VARIABLE SPEED POWER TURBINE PRELIMINARY DESIGN OPTIMIZATION FOR ROTORCRAFT APPLICATIONS

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Abstract. Variable speed rotor studies represent a promising research field for rotorcraft performance improvement and fuel consumption reduction. The turboshaft engines employed to drive helicopter rotors usually operate at a constant design speed, within a narrow RPM range. One of the reasons for choosing a constant speed is linked to free power turbine (FPT) performance deterioration in off design conditions. However, in order to minimize helicopter absorbed power, main rotor speed should be adjusted depending on advancing speed, weight and altitude. In fact, each different flight condition is characterized by a specific optimal rotor speed; unfortunately, optimal main rotor speed and optimal engine speed, when employing a fixed ratio transmission, represent two mutually exclusive goals. The benefits related to optimal main rotor operation may be eventually cancelled by strong deviations from FPT design speed, leading to higher turbine losses and thus higher fuel consumption. A possible way to overcome this problem is given by an appropriate redesign of the FPT stages, in order to decrease the stage efficiency sensitivity to RPM variation. The present study analyzes the abovementioned issue focusing on the design methodology required to obtain improvements in turbine efficiency at off design RPM values. The work is carried out upon the GE T700 turboshaft engine, mounted on the UH60 Black Hawk helicopter; performance data related to main rotor power and baseline engine fuel consumption are obtained by means of validated numerical simulators. The redesign phase of the T700 two-stages axial power turbine is reported; the final objective is to prevent engine performance deterioration when operating at optimal main rotor speed for different flight conditions.

1 INTRODUCTION

The turboshaft engines employed to drive helicopter rotors operate at a nearly constant design speed, within a narrow RPM range. The reasons for choosing a constant speed are linked to structural vibrational issues and free power turbine (FPT) performance deterioration in off design conditions. However, in order to minimize helicopter absorbed power, main rotor speed should be adjusted depending on advancing speed, gross weight and altitude [1]. In fact, each different flight condition is characterized by a specific optimal rotor speed; unfortunately, optimal main rotor speed and optimal engine speed, when employing a fixed ratio transmission, represent different goals. The benefits related to optimal main rotor operation may be eventually cancelled by strong deviations from FPT design speed, which lead to higher turbine losses and thus higher fuel consumption. In fact, when FPT speed is far from the design value, the blade incidence angles are far from the optimal values and this implies an increment in blade profile losses. A possible way to overcome this problem is given by an appropriate redesign and optimization of the FPT stages, in order to decrease the stage efficiency sensitivity to RPM variation. Previous studies on this subject can be found in literature; the work carried out by D'Angelo [2] is the first analysis upon the feasibility of a wide speed range turboshaft. Recent activities at the NASA Glenn Research Center related to the development of a variable speed FPT for the Large Civil Tilt-Rotor project are also pointed towards this objective [3],[4],[5],[6],[7].

The present work is focused on the preliminary design and optimization procedure of a variable speed FPT for rotorcraft applications. This task is carried out by employing an in-house 1D meanline analysis code able to predict turbine stages efficiency related to different designs. The stage loss correlation model implemented is a slightly modified version of the well-known model proposed by Craig and Cox [8].

The present study is carried out upon the GE T700 turboshaft engine, mounted on the UH60 Black Hawk helicopter. The redesign of the T700 two-stages axial power turbine is performed with the aim to prevent engine performance deterioration when operating at optimal main rotor speed for different flight conditions. Performance data related to main rotor power and engine fuel consumption are obtained by means of validated numerical simulators. Firstly, using a simple helicopter model (a detailed description and validation of which can be found in [1]) the optimal main rotor speed minimizing main rotor power is determined for different flight conditions of the rotorcraft. The computed values of main rotor absorbed power and engine RPM are passed as an input to TSHAFT, the gas turbine performance simulator developed at the University of Padova. Overall engine performance can thus be calculated. Instead of using an interpolated FPT map, the previously mentioned 1D code is used to calculate FPT performance in the matching loop inside TSHAFT. In this way different turbine stage designs can be tested using the correct FPT boundary conditions which can only be computed inside the engine matching routine inside TSHAFT.

