TURBOSHAFT ENGINE PERFORMANCE COMPARISON BETWEEN CVT AND FIXED RATIO TRANSMISSION FOR A VARIABLE SPEED ROTOR

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Abstract

Variable speed rotor studies represent a promising research field for rotorcraft performance improvement and fuel consumption reduction. The problems related to employing a main rotor variable speed are numerous and require an interdisciplinary approach. There are two main variable speed concepts, depending on the type of transmission employed: fixed ratio transmission (FRT) and continuously variable transmission (CVT) rotors. The impact of the two types of transmission upon overall helicopter performance is estimated when both are operating at their optimal speeds. This is done by using an optimization strategy able to find the optimal rotational speeds of main rotor and turboshaft engine for each flight condition. The process makes use of two different simulation tools: a turboshaft engine performance code and a helicopter trim simulation code for steady-state level flight. The first is a gas turbine performance simulator (TSHAFT) developed and validated at the University of Padova. The second is a simple tool used to evaluate the single blade forces and integrate them over the 360 degree-revolution of the main rotor, and thus to predict an average value of the power load required by the engine. The results show that the FRT does not present significant performance differences compared to the CVT for a wide range of advancing speeds. However, close to the two conditions of maximum interest, i.e. hover and cruise forward flight, the discrepancies between the two transmission types become relevant: in fact, engine performance is found to be penalized by FRT, stating that significant fuel reductions can be obtained only by employing the CVT concept. In conclusion, FRT is a good way to reduce fuel consumption at intermediate advancing speeds; CVT advantages become relevant only near hover and high speed cruise conditions.

1. INTRODUCTION

The need to comply with more and more restricting limits on engine emissions and fuel consumption leads to new challenges for the rotorcraft industry. A number of environmental goals has been set by the Advisory Council for Aeronautics Research in Europe (ACARE), which include reductions in CO_2 and NO_x emissions of the order of 50% and 80%, respectively, for new aircrafts entering service in 2020 [1].

A promising research field toward fuel consumption reduction is represented by the study of variable speed rotors. Modern helicopters usually have their main rotor operating at constant rotational speed, with typical allowed variations in speed not exceeding 15% [2]. The reasons for choosing a constant rotational speed operation are mainly two:

1. Resonant frequencies in the airframe. Resonant vibrations may occur not only due to operation at shaft critical speeds, but also in the airframe[3], where a particular rotor speed inside the operating envelope could excite the natural frequency of different rotorcraft structural elements.
2. Decrease in engine efficiency in off-design conditions. Turboshaft engines operate at high efficiencies only in a narrow RPM range, with the component mostly affected by speed variation being the free power turbine (FPT) [4].

The first is a dynamical stability issue, and there are already practical examples demonstrating that it can be solved by means of damping techniques and bringing up composites into the airframe. Recent examples are Boeing's A160 Hummingbird and Bell Helicopter's Eagle Eye UAV, both employing a variable speed rotor.

The second is a performance issue. Although consistent drops in FPT efficiency are typical for a turboshaft engine operating at rotational speeds far from the design conditions, theoretical studies related to main rotor and engine efficiency variation with speed already showed the possibility to achieve a reduction in fuel consumption. As explained in refs. [4],[5], the analysis of main rotor and turboshaft engine subsystems coupling is fundamental to correctly understand fuel saving possibilities. For each different helicopter flight condition (depending on advancing speed, helicopter weight, and ambient conditions) it is possible to find an optimal rotational speed of the main rotor $\widehat{\Omega}_{MR}$, which minimizes helicopter absorbed power. In addition, for each different power load condition it is also possible to find an optimal FPT speed value $\widehat{\Omega}_{FPT}$, which minimizes engine/s fuel consumption. These two optimal speeds are different, depending on each subsystem characteristics, and vary with flight conditions. In order to achieve maximum fuel saving, it is clear that optimal helicopter operation should employ $\widehat{\Omega}_{MR}$ for the main rotor and $\widehat{\Omega}_{FPT}$ for the engine FPT. However, state of the art helicopters usually employ a fixed transmission ratio (TR) between engine and main rotor angular speeds, therefore stating the impossibility of optimal operation for both subsystems, since main rotor speed is strictly dependent on engine speed.

Following this, the fuel consumption reduction issue can be dealt with by using two possible approaches: the former is to find the best compromise between the engine and main rotor angular speeds, still maintaining the fixed ratio transmission (FRT); the latter is to let the two subsystems rotate at their different optimal speeds, by employing a variable speed transmission, in either form of a continuously variable transmission (CVT) or a multiple speed gearbox concept.

In order to improve global helicopter performance both the approaches require adequate research studies in different subjects, as will be clear in the next sections.

The present work aims at investigating the different theoretical performance achievable by the two different variable speed concepts, the FRT and the CVT. The impact of the two types of transmission upon overall helicopter performance is estimated through a comparison between a FRT and a CVT, both operating at their optimal speeds. This is done by using an optimization strategy able to find the optimal rotational speeds of main rotor and FPT for each flight condition (level flight from 0 to 90 m/s). Three different altitudes are considered, and three different helicopter weights are simulated, in order to understand in which particular flight conditions the two variable speed concepts achieve the best reductions in fuel consumption.

The optimization process employs two different simulation tools: a turboshaft engine performance code and a helicopter trim simulation code for steady-state level flight. The first is TSHAFT, a gas turbine performance simulator developed and validated at the University of Padova [4]. The second is a simple tool used to evaluate the single blade forces and integrate them over the 360 degree-revolution of the main rotor, in order to predict an average value of the power load required by the engine in different flight conditions.

The helicopter case chosen for this comparative study is a UH-60 Black Hawk helicopter mounting a GE T700 turboshaft engine, since several input data needed by the models are found in literature [6].

The paper is structured as follows: firstly, a brief literature review focused on research related to both the variable speed approaches is given, in order to underline the pros and cons related to the application of both concepts. Subsequently, the simulation tools employed to simulate turboshaft engine and main rotor performance are briefly described; to prove the reliability of the employed methodology, the validation results against experimental data are also presented for the two models. Finally, the results obtained by means of numerical simulations are discussed in detail.

2. VARIABLE SPEED ROTORS WITH FIXED RATIO TRANSMISSION

Fixed ratio transmissions represent the state of the art technology for helicopter drivetrains. The most common fixed ratio gear type for a helicopter main rotor is a planetary stage (the main module in Figure 1) which features an output shaft driven by several planets [7]. An advantage of the planetary stage compared to a simple parallel shaft arrangement is that each planet gear must transmit only a part of the total torque. This load sharing results in a smaller, lighter transmission. A valid alternative to planetary stages is given by split torque stages (Figure 2). Split torque design transmissions offer several advantages over conventional planetary gears arrangements, such as lower weight, lower energy losses, higher reduction ratio and reliability [7],[8].

FRT efficiencies usually range from 97% to 99% in helicopter applications [9]; this is an important value to be considered for comparison with variable speed transmissions.

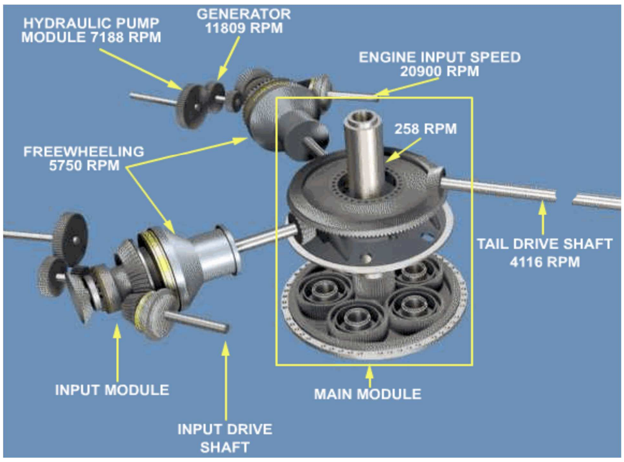

Figure 1. UH-60 transmission employing a planetary stage (main module).

