HELICOPTER CONFIGURATIONS AND DRIVE TRAIN CONCEPTS FOR OPTIMAL VARIABLE ROTOR-SPEED UTILIZATION

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Abstract

Recent studies [1]–[4] have shown that a variation of helicopter main rotor speed allows a significant reduction of the required power. Therefore an appropriate drive train technology is necessary to enable variable rotor speed. However, such a technology entails drawbacks such as increased weight and reduced efficiency [5]. This study provides arguments and results to enable a decision process towards a promising helicopter configuration incorporating a variable rotor speed and related applications. These are mainly obtained from mission performance calculations and additional transmission weight investigations. Benchmark missions are derived and presented while two promising drive train concepts are introduced. A continuously variable gearbox stage is shown to be especially useful for utility helicopter applications while a dual-speed, clutched stage gearbox is particularly suitable for tilt-rotor concepts. The capability to vary the main rotor speed extends the flight envelope and reduces fuel consumption. This study shows that the portfolio of missions that can be carried out efficiently and the efficiency itself is enhanced by this technology.

SYMBOLS AND ABBREVIATIONS

CVT		Continuously Var. Transmission
FVL		Future Vertical Lift
GW	[lb]	Gross Weight
IRP	[hp]	Intermediate Rated Power
ISA		Int. Standard Atmosphere
MCP	[hp]	Maximum Continuous Power
MTOW	[lb]	Maximum Take of Weight
OEI		One Engine Inoperative
SAR		Search and Rescue
SFC	[lb/hp-hr]	Specific Fuel Consumption
h	[ft]	altitude
i	[-]	transmission ratio
m	[lb]	weight
$\dot{m}_{fuel}$	[lb/hr]	fuel flow
P_{av}	[hp]	available power
P_{req}	[hp]	required power
V	[kts]	cruise speed
V_{tip}	[ft/sec]	rotor tip speed
Φ	[-]	spread of rotational speed

INTRODUCTION

One objective of the German and Austrian Aviation Research Program (LuFo V-2 and TAKE-OFF) is to promote technologies that enhance the ecological efficiency of future rotorcraft. Under ecological aspects a variable rotor speed offers the opportunity to operate the rotor at an optimal pitch to improve fuel efficiency and to reduce emissions. With a variable rotor speed, rotorcraft can therefore be developed and optimized for a whole operational design range rather than a specific design point. However, most rotorcraft are still operating at constant rotor speeds. The transnational project VARI-SPEED intends to give answers about the applicability and the determination of decision factors of such a technology. In the project it is also intended to design a rotor and transmission system for a selected configuration to investigate structural and vibrational problems encountered by a variable rotor speed. Stability and feasibility will then be studied as well as a proof of concept.

In the first study of the project the effects of a variable-speed rotor design on power savings and flight envelope are discussed for various existing helicopter configurations [4]. Calculations were

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performed using NDARC (NASA Design and Analysis of Rotorcraft). The aircraft chosen for the study are the UH-60A single main-rotor and tail-rotor helicopter, the CH-47D tandem helicopter, the XH-59A coaxial lift-offset helicopter and the XV-15 tiltrotor. Areas of possible power savings, ranges of rotational speed and main-rotor torque effects are presented. Depending on the aircraft, the study shows that significant power savings of up to 15% are possible at certain flight regimes within the engine limit [4].

This first investigation also shows the sensitivity of additional transmission weight relating to the possible power savings with variable rotor speed. This elucidates that a slender design area exists, where the configuration with reference rotor speed is the better choice over a variable rotor system with additional transmission weight. This non-beneficial design area enlarges with increasing empty weight of the aircraft.

Missions need to be considered in order to decide whether the variable rotor speed technology is favorable over a lighter reference configuration, because helicopters do not operate at one point of the envelope. Most missions will contain segments within the non beneficial area and segments where power can be saved. A holistic examination of a variable speed rotor system can only be made with representative missions that allows to compare the different configurations.

This study extends the research to a mission perspective, based on operator requirements, while at the same time possible variable speed gearbox architectures and weight estimations are presented. By calculating and comparing the different mentioned configurations this study expands the perceptions about the value of such a technology. The investigation is limited to ISA (International Standard Atmosphere), hover and level flight conditions. Note that both the tail rotor and engine speed are kept constant throughout the entire study.

