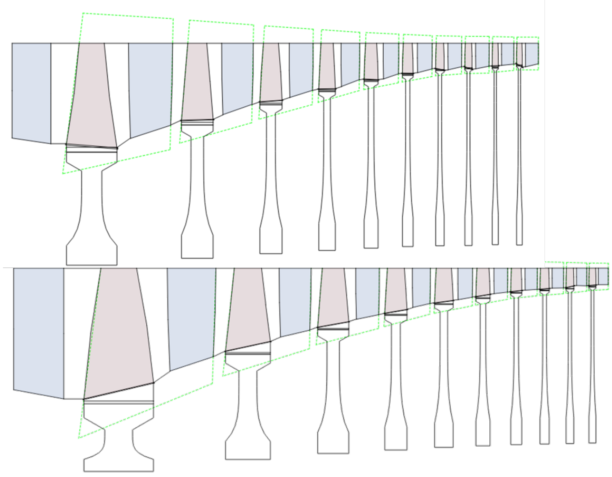

Figure 6: HPC design for two different radii (310 mm and 270 mm)

The mass moment of inertia increases with increasing tip radius while the efficiency shows the opposite behavior, see Figure 7. An adequate indicator for the thermal inertia of a mass is its time constant τ. This quantity can be calculated with the aid of the mass (M), thermal capacity (c), heat transfer coefficient (HTC) and the surface area (A): $\tau = \frac{M*c}{HTC*A}$ [4]. The time constant for the blade and the casing of the first compressor stage is shown in Figure 7.

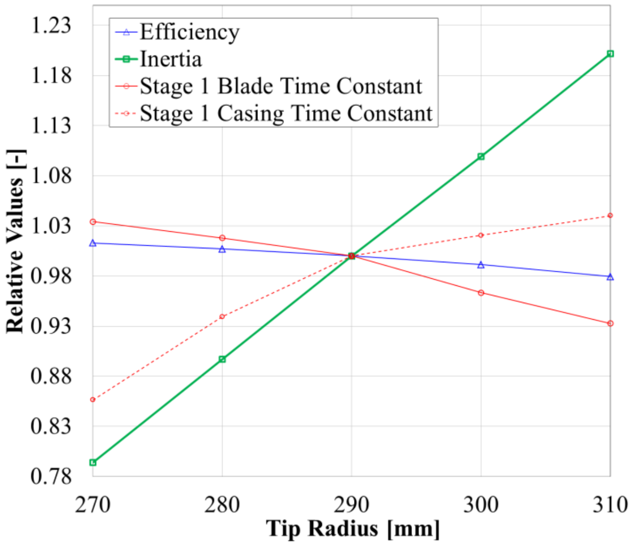

Figure 7: Meanline results for different tip radii

If the compressor tip radius is increased the time constant for the blade decreases, while the one for the casing increases. Although the mass of the first blade is lowered in Case01 (270 mm) compared to Case03 (290 mm), the time constant is higher. That is, because the reduced surface area outweighs the influence of the mass.

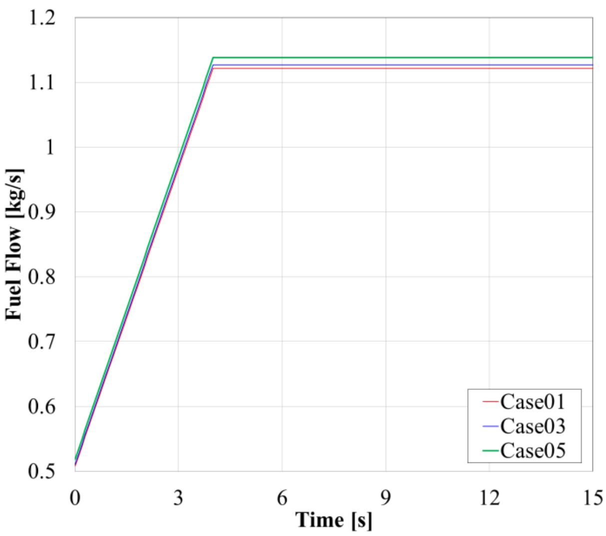

Figure 8: Fuel flow schedules for 3 different tip radii

For the subsequent transient analysis the fuel flow schedule is determined, see Figure 8. Owed to the fact that the efficiency decreases from a HPC tip radius of 270 mm to 310 mm, the required fuel flow for the same thrust is higher.

Employing this fuel flow schedule to conduct the transient maneuver, the temperatures of the casing and the blade of the first compressor can be retrieved, see Figure 9. Taking into account that the time constant of the casing in Case01 is lower (Figure 7), it becomes clear that the mass temperature is adapted faster compared to Case03. Using the same argumentation, the temperature of the blade in Case01 adapts slower compared to Case03 during the acceleration of the engine.