At this point all the simulation tools needed to build an optimization procedure on the turbine stages have been developed. The stages' design variables (such as blade metal angles, solidity, leading edge radius, etc.) are chosen and a multi-point single objective optimization based on genetic algorithms is run. To achieve a FPT design able to perform well at different speeds, three operating points are chosen to be optimized, corresponding to the following flight conditions: hover, cruise and minimum power condition; the objective function to be minimized in every point is fuel consumption.

2 DEFINITION OF HELICOPTER MAIN ROTOR SPEED VARIABILITY

A helicopter trim code is employed to calculate the optimal RPM which minimize total helicopter power for each different flight condition; the code has been validated on experimental data related to the UH60 Black Hawk helicopter, as extensively described in [1]. The main rotor model utilized in calculations combines momentum theory and blade element theory at an advanced level. Only steady state level flight at different advancing speeds is considered in the present analysis. For the implementation of this model the guidelines followed are those indicated by Howlett [9] and Steiner [10]. A grid is built on the rotor disk: in the radial direction, the rotor surface is subdivided in a prescribed number of equal area annuluses, while in the circumferential direction it is divided in equal circular sectors of the same angle. The aerodynamic forces are calculated for each sector; the loads are first integrated over the rotor blade and then they are integrated and averaged along the azimuthal angle, in order to calculate the forces and moments on the rotor.

Lift and drag are calculated with two-dimensional thin airfoil theory for each sector, employing the introduction of nonlinear lift and drag coefficients. These coefficients are derived by interpolating the SC1095 airfoil characteristics found in [11]; the interpolation also accounts for Mach number variation. A similar interpolation is used to account for the slightly nonlinear twist distribution.

The results related to the optimal main rotor RPM analysis carried out on the UH60 model can be found in Figures 1-2. In Figure 1 the optimal main rotor speed obtained is converted to the engine speed via the reduction ratio specified by the planetary gear transmission. In Figure 2 the correspondent power requested to the engine is given. Both the variables are plotted vs helicopter forward speed for different values of the altitude.

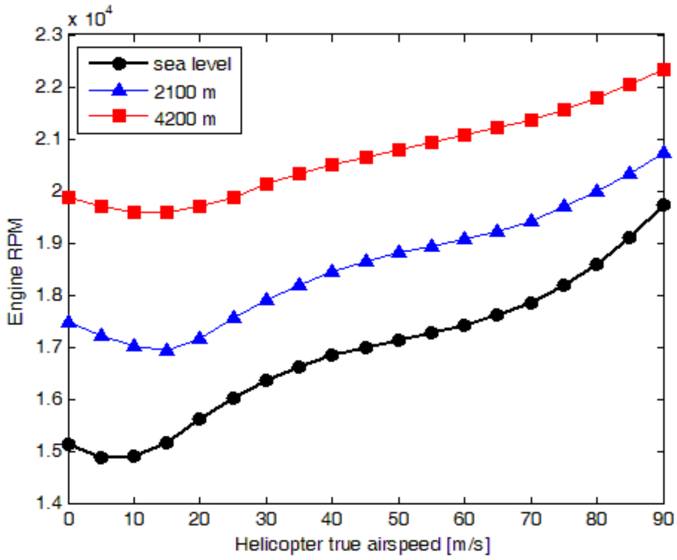

Figure 1. Engine RPM corresponding to optimal main rotor speed for different helicopter flight conditions.