Two current undertakings, that consider variable rotor speed, are the United States' Future Vertical Lift (FVL) program and the Europeans Clean Sky 2 - Fast Rotorcraft program. Both programs intend to extend high-speed helicopter capabilities, while still incorporating excellent hover and vertical take-off and landing (VTOL) capabilities. Future programs are foreseen to target noise reduction by variable rotor speed control [6]. The FVL comprises two Joint Multi-Role Demonstrators (JMR-TD), the Sikorsky Boeing SB>1 DEFIANT™and the Bell Helicopter, Lockheed-Martin V-280 Valor [7]. The Clean Sky 2 program aims likewise to build two demonstrators, the Airbus Helicopters' LifeRCraft and the Leonardo Helicopters' Next Generation Civil Tilt-Rotor (NextGenCTR) [6]. Each program tracks the idea of a compound helicopter competing against a tilt-rotor configuration.

Examples of existing high speed compound helicopter concepts are the Eurocopter X^3, the ABC™(Advancing Blade Concept) demonstrator XH-59A [8], Sikorsky X2 Technology™demonstrator [9] and the Sikorsky S-97 RAIDER™. The rotor speed of these examples is reduced in fast forward flight in order to avoid sonic conditions. Examples of existing tilt-rotor configurations are the Bell XV-15 demonstrator, the Bell Boeing V-22 Osprey and the Leonardo Helicopters AW609. Such configurations reduce rotor speed in fast forward flight to adjust the rotor speed towards propeller mode.

In both cases two different rotor speeds are required: a high rotor speed to meet the hover requirements and a speed reduction in fast forward flight. Concerning the considered compound configuration [10] reveals OEI hover condition as design driver. This condition also requires excellent hover efficiency to keep engine dimensions small. In this study OEI conditions are not covered within the mission calculation. Furthermore, heavy lift configurations, as examined in [10], are not considered in this study.

The Boeing A160T Hummingbird is an example of a main-/tail-rotor configuration that utilizes variable rotor speed by a dual-speed transmission, to gain advantages in ceiling and gross weight [11], [12].

A previous study was executed in the project VARI-SPEED to evaluate different possibilities for a speed variable drive train [5]. This study examined hybrid/electric drive train, variable speed turbine and variable speed gearbox concepts. Known variable drive train solutions were analyzed according to their suitability for the given problem. This was done to determine the possible range of speed variation and the thereby associated weight increase.

Mistè et al. [3] presented a methodology to determine the optimal rotational speed of a variable RPM main rotor and turboshaft engine system. The optimization goal was minimal fuel consumption. He identified that it is necessary to optimize the RPM for the rotor and the turboshaft engine independently according to each flight state of the helicopter. This means, that the optimum RPM for the rotor is not the same as for the turboshaft engine. Using a variable-speed transmission could enable to use both optima of the turboshaft engine and the rotor at the same time.

METHODOLOGY

NDARC [13], [14] is used to perform discrete performance calculations to provide grid points for subsequent mission calculations. These vary in four dimensions: flight speed, altitude, gross weight and rotor speed. In each dimension 30 discrete solutions are calculated and 50 discrete solutions in a range of ±50% of the reference rotor speed respectively. This leads to >10^6 discrete performance solutions for each configuration. NDARC sums up the induced and profile power, interference and parasitic terms, transmission and accessory losses to determine the required power from momentum theory. In order to account for non-uniform inflow, non-ideal span loading, tip losses, swirl, blockage, stall, compressibility as well as Reynolds number corrections and other phenomena, surrogate models are added [13]. Furthermore, NDARC provides trim results, rotor states as well as engine performances. The considered helicopters are validated against flight test data.