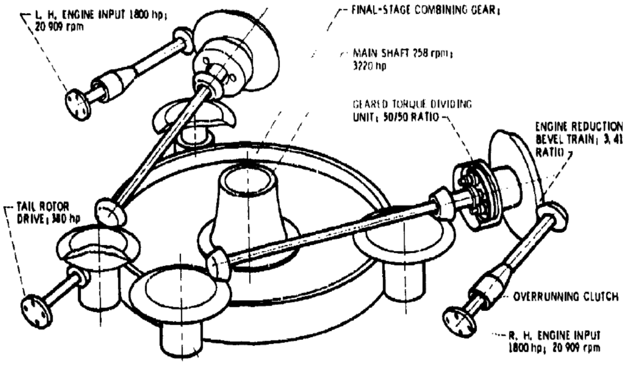

Figure 2. Split torque transmission design compatible with the UH-60 [8].

Due to the fixed ratio transmission the rotational speed of the main rotor is strictly dependent on engine RPM, as can be seen by TR definition:

$$TR = \frac{\Omega_{FPT}}{\Omega_{MR}} = const \qquad (1)$$

As a consequence, optimal speed operation implies a trade-off among the requirements of main rotor and engine subsystems. The research effort is mainly dedicated to solving the problem of turboshaft engine efficiency losses in conditions far from the engine design point, which can be solved by improving the FPT stages design in order to widen the high efficiency interval of the turbine. The work carried out by D'Angelo [10] is the first analysis found in literature upon a wide speed range turboshaft. Recent studies at the NASA Glenn Research Center are also pointed towards this objective: with the aim of assessing the feasibility of a variable speed tilt-rotor concept, Welch et al. [11] studied the redesign of the FPT in order to obtain a good performance on the entire RPM interval, from 100% (take off) to 54% (cruise). The new turbine design is characterized by high work factors in the cruise condition and wide incidence angle variations in vanes and blades among the entire operating range. The results emerged from this research state that operating the turboshaft engine at variable speed without losing too much efficiency is viable.

3. VARIABLE SPEED ROTORS WITH VARIABLE SPEED TRANSMISSION

A wide variety of variable speed transmissions is technically available for standard applications; unfortunately, very few seem to be suitable for the case of high helicopter specific power loads. Stevens et al. [12] exclude the possibility to use any traction/friction drive and fluid-traction transmissions, widely used in the automotive industry, for rotary wing applications, mostly because of low reliability, excess weight and heat generation problems.

Litt et al. [2], instead of using CVT, propose a solution to the problem by means of multiple speed gearboxes. A sequential shifting control algorithm for a twin-engine rotorcraft that coordinates both the disengagement and engagement of the two turboshaft engines is developed with the objective to vary main rotor speed smoothly over a wide range, still maintaining the engines within their prescribed speed bands.

However, from a functional point of view, the idea of CVT is highly desirable contrasted to the operability of a discrete multispeed drive [12] for various reasons, one of them being the possibility for CVTs to reach optimal speed continuously depending on the flight condition.

Lemanski [13] patented an innovative variable speed transmission, the pericyclic CVT (P-CVT), which is a non-traction nutating drive mechanism incorporating positive engagements of rollers and cams. The main advantages given by this type of CVT are much higher torque density and power transmission efficiency than any other known continuously variable mechanical power transmission systems. The pericyclic mechanism (Figure 3) can operate both as a fixed transmission or a CVT, whether the speed of the reaction control component (light blue in figure) is hold to zero or is varied by means of a speed control unit. The following is the main drawback of the P-CVT: two different power inputs are needed in order to achieve speed variability. If the speed input to the reaction control member has to be varied continuously, the most plausible power input has to be electromechanical. In a paper on CVT for hybrid vehicle applications, Elmoznino and Lemanski [14] suggested a power flow configuration in which part of the mechanical energy produced by an internal combustion engine is converted in electrical power and then reconverted in mechanical energy, providing the necessary torque and speed for the reaction control member (Figure 4). The worthiness of this double conversion depends on the energy conversion efficiency and the power flow magnitude into the two different members, i.e. the input shaft and the reaction wheel. In fact, if only a small part of the power is flowing in the reaction wheel member, even poor energy conversion efficiency could be acceptable. The application of pericyclic CVT to helicopter main rotors is discussed by Saribay [15],[16] and Hameer [17]. In their studies, they discovered that in various configurations in which the output speed was varied between 50% to 100% of design point value, the power flow in the reaction member could be as high as 50% of the total power coming from the turboshaft engine, which implies very large energy conversion devices. Thus, using electric generators as variable control units is not a viable solution for helicopters, for mainly three reasons: weight, energy conversion efficiency and reliability. Research has still to be done in order to understand if there are possible alternative power paths which can reduce loading on the reaction wheel. However, the pericyclic transmission is a very promising mechanism, since it was demonstrated that more than 40% drivetrain weight reduction was possible when compared to previous gear designs (planetary and split torque) [17].

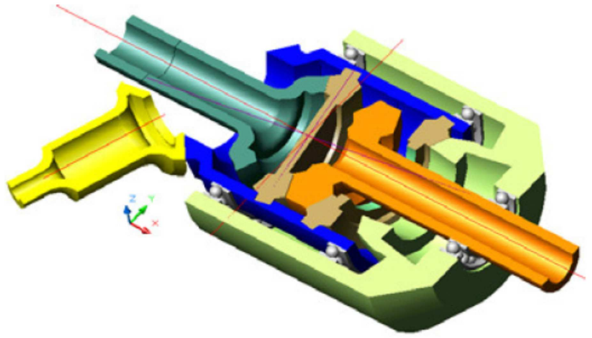

Figure 3. Example of pericyclic transmission [17].

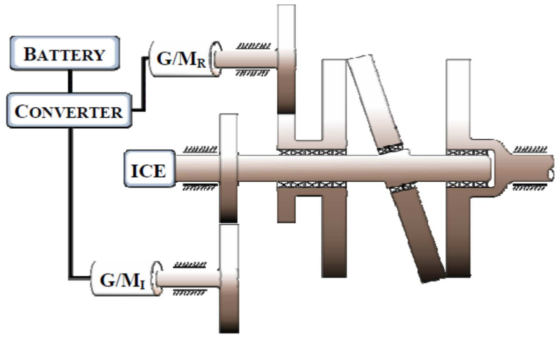

Figure 4. Hybrid vehicle P-CVT: a part of the mechanical energy produced by the internal combustion engine (ICE) has to be converted in electricity by the generator G/M_I and reconverted by G/M_R at the desired speed.

A possible great innovation in helicopter drivetrain technology could be instead represented by magnetic gears. A magnetic gear (Figure 5) uses permanent magnets to transmit torque between an input and output shaft without mechanical contact. Atallah invented and demonstrated a high-torque magnetic gear in 2001. Compared to mechanical gears, his invention is claimed to offer advantages including reduced maintenance, improved reliability, no need for lubricants, higher efficiency (>99%), high torque density, inherent overload protection, reduced drivetrain pulsations and low noise. Atallah cofounded the firm Magnomatics®, where it is claimed that an efficient magnetic variable speed technology has been already developed, along with wind turbine applications [18]. Davey et al. [19] state that preliminary assessments of magnetic gears with TR=50:1 are characterized by weight-to-torque ratios of 0.018 lbs/ftlbs (based on an 8 MW capability) which are torque densities even higher with respect to normal helicopter gearing.