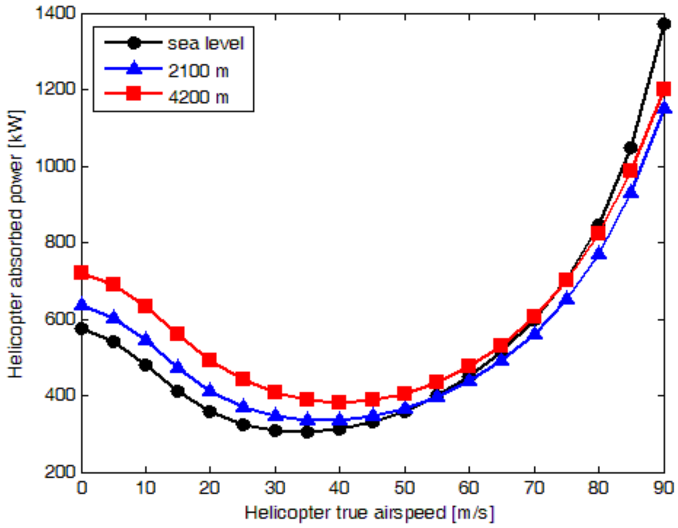

Figure 2. Helicopter absorbed power at optimal main rotor speed for different helicopter flight conditions.

It can be clearly seen that depending on the flight conditions the RPM values minimizing the power requested to the engine vary significantly, and so does also the power load. It may seem that choosing the engine RPM related to minimum rotor power can be the best choice to minimize helicopter fuel consumption. However, a big change in engine RPM, with respect to engine design conditions, causes a rapid decrease in engine efficiency, which is able to completely cancel the benefits of minimum rotor power operation and can even lead to higher fuel consumption. The component directly affected by RPM variability is the FPT, which is the main responsible for engine efficiency degradation, because it is directly linked to the main rotor through the transmission. The other components, the compressor and gas generator turbine (GGT), are linked together on a different spool, so that the influence of a main rotor RPM variation on their efficiencies is almost negligible. This can be more clearly understood by having a look at the configuration of the GE T700 turboshaft engine, visible in Figure 3.

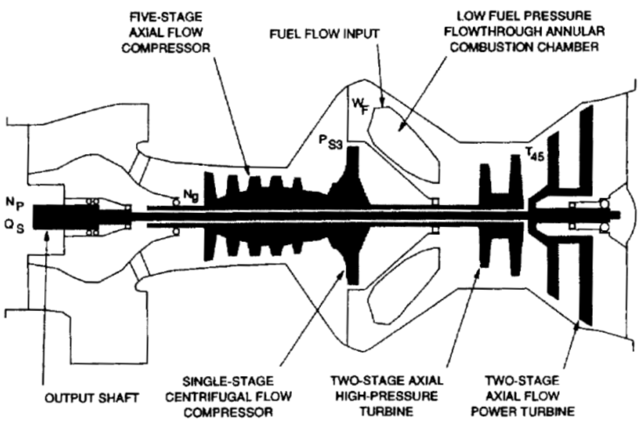

Figure 3. Cross section of a GE T700 turboshaft engine [18].

3 TURBOSHAFT ENGINE MODEL

The values of FPT power load and speed requested for main rotor optimal operation can be used as an input to be given to a gas turbine simulator; with this information it is possible to obtain engine performance estimations. In the present study TSHAFT, an in-house lumped parameters performance prediction software, implemented at the University of Padova, is utilized. The code, written in MatLab® language, has been validated through several comparisons with engine performance data given by experimental measures and commercially available software. It was also employed to assess the installation performance of the ERICA tilt-rotor (Enhanced Rotorcraft Competitive Effective Concept Achievement), within the framework of the Clean Sky GRC-2 research project [12]. A complete description of the engine simulator along with the equations implemented in the model can be found in [13], whereas the validation against the GE T700, which will be our case study in the next sections, is presented in [12].