Based on all discrete performance solutions, a multi-dimensional linear interpolation provides the function (1):

$$\begin{bmatrix} P_{req} \\ P_{av} \\ \dot{m}_{fuel} \\ SFC \\ \vdots \end{bmatrix} = \mathbf{f}\left(V, GW, h, V_{tip}\right) \tag{1}$$

The function **f** covers the helicopter performance and efficiency in four dimensions. Thus, missions are iteratively calculated by forward time integration with equidistant time steps. This can be understood as a time-weighting of discrete solutions and its related performance gains. Fuel flow and the specific fuel consumption (SFC) are determined from the 'Referred Parameter Turboshaft Engine Model' (RPTEM) within NDARC [13]. This model provides the available power P_{av} as well as fuel flow $\dot{m}_{fuel}$ and the SFC depending on pressure altitude, air temperature and cruise speed. Thus, the successive reduction of weight by fuel burn can be considered at each time step and the speed for best range can be calculated. Segments of climb and descent are neglegted, as level flight conditions are calculated exclusively.

One time step of the integration scheme is depicted in figure 1. The mission calculation starts at time 0 and the process, exemplary illustrated for the time between j and $j+1$, is continuously repeated. During one time-step the weight, cruise speed, rotor speed, altitude and fuel burn are kept constant. In the beginning gross weight, elapsed time, range, and burned fuel are initialized. Subsequently, cruise speed, altitude, rotor speed and the tilt angle are calculated, fulfilling constraints. The constraints are either defined by specific cruise speed, altitude, rotor speed and tilt angle, or maximum range, endurance, altitude and speed. In the first case constraints can by directly applied. To maximize range and endurance the related states are determined by optimization. In case of maximum altitude and speed Lagrange Multiplier are used to account for the available power constraint. Hence, the input variables of **f** are determined and thus, performance variables and fuel consumption can be obtained. This allows to update the gross weight, elapsed time, range and burned fuel. The selected time step is always 20 seconds.

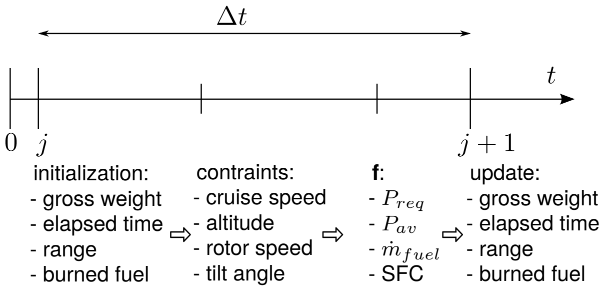


Figure 1: Illustration of one time-step of mission calculation.

To achieve a meaningful evaluation of mission advantages by variable rotor speed, the performance is compared to a constant rotor speed. The original rotor speed of each configuration is selected as reference, rather than a mission-optimized constant rotor speed. Thus, a rotor speed may exist that diminishes the mission advantages but the selection retains full hover performance, as this capability is crucial for all considered helicopters and related missions. In addition to the continuously variable and constant rotor speed the dual-speed rotor concept is investigated to draw conclusions about a two speed variable gearbox. The missions are determined individually for each configuration to consider the individual characteristics and advantages.

The maximum speed is always limited by MCP. This limit is applied to demonstrate mission performance gains with the same underlying available power and corresponding fuel flow, because the investigation focuses on efficiency. Neither a hub load limit, a aerodynamic limit nor a trim limit is applied. Speed improvements are resulting from excess power improvements that are used to increase the speed. The engine model's MCP is slightly depending on speed, but power and the related fuel burn can be treated as being approximately independent from speed.

Originally, the compound configuration was equipped with additional jet engines to overcome the power limit, in order to demonstrate aerodynamic advantages of slowed rotor speed and the Advancing Blade Concept. If distinct aerodynamic improvements are achievable beyond the MCP limit, particularly at slowed rotor speed and high cruise speed, this approach may not reveal the full potential of the technology. Besides, the models are not suitable to correctly represent physical rotor limits like compressibility, vibrational level and structural loads and they were exclusively validated against power demand.

The maximum acceptable, additional transmission weight that would cause a vanish of the achieved fuel savings is calculated for each mission. These results are compared to gearbox weight estimations. Different drive train technologies offer different range of speeds with different drawbacks in weight and efficiency. State of the art of transmission systems and gearboxes are not fulfilling the requirements of the project, as shown in [5]. A distinct shifting module is designed to be added to the UH-60 transmission system, to see if this technology is suitable for rotorcraft. The boundary conditions to the solution of the problem were set in form of input power – i.e. torque and speed –, mass and dimensions. Furthermore, one dual-speed and one Continuously Variable Transmission (CVT) solution are required. In particular, the shifting module has to change the speed of the main rotor, while other components should not to be influenced by a speed change, e.g. hydraulic pumps. Hence, only the shaft before or after the last gear stage is a plausible option, resulting in very high torques – i.e. weight. Another aspect of high relevance is represented by the fail-safe requirement of the shifting module itself. Indeed, in case of failure of a hydraulic or friction-based component, the shifting module has to continue working, allowing the rotor to rotate at nominal speed.