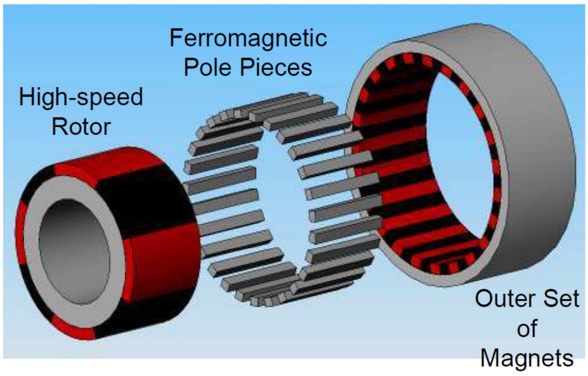

Figure 5. Exploded view of a magnetic gear.

In conclusion, all the possible variable speed transmission types presented here are still in the concept design phase and it is still not well defined which of the ones presented would be the most suitable for helicopter operation. Magnetic gears seem to be promising, but still no research has been done inside the rotorcraft industry to the knowledge of the authors.

The research effort in this particular field may lead to interesting results and is justified by the fact that employing a variable speed transmission makes it possible for both main rotor and turboshaft engine to operate at their optimal speeds.

4. COMPARISON BETWEEN CVT AND FIXED RATIO TRANSMISSION CASES

4.1 Reasons for the comparison

The existence of a great number of variator concepts and the lack of reliable information about variable transmission weight and efficiency does not permit to make sound hypotheses on CVT performance, which has to be integrated in the helicopter and turboshaft engine models.

Nevertheless, even without knowing weight and efficiency characterizing the CVT that has to be simulated, a valuable comparison between CVT and FRT can still be made. In fact, by employing in simulations the same weight and the same efficiency used to evaluate FRT helicopter performance, it is possible to compare the two variable speed concepts independently from different CVT types. It is clear that the CVT case will present the higher fuel saving: as stated above, it makes it possible for both main rotor and turboshaft engine to operate at their optimal speeds, whereas the FRT can only achieve a single intermediate value between these two. However, if the fixed ratio transmission case presents comparable values of fuel saving, it will emerge that only high efficiency and lightweight CVT would be worth the research effort. If no efficient CVTs appear to be employable, a research devoted to FPT efficiency improvement at off design speeds would seem to be the most reasonable choice to achieve fuel consumption reduction. Therefore, the methodology presented here becomes a preliminary design tool, which may help choosing one of the two approaches depending on the research project performance goals and the estimated research costs.

4.2 Optimal Ω calculation

The two variable speed concepts, the FRT and the CVT, will be tested at their own optimal speeds and compared to the constant RPM speed case to evaluate fuel consumption reduction.

Once the main rotor model and the turboshaft engine model are merged together, it is possible to build an optimization algorithm which runs the helicopter model seeking for main rotor and engine optimal speeds for each different flight condition.

Fixed ratio transmission. The algorithm's scope is to adjust Ω_{MR} in order to minimize the engine fuel mass flow, taking into account the different requirements of the main rotor and the turboshaft engine. The optimization algorithm, despite the great number of nonlinear equations employed in the two different models, has to solve a univariate minimization problem, thus a wide variety of algorithms can be used. For the case study analyzed, a derivative-free algorithm, namely the golden section search with parabolic interpolation is chosen.

In Figure 6 the optimization process is graphically schematized. The input values of ambient conditions and forward speed are needed for both the main rotor and engine models. Once a value for Ω_{MR} is chosen, from the helicopter trim simulation it is possible to derive the power absorbed by the rotor P_{MR}, whereas from eq. (1) the FPT speed can be evaluated.

The power requested to the engine is given by the sum of main rotor power, tail rotor power and additional accessory power. If a helicopter is mounting two different turboshaft engines, the power is supposed to be equally divided between the two. Therefore, accounting also for transmission losses, the engine power load for a single engine becomes:

$$P_{load} = \frac{(P_{MR} + P_{TR} + P_A)}{2\eta_{trans}} \quad (2)$$

These data are then inserted as input values in the engine model, which in turn computes engine fuel consumption m_f. At this point the optimization algorithm computes a new value of Ω_{MR} and restarts the process until the minimum in fuel consumption is reached.

Continuously variable transmission. In this case two separate optimization procedures are employed, since Ω_{MR} and Ω_{FPT} are independent. Firstly, an optimization routine has to find the Ω_{MR} minimizing the power load requested to the engine. Then, P_{load} is used as input value inside a second optimization routine containing the turboshaft engine model alone, which computes the best Ω_{FPT}, minimizing fuel consumption.

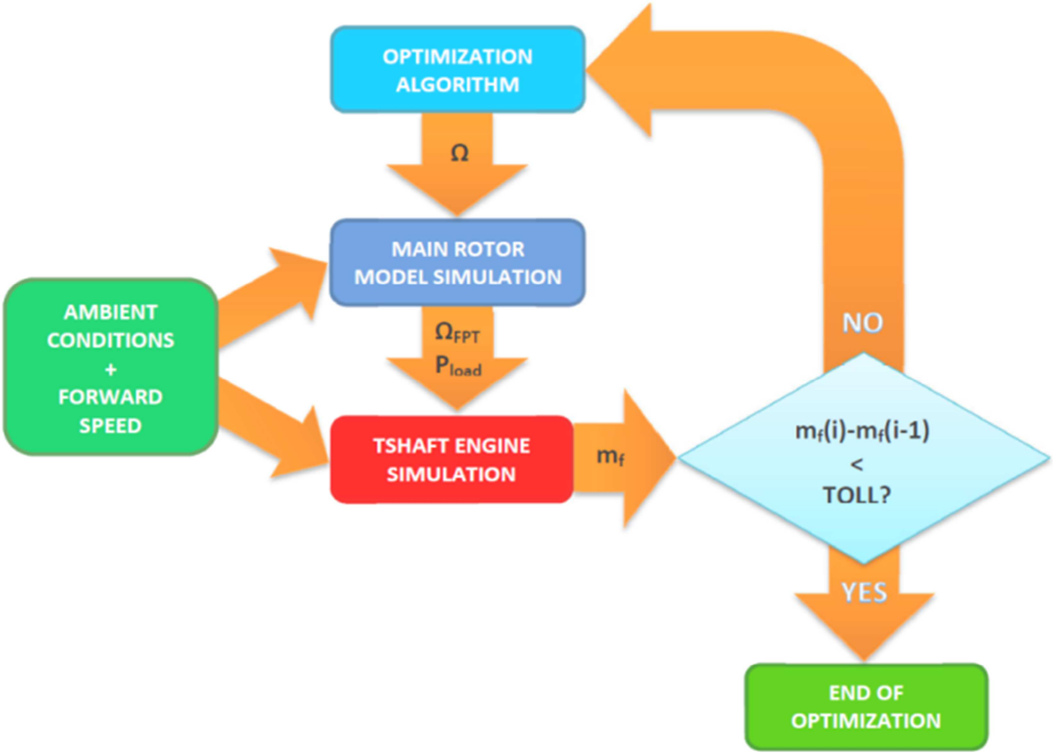

Figure 6. Fixed ratio transmission: optimal main rotor determination process.

5. TURBOSHAFT ENGINE MODEL

5.1 Model description

To simulate the GE T700 turboshaft engine performance, 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 [20].

The turboshaft engine is modeled by connecting the following components (see Figure 7):

- Inlet
- Compressor
- Combustor
- Gas generator turbine (GGT)
- Free power turbine (FPT)
- Nozzle
- External load.