The general physical assumptions for the engine model are the following:

1. Steady state operation;
2. Lumped parameters model: within each component there are only input and output values of state variables which do not vary continuously in space;
3. Working fluid consisting of a mixture of ideal gases with variable specific heats;
4. Adiabatic components: each component has no heat exchange with the environment;
5. Ambient conditions are determined by altitude selection; an ISA standard model is implemented to relate altitude to the values of static pressure and temperature;
6. Variable specific heat.
7. Off-design performance is calculated employing different scaled characteristic maps for the various engine components; an algorithm is able to calculate the matching between the different turbomachines composing the engine.

The engine model has an important task in the design process: it is used to assess the impact of different FPT design choices upon the overall engine fuel consumption. However, the code needs to be fed with component map characteristics derived from experimental data. If suitable maps are found for the compressor and the gas generator turbine (GGT), the FPT map has to be changed every time it is decided to test a different design choice. Since the FPT design procedure has to be inserted inside an optimization loop, it is necessary to possess a tool able to estimate the FPT performance maps related to different FPT designs. To this aim, TDES, an axial turbine performance analysis code developed at the University of Padova, is employed.

4 TURBINE MEANLINE ANALYSIS CODE

In the preliminary design phases of axial turbines, 1D meanline analysis is extensively used to create a solid base for subsequent design optimizations, which usually employ more complex 2D-3D analyses and CFD viscous analyses. This phase is extremely important to obtain a sound design, and to decrease the time effort in the subsequent design phases [14]. For this reason, in order to compare different FPT designs, it is decided to use TDES, an in-house meanline analysis tool. The code is able to predict turbine single stage efficiency related to different designs by using loss correlation models proposed by Craig and Cox [8]; some additional correlations are introduced to increase the accuracy in incidence loss calculations, following suggestions by Moustapha [15] and Bertini et al. [14]. TDES is capable of affording either subsonic or supersonic stage exit flow, and performs the stage stacking by matching the different stages and outputting the overall turbine performance. It accepts the thermodynamic boundary conditions and the basic design geometry of the stages as an input (blade metal angles, solidities, duct diameters, etc.) and outputs turbine specific work, efficiency, pressure ratio, and corrected mass flow.

A quite satisfactory validation of the code has been carried out on different cascade geometry experimental tests, two examples of which are represented in Figures 4-5.

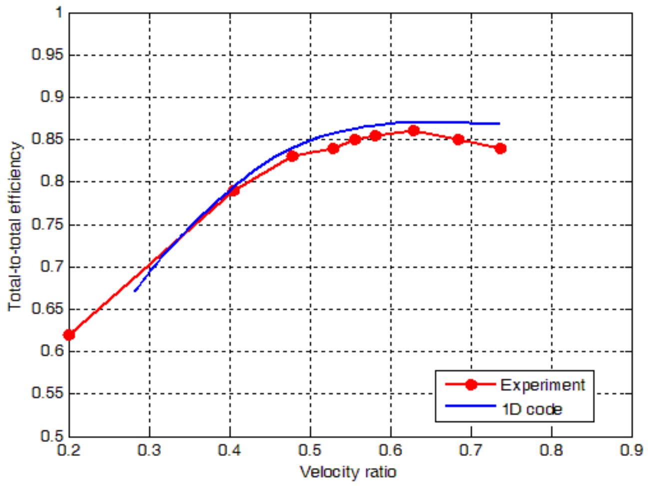

Figure 4. Validation of TDES code upon single stage A.

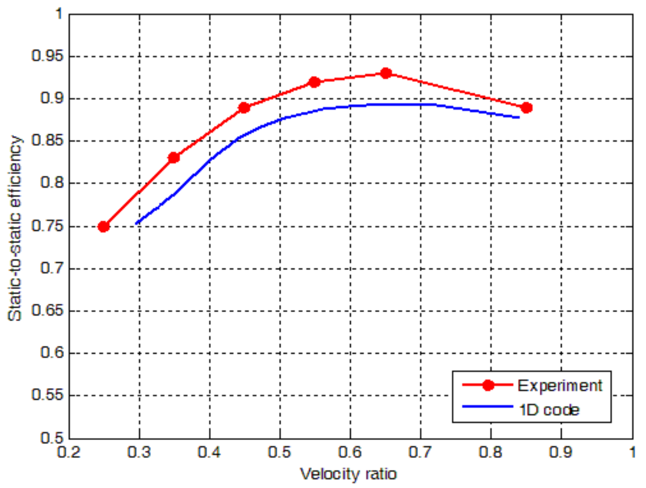

Figure 5. Validation of TDES code upon single stage B.