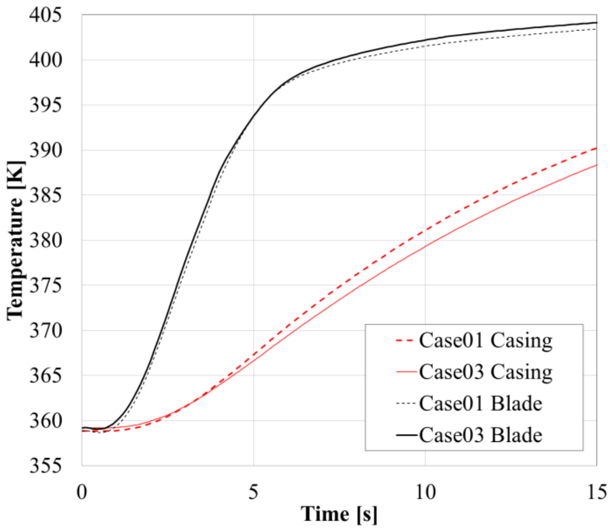

Figure 9: Mass temperatures of casing and blade of the first compressor stage

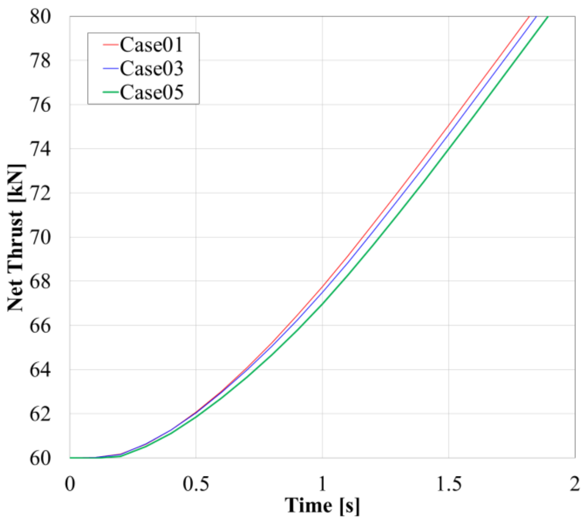

Figure 10: Net thrust during transient maneuver for 3 different tip radii

The net thrust of the first two seconds of the maneuver is shown in Figure 10. As can be seen, the acceleration of Case05 is delayed compared to Case03, while for Case01 the engine reaches the thrust faster.

In order to determine the impact of each of the three major contributions (stage maps, mass moment of inertia and geometric data for thermal calculations) the net thrust is depicted for the remaining cases in Figure 11. For the cases 11 to 15 the mass moment of inertia of the high-pressure shaft is taken as the constant value of Case03, which also equals Case08. Therefore Case13 equals Case08 in general and is skipped in Figure 11 for clarity.

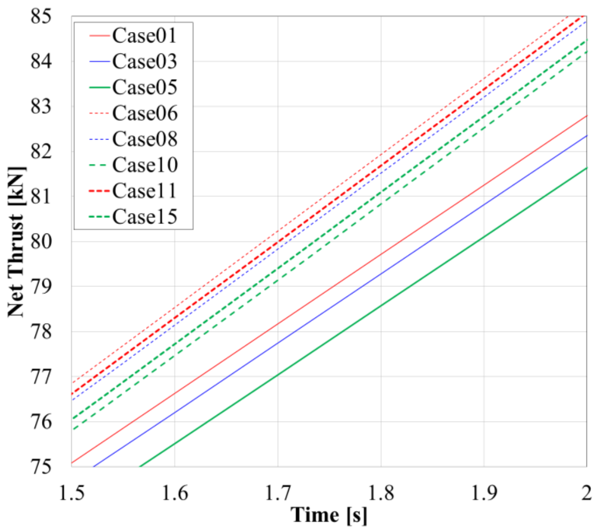

Figure 11: Net thrust during transient maneuver for 3 different tip radii and different setups

To find a measure for the contribution of each setup (A: Case01-05, B: Case06-10, C: Case11-15) to the delay in the net thrust the time delta is determined in each of the three setups to reach 80 kN. Including all effects (setup A) leads to 0.075 seconds time delay of the 310 mm tip radius compressor compared to 270 mm tip radius. In setup B the time difference is 0.064 seconds and including only the stage maps in the model leads to a difference of 0.035 seconds. This leads to the conclusion that inclusion of the stage maps of the meanline routine into the performance model is of similar order of importance as the mass moment of inertia. Due to the fact that the inertia of the high-pressure shaft is generally small compared to the low-pressure shaft, its variation is according to the current study not the only predominant contribution.

5 Conclusion and Outlook

A methodology to couple predesign and transient performance disciplines for turbofan engine modeling was established to provide a more integral view of digital engine designs. The linkage between those tools is ensured via GTlab’s central data model. The predesign calculation routines were restricted to the high-pressure compressor to give a comprehensible insight into this method. The established process chain was used to perform a variation of compressor tip radius. By that, the effect on engine acceleration from 60 kN to 120 kN of net thrust at sea-level static conditions was analyzed. A higher compressor tip radius leads to a slower acceleration when the appropriate steady-state fuel flow values of 60 kN and 120 kN are applied in the transient fuel flow schedule in each case. This phenomenon is separated into three different contributions: The application of the stage maps, the mass moment of inertia and geometric data to the performance model. The investigated model leads to the conclusion that the first two contributions are of predominant importance.

For a more comprehensive analysis the remaining turbo-components (booster, high- and low-pressure turbine) may be included as well. By that, the whole engine can be designed and simulated transiently. This step is skipped for future work.

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