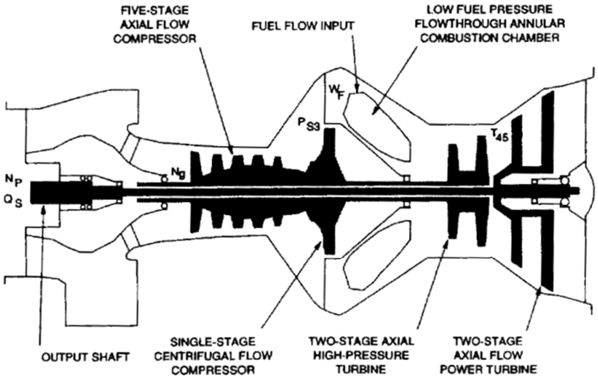

Figure 7. Cross section of a GE T700 turboshaft engine [18].

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. Thermodynamic irreversibilities are included in calculations through the use of different types of efficiencies;
6. Ambient conditions are determined by altitude selection; an ISA standard model is implemented to relate altitude to the values of static pressure and temperature;
7. Variable specific heat.

Off-design performance is calculated employing different characteristic maps for the compressor and turbine components. A matrix method is used to solve for the non-linear equations system resulting from formalization of the matching problem. In the matching problem, the values of corrected mass flow and power predicted by the thermodynamic model are matched with those obtained through characteristic map interpolation in order to guarantee the mass and energy conservation for steady state operations.

A complete description of the engine simulator along with the equations implemented in the model and the GE T700 design data can be found in [4].

5.2 GE T700 model validation

A brief description of the validation upon experimental data of the GE T700 model is given. The outputs from the TSHAFT code are compared against the results obtained using the commercial gas turbine simulation software GSP and against experimental data collected at the NASA Lewis research center. Six different operating conditions are simulated, with different external loads; test specifications are well summarized in ref. [21]. The validation assessment is represented in Figures 8-13. Fuel consumption is the most interesting parameter to analyze. The operational points generated by TSHAFT are in good agreement with the experimental data, with a maximum relative error on the various performance quantities in line with and sometimes even better than GSP calculations. The principal cause of discrepancies between experimental and simulations' results is mainly due to the lack of some data related to single engine component performance. Nevertheless, these comparisons show that the model built using TSHAFT predicts the engine behavior with an acceptable accuracy.

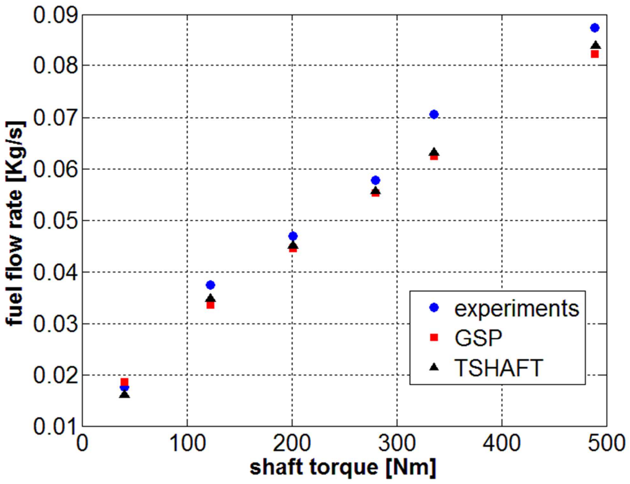

Figure 8: Fuel flow.

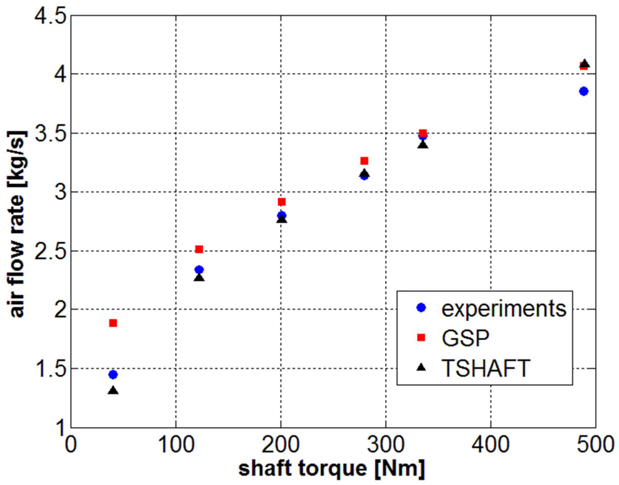

Figure 9: Air massflow.

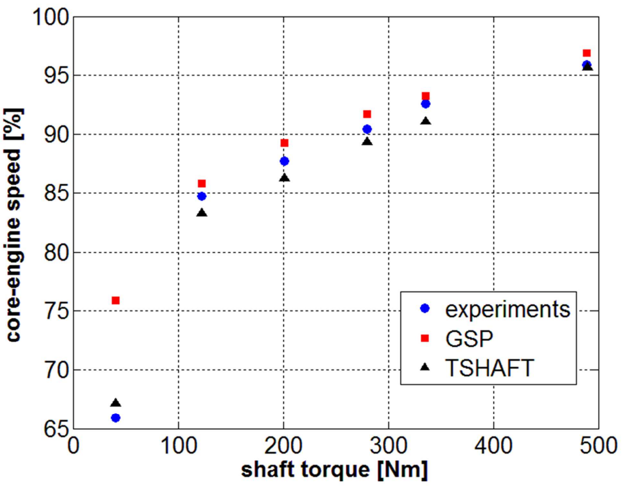

Figure 10: Core-engine speed.

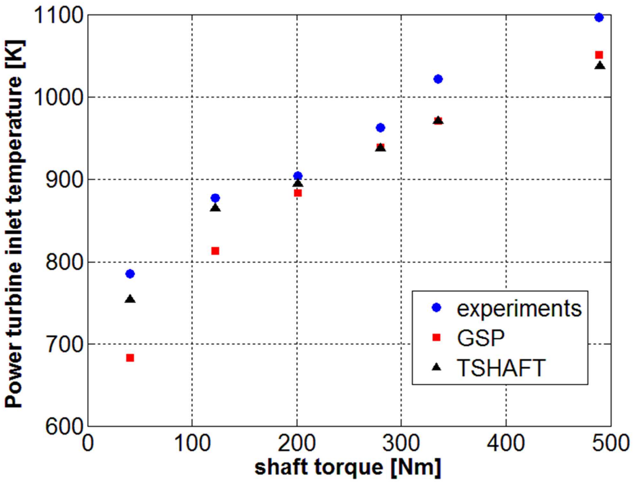

Figure 11: Power turbine inlet temperature.

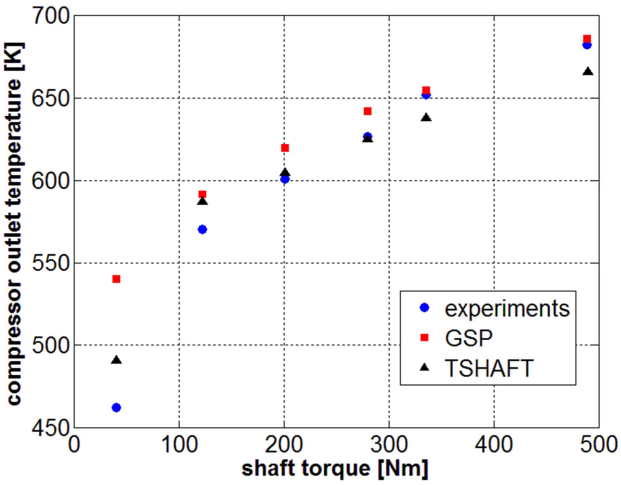

Figure 12: Compressor outlet temperature.