6 DESIGN OPTIMIZATION METHODOLOGY PROPOSED

The objective of the present work is to introduce an optimization procedure able to perform a preliminary redesign of the FPT turbine stages taking into account the RPM variability. Now that all the tools needed to carry out this analysis have been exposed, the optimization procedure itself has to described. First of all, it is important to define the design variables that are to be changed with respect to the original FPT baseline design. Among the most significant parameters in a turbine stage are the blade metal angles, solidities, and curvature at the turbine passage throat; these are therefore chosen to be varied by the optimizer. The remaining input variables are fixed in order to respect geometrical and structural constraints related to the original design or, as in the case of the stagger angle, are chosen using recommendations from literature [16]. In Table 1 the different input and output variables managed by the TDES code are reported for clarity.

Table 1: Single cascade input and output variables in the TDES code for the design optimization.

Design Input Variables	Fixed Input	Output
Blade metal angles	Number of blades	Specific work
Blade solidities	Stagger angles	Efficiency
Curvatures at the passage throat	Duct dimensions	Pressure ratio
	Hub-Tip ratios	Corrected mass flow

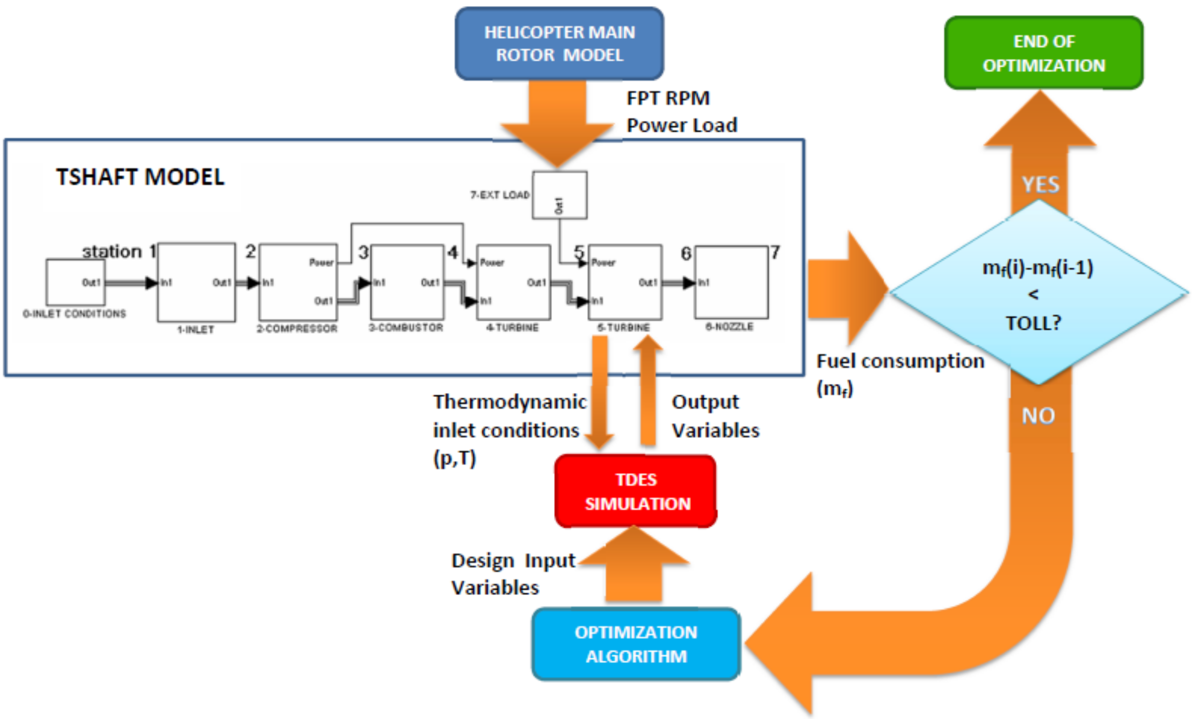

Figure 6. FPT redesign optimization procedure.

The optimization procedure is structured as outlined in Figure 6. The optimizer gives initial values for the design input variables related to each stator/rotor cascade composing the turbine. In the GE T700 case, there are two stages, therefore four cascades leading to 12 free design input variables. The TSHAFT model is run using as external load parameters the RPM and power calculated by the main rotor model. The values of total pressure and temperature at the inlet of the FPT are passed to TDES, which in turn is able to compute the FPT performance data in terms of work, efficiency and mass flow. The TSHAFT matching procedure to calculate the engine fuel consumption thus uses TDES as a subroutine in its iterative process. Fuel flow is passed back to the optimizer and represents the