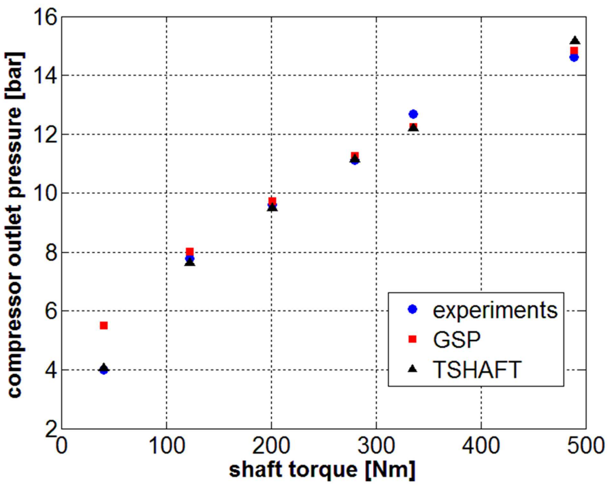

Figure 13: Compressor outlet pressure.

6. HELICOPTER TRIM MODEL

6.1 Model description

The main rotor model for the UH-60 Black Hawk helicopter is developed using a combination of momentum and blade element theory. For the implementation of this model the guidelines followed are those indicated by Howlett [6] and Steiner [22]. 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. Some important features and assumptions employed in the helicopter trim model are reported below:

1. Rigid rotor: no blade deformations are taken into account.
2. Flapping and lead-lag motion are neglected: since the main goal of the current analysis is given by a correct modeling of the engine power demand, there is less interest in accurate blade dynamics simulation. This assumption is not penalizing performance prediction, as will be demonstrated in section 6.2.
3. Quasi steady-state level flight operation: for a fixed forward speed *V* and main rotor speed Ω_{MR}, in order to trim the helicopter, the collective, cyclic and lateral pitch controls must be adjusted to find the equilibrium. This means that the sum of the forces and moments acting on the helicopter must be zero, since zero helicopter acceleration is assumed. The periodically varying loads on the main rotor are averaged along an entire revolution to find the quasi-steady forces and moments needed in trim calculations.
4. Blade lift and drag are calculated with 2-dimensional thin airfoil theory, employing the introduction of nonlinear lift and drag coefficients. These coefficients are derived by interpolating the SC1095 airfoil characteristics found in [23]; the interpolation also accounts for Mach number variation. A similar interpolation is used to account for the slightly nonlinear twist distribution.
5. To calculate the attitude of the helicopter, an estimation of the aerodynamic forces and moments acting on the fuselage is needed. In the present helicopter model, only fuselage drag is calculated, using an empirical expression found in Yeo et al. [24]; fuselage lift and moments, relatively small in normal operation, are neglected for lack of data.
6. The sideslip angle is assumed null, so that the helicopter advancing motion is considered unyawed.

The relationships used inside the model are highly non-linear and interdependent, and also include the evaluation of numeric integrals; for this reason, they are implemented as a non-linear system of the type ***f(x) = 0***, where ***f*** is a vector-valued error function and ***x*** is the vector of the variables. In the present helicopter model the number of equations to be solved are nine. The vector of the variables in this case becomes:

$$x = [\vartheta_0, \vartheta_{1c}, \vartheta_{1s}, \Theta, \Phi, \lambda_0, \lambda_{TR}, C_T, C_{TTR}] \tag{3}$$

The equations that compose the system ***f(x)*** are: the six equations for helicopter equilibrium, the inflow equations for both main rotor and tail rotor, and finally the equivalence between the guessed coefficient of thrust and the thrust force *T* calculated by numerical integration. A more detailed explication of the helicopter model along with the equations and UH-60 construction data employed can be found in [5].

6.2 UH-60 Black Hawk model validation

The previously discussed decision of neglecting flapping and lead-lag motion is not penalizing the goodness of the analysis, as can be seen in Figures 14-19. In fact, for the entire range of flight speeds the flapping angle β is around 3° (from experimental data [24]) and the effects on calculated helicopter power are small. However, apart from the flapping angles, all the other helicopter trim parameters find a very good adherence with experimental measurements by using this assumption.

Figure 14 shows the comparison between our current model, an aeromechanical analysis performed with CAMRAD II [25] and experimental measurements found in Yeo et al. [24]. The results predicted by the new model for the analyzed variables show a very good compatibility with the experimental values.

Particularly important for the present analysis is the good prediction of both the power coefficient and collective angle. As well, the longitudinal cyclic angle estimation is quite accurate according to what has been encountered experimentally.

Summarizing, this approach can be considered valid in first approximation, since the most important parameter estimated, the power coefficient, is very close to the C_p measured.

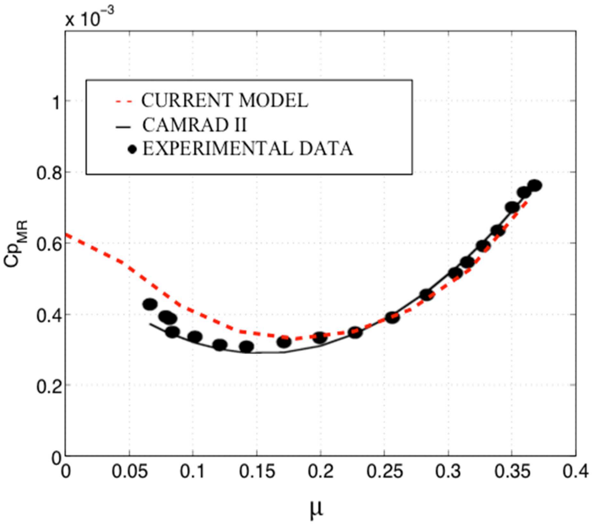

Figure 14. Power coefficient.

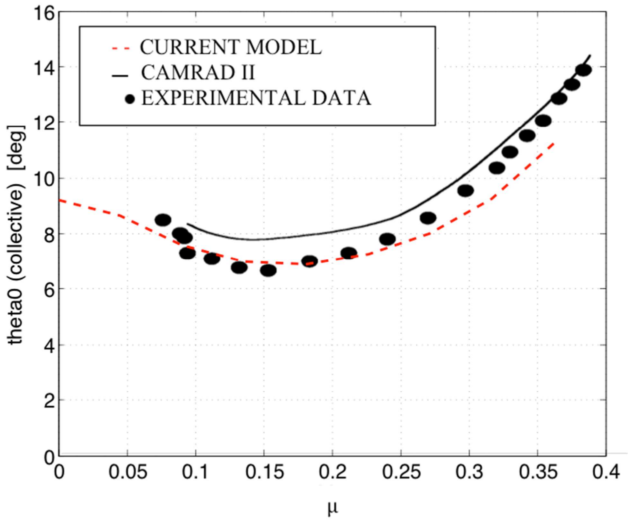

Figure 17. Collective angle.

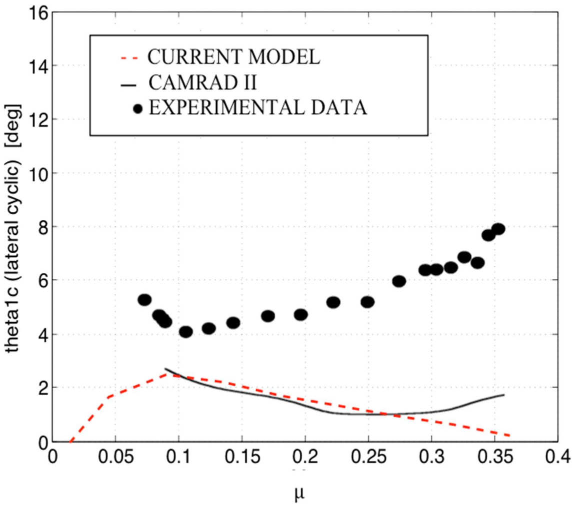

Figure 15. Lateral cyclic angle.

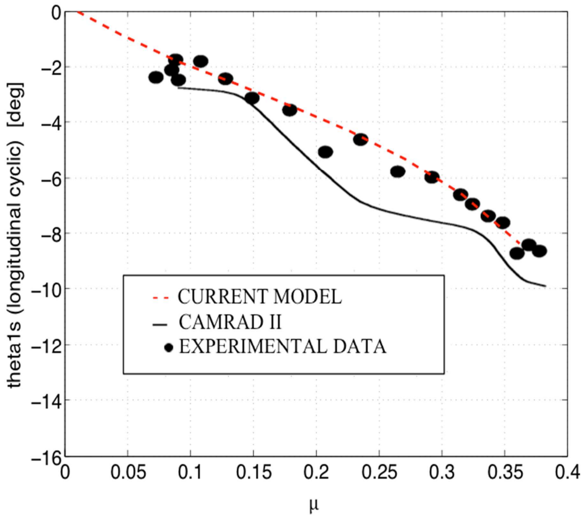

Figure 18. Longitudinal cyclic angle.

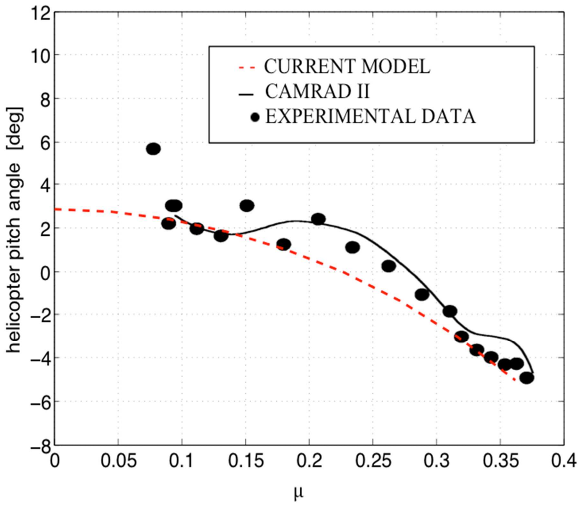

Figure 16. Pitch attitude.

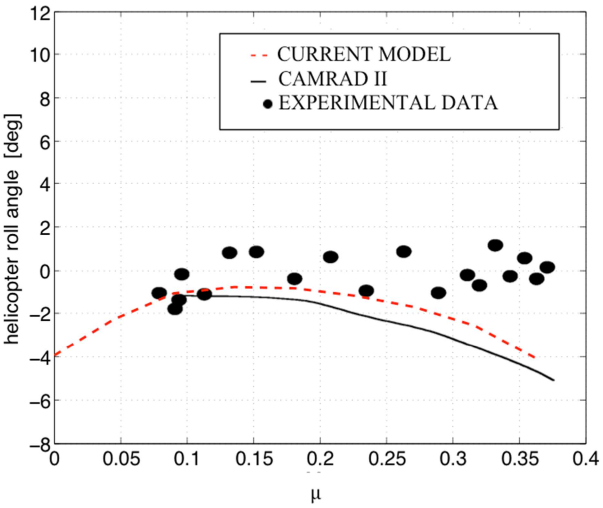

Figure 19. Roll attitude.

7. SIMULATION RESULTS

In order to obtain a good overview of how an optimal main rotor speed could reduce fuel consumption, five steady state cases at level flight are simulated with different weights and altitudes. For each case 19 simulations are carried out to cover the advancing speed interval from 0 to 90 m/s. It is clear that there will be different optimal speeds depending on different weights and altitudes, since the power required to maintain level flight is clearly dependent upon these parameters.

Three simulations are performed with a constant weight of 7257 kg (16000 lbs) varying the altitude from sea level to 4200 m, passing through the 2100 m condition. The reference temperatures used for the three different altitudes are chosen as typical of a hot summer day: 302 K at sea level, 288 K at 2100 m and 275 K at 4200 m. Another two simulations are carried out maintaining the constant altitude of 2100 m and varying the weight from 5443 kg (12000 lbs) to 9071 kg (20000 lbs).

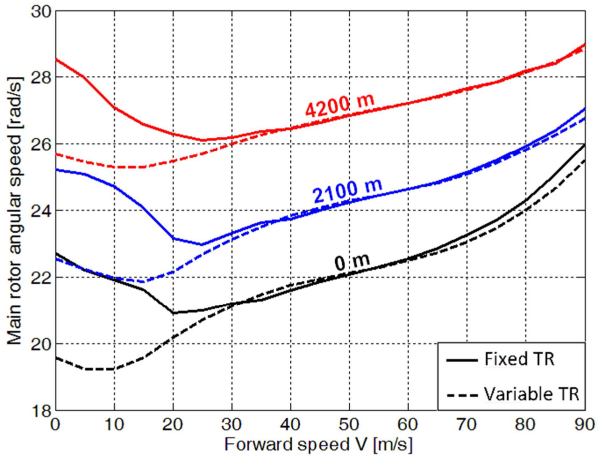

Figure 20. Optimal main rotor angular speeds at different altitudes for fixed and variable TR cases (W=7257 kg).

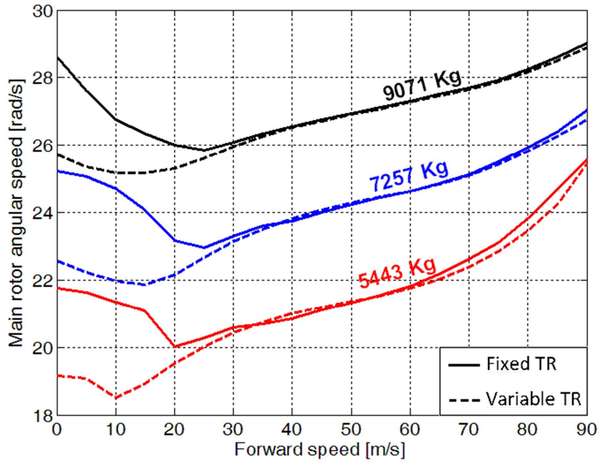

Figure 21. Optimal main rotor angular speeds at different helicopter gross weights for fixed and variable TR cases (h=2100 m).

In Figure 20-21, the optimal main rotor speed $\widehat{\Omega}_{MR}$ is calculated for both the FRT and the CVT cases at different weights and altitudes. The UH-60 main rotor design speed is 27 rad/s. It can be observed that $\widehat{\Omega}_{MR}$, at intermediate advancing speeds V, is found to be lower than the design constant value for both FRT and CVT cases. This happens because of the increase in the angle of attack of the blades when operating at optimal speed: the optimization process is reducing blade profile power by lowering the rotational speed [5]. Instead, at high V, main rotor speed is increased even more than the design value, in order to prevent retreating blade stall.

The dashed lines (CVT) can be viewed as the result of an unconstrained optimization on main rotor performance, whereas the continuous lines (FRT) are the result of a main rotor optimization constrained by engine speed linkage. Beyond the 30 m/s condition, there are no big differences between the FRT and CVT cases. This means that in this region main rotor efficiency is affecting overall

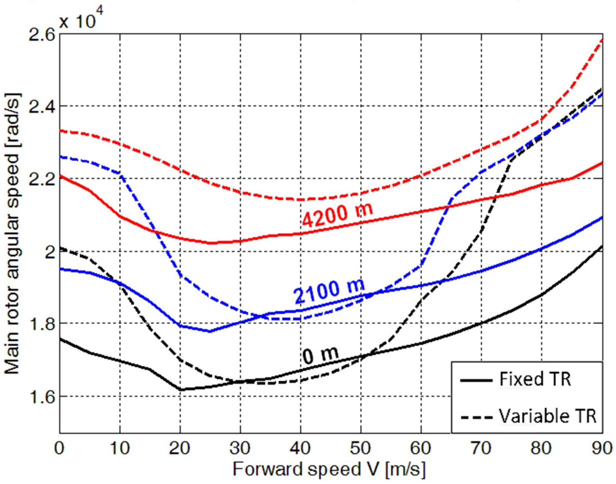

Figure 22. Optimal FPT speeds at different altitudes for fixed and variable TR cases (W=7257 kg).