objective function to be minimized. The optimization procedure chosen is multi-objective, and the procedure is executed for more than one flight condition, in order to let the designer decide the best compromise in consumption between different operating points. For the GE T700 case, three points have been chosen: hover, design cruise and best endurance condition.

The algorithm that is suggested to be used in the optimization process is a genetic algorithm; other choices can be made, but it is strongly recommended to use global derivative-free optimization algorithms.

Before starting the optimization, it is important to have a good starting choice for the baseline FPT configuration. In the GE T700 case, since not all the data were known to build the baseline configuration, several adjustments to the design input variables have been made in order to obtain a turbine design matching the experimental data of the engine. The results of this adjustment represent an additional validation to the TSHAFT and TDES models. Among all, fuel consumption is the most interesting variable to be used as a comparison with experimental tests. As can be seen in Figure 7, there is a good agreement between this methodology and the experiments, even better than between the original TSHAFT model without TDES and the tests.

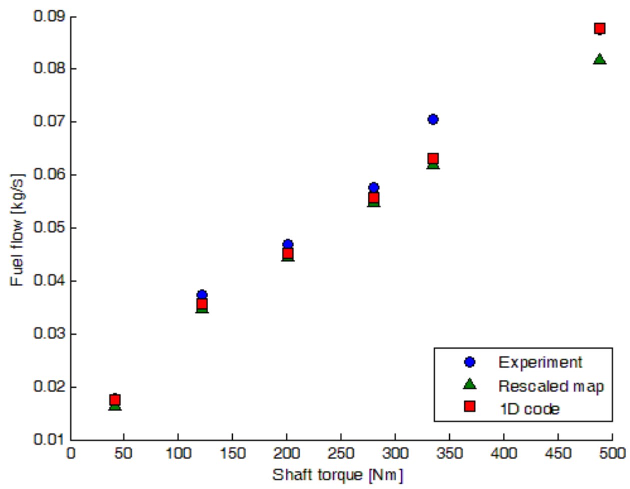

Figure 7. TSHAFT engine model validation coupled with TDES model: fuel flow comparison with experimental data and rescaled characteristic map.

7 CONCLUSIONS

An optimization procedure aimed at FPT design taking into account variable RPM derived from an optimized main rotor speed has been extensively described. The procedure can serve to test different solutions to the incidence losses problem in the FPT, in order to find the best design to reduce overall engine fuel consumption. At the moment different design parameters and different solutions to this issue are analyzed at the University of Padova; future work will be focused on the improvement of the design capabilities of this methodology, possibly introducing in the loop more complex 2D-3D models to accurately account for the different types of turbine losses.

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