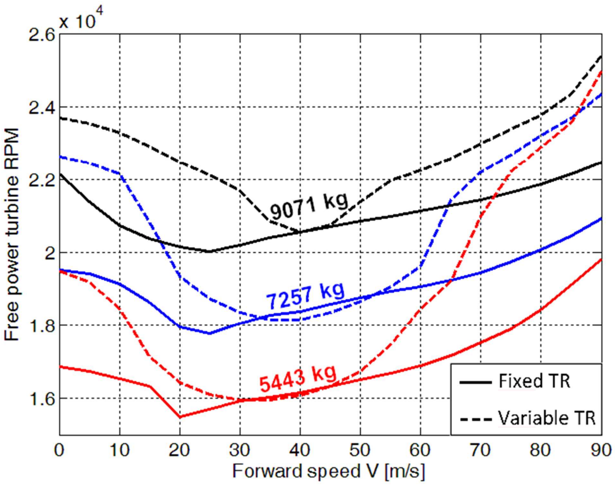

Figure 23. Optimal FPT speeds at different helicopter gross weights for fixed and variable TR cases (h=2100 m).

helicopter performance more than turboshaft engine efficiency. On the other hand, near the hover condition there is a significant difference between the two transmission concepts, stating that FPT efficiency starts playing an important role in the optimization process: minimizing main rotor power is no more equivalent to minimizing fuel consumption.

In Figure 22-23 the optimal engine FPT speed is calculated for both the FRT and the CVT cases at different weights and altitudes. The GE T700 design speed is 20900 RPM. In this case a significant variation between the CVT and FRT cases is observed for the majority of the flight conditions (maximum discrepancy of 25%). The FPT, once let free to seek for its maximum efficiency, reaches considerably higher rotational speeds. The dashed lines (CVT) can be viewed as the result of an unconstrained optimization on turboshaft engine performance, whereas the continuous lines (FRT) are the result of an engine optimization constrained by main rotor speed linkage.

In Figure 24-28 the most important performance results, objective of this paper, are presented. The percentages in fuel savings with respect to the constant design speed case (normal helicopter operation) are represented. In addition to the two optimized FRT and CVT cases, another possible design configuration is assessed, which employs a variable speed main rotor with constant speed FPT, at the usual design value of 20900 RPM. The figures represent valuable information clarifying the different contributions to helicopter performance improvement given by the single subsystems' optimization. The following considerations can be derived from the figures below:

1. The optimal main rotor speed, for every case considered, achieves better results, in terms of fuel consumption, at lower weights and lower altitudes, i.e. at lower C_T. This is mainly due to the fact that optimal operation at high C_T is found to be very close to the design speed conditions. Actually, the farther from the design conditions the more useful the optimization approaches presented. This is true for advancing speeds still far from the blade stall condition.
2. In Figure 26 and 28, $\widehat{\Omega}_{MR}$ produces another beneficial effect at high C_T and high V (beyond 65 m/s): blade stall delay. This results in an extended helicopter flight envelope. In these operating regions, constant design speed operation is no more viable because of large diffused retreating blade stall. As a consequence to stall, rotor absorbed power suddenly increases, and requires a strong increase in fuel flow. The optimization process (in both FRT and CVT cases) avoids retreating blade stall by increasing Ω_{MR} which in turn permits to decrease the blade angle of attack*; rotor power is maintained at acceptable levels, hence high gains of fuel consumption are output by the turboshaft model. It is important to notice that, in the constant speed case simulated, the combustor temperature increase driven by the high power demand would not be realistically affordable by the engine.
3. The highest fuel consumption reduction achieved by the optimizations (excluding the blade stall regions) is found to be almost 13%, at intermediate advancing speeds (low C_P region). It is interesting to observe that this peak is common to both the CVT and FRT cases. Instead, the use of a variable speed main rotor with constant speed FPT prevents from reaching the maximum fuel reduction, stating that at intermediate speeds the FRT is more effective than mere main rotor and engine decoupling; but near cruise and hover conditions, the constant FPT speed approach, compared to FRT, results in better performance.
4. The CVT concept behaves better than the FRT over the entire advancing speed interval, as expected. However, at intermediate speeds the differences between the two approaches are negligible: in fact, $\widehat{\Omega}_{FPT}$ divided by the fixed TR (1) is almost equivalent to $\widehat{\Omega}_{MR}$. This can be seen by comparing Figures 20 and 22 (altitude sweep), and Figures 21 and 23 (weight sweep). On the contrary, in hover and high speed cruise the two optimal speeds tend to diverge: the FRT is no more able to find a good compromise between the speeds of the two subsystems. In fact, at high V values $\widehat{\Omega}_{FPT}$ increases more rapidly than $\widehat{\Omega}_{MR}$, since optimal engine operation requires a higher rotational speed with increasing power†. In addition, when close to hover, $\widehat{\Omega}_{MR}$ and $\widehat{\Omega}_{FPT}$ are even characterized by opposing trends. In fact, from intermediate to low V values the power requested to the engine is increasing, and hence also $\widehat{\Omega}_{FPT}$ increases; on the other hand, $\widehat{\Omega}_{MR}$ decreases to minimize blade profile power. The minimum value of $\widehat{\Omega}_{MR}$ is reached very close to hover, whereas the $\widehat{\Omega}_{FPT}$ minimum is found between the 30-50 m/s interval.
5. Even if the CVT presents better performance, no giant differences with the FRT are encountered. For this reason, the efficiency and weight of the CVT mechanism have to be comparable with current fixed ratio transmission technology, otherwise even a few percentage point variation in these quantities would be able to erase any CVT performance benefit.

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[*] Increasing Ω_{MR} can be beneficial until sonic conditions are encountered at the advancing blade tip.

[†] Higher engine power means higher engine mass flow: therefore, $\widehat{\Omega}_{FPT}$ has to be increased in order to maintain optimal turbine blade angles with respect to the flow.

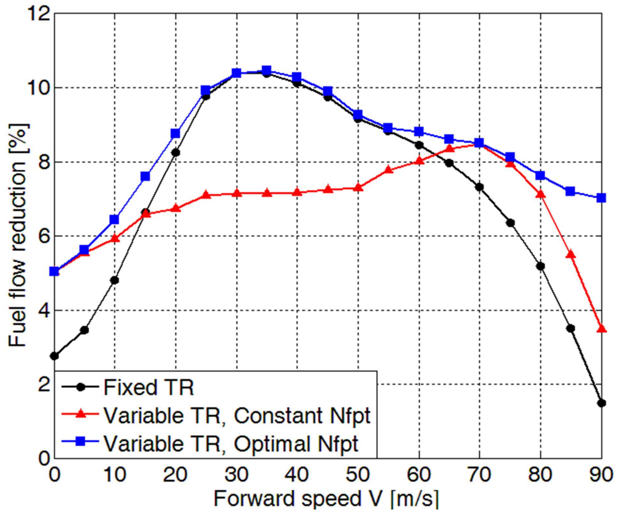

Figure 24. Fuel saving comparison for W=7257 kg, sea level.

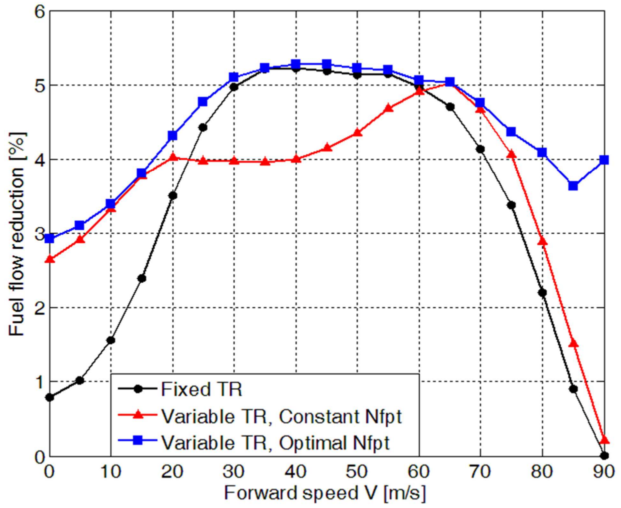

Figure 25. Fuel saving comparison for W=7257 kg, h=2100m.

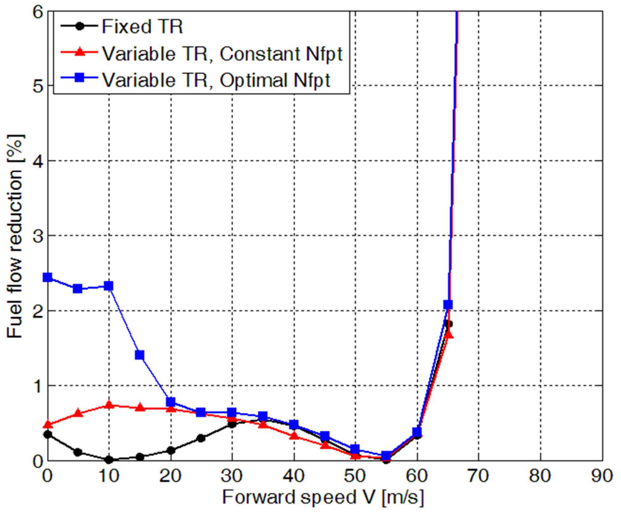

Figure 26. Fuel saving comparison for W=7257 kg, h=4200m.

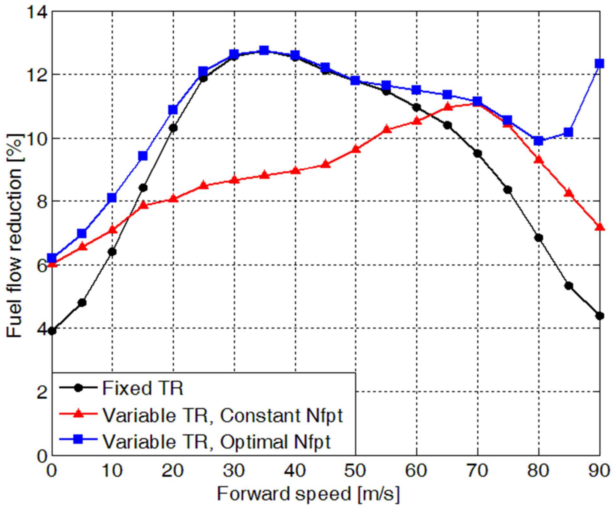

Figure 27. Fuel saving comparison for W=5443 kg, h=2100m.

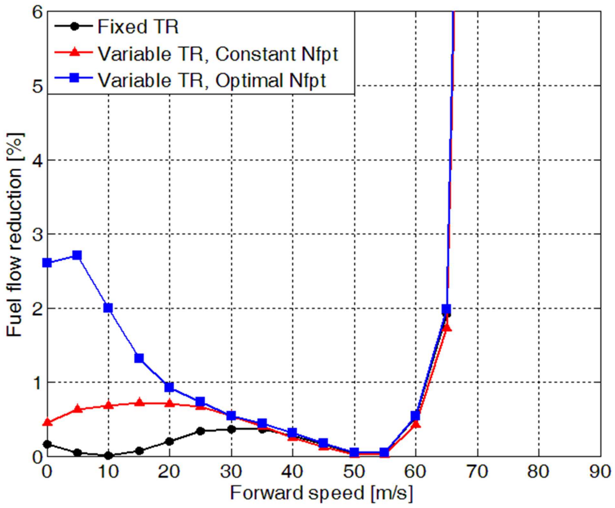

Figure 28. Fuel saving comparison for W=9071 kg, h=2100m.

8. CONCLUSIONS AND FUTURE STUDIES

It has been shown that variable speed rotor operation is a viable way to reduce fuel consumption. In fact, it is possible to find main rotor and turboshaft engine optimal speeds for any flight condition. Moreover, at high C_T values and high advancing speeds, it has been found that variable speed operation permits to extend the helicopter flight envelope, alleviating retreating blade stall.

Two different approaches have been analyzed, the FRT and CVT concepts, and their performance results have been compared. Considerable reductions in fuel consumption (almost 13% maximum) have been reported for both FRT and CVT cases with respect to standard constant speed rotor operation. At high C_T values, fuel saving is reduced because optimal rotor speed is found to be very close to the design constant speed value.

It was found that FRT and CVT fuel savings are comparable for intermediate advancing speeds, but tend to diverge in the hover and high advancing speed regions, where CVT clearly outperforms FRT, with a maximum of 8% better fuel reduction. The FRT concept thereby represents a good way to reduce fuel consumption for helicopter missions characterized by a high operating time in the intermediate advancing speed region (surveillance, taxiing, sightseeing, etc.), but is not performing well in hover and high speed forward flight. To overcome this behavior, a possible solution comes from wide speed FPT studies, employing variable guide vanes able to maintain acceptable FPT efficiency at different rotational speeds. The theoretical maximum fuel saving attainable is asymptotically defined by CVT performance.

The CVT concept, instead, will be a valuable alternative to FRTs only if the CVT mechanism is able to preserve state of the art FRT weight and efficiency. In fact, especially at high C_T, a few percentage points drop in transmission efficiency or even additional weight would imply a higher fuel consumption than with the constant speed case. Since most of the helicopter operation time is usually spent in the hover and cruise conditions, CVT represents the best theoretical choice for variable speed rotors; however, it cannot be employed until a reliable, efficient and inexpensive CVT design will comply with rotorcraft industry requirements.

The natural development of this work will be pointed towards the implementation of an aeroelastic model, to understand the vibrational problems arising when eventually reaching critical speeds; in fact, the analysis of the vibrational spectrum transmitted to the hub has still to be carried out and is of prior importance to assess the viability of the variable speed concept.

Finally, collaboration of different interdisciplinary research groups on this subject is strongly desirable, since both FPT efficiency improvement and innovative CVT design implementation need to employ a diversified set of skills and knowledge. With innovative helicopter designs, maybe employing wide-speed range power turbines and rotor blades expressly designed for variable speed rotors, the fuel savings achieved could be even much higher than those encountered in the presented analysis.

9. SIMBOLOGY

Acronyms

CVT	continuously variable transmission
FRT	fixed ratio transmission
FPT	free power turbine
ICE	internal combustion engine
TR	transmission ratio

Latin Symbols

C_P	Main rotor power coefficient
C_T	Main rotor thrust coefficient
C_{TTR}	Tail rotor thrust coefficient
m_f	Engine fuel consumption
P_{MR}	Main rotor power
P_{load}	Engine power load
P_A	Accessory power
P_{TR}	Tail rotor power
V	Helicopter advancing speed
W	Helicopter weight

Greek symbols

β	Blade flapping angle
η_{trans}	Transmission efficiency
ϑ_0	Collective pitch angle
ϑ_{1c}	Lateral pitch angle
ϑ_{1s}	Longitudinal pitch angle
Θ	Helicopter pitch attitude
λ	Rotor inflow ratio
λ_{TR}	Tail rotor inflow coefficient
μ	Rotor advance ratio
Φ	Helicopter roll attitude
Ω_{MR}	Main rotor angular speed
Ω_{FPT}	Free power turbine angular speed
$\hat{\Omega}_{MR}$	Main rotor optimal angular speed[
$\hat{\Omega}_{FPT}$	Free power turbine optimal angular speed

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