The possible drive train technologies which provide a variable rotor speed in connection with five different rotorcraft configurations are investigated regarding fuel savings and mission performance. A decision making process is used subsequently with the goal to find the most suitable rotorcraft configuration with a related gearbox technology for rotor speed variation.

RESULTS

A concept of a dual-speed transmission was developed in order to allow a shifting process under full load. In this case, the most appropriate gear stage is represented by an epicyclic gear stage, due to its high power density with respect to mass. Three transmission ratios can be obtained, in particular by braking or coupling in turn sun, planet carrier and ring gear. As slowing the carrier would result in a negative overall transmission ratio and as the required spread of $i_{in}/i_{out} = \Phi$=1,75 would be too small to slow the ring gear and drive off with the carrier, a double pinion epicyclic gearbox was chosen as illustrated in figure 2.

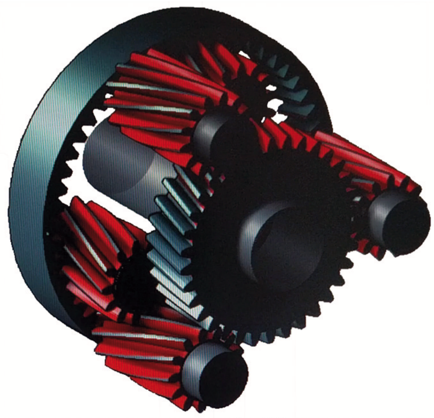


Figure 2: Double pinion epicyclic gearbox for the dual-speed approach.

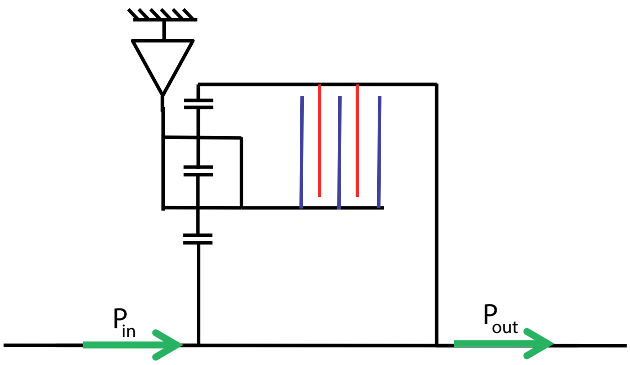


Figure 3: Schematic cross-section of double pinion epicyclic gearbox with clutch.

When the clutch is engaged, the system rotates as a block, causing no losses and having a ratio i=1. As the clutch opens, the absolute value of the carriers velocity reduces until the sprag clutch catches up giving an overall ratio i<1 and depending on the geometry of the epicyclic gearbox. A scheme is illustrated in figure 3 in principle. A concept of a self-shifting multi-disk clutch was developed combined with a dog clutch to achieve a form-locking to guarantee a fail-safe behavior of the clutch, figure 4. The overall additional weight of the module can be estimated by using a dimensioning software tool for the calculation of gears and results in m=661lb.

The weight of the gears is a very good indicator of the overall weight increase with decreasing RPM. An analysis, based exclusively on this data, has been

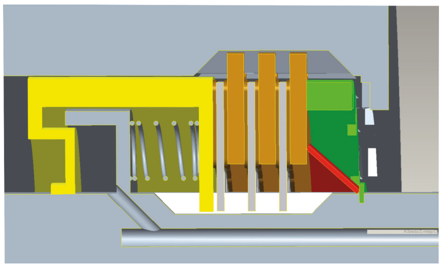


Figure 4: Principle of clutch for dual-speed approach.

performed to illustrate how placing the shifting module at an earlier stage would reduce the weight. The results, plotted in figure 5, show that an increase of velocity has significant effects on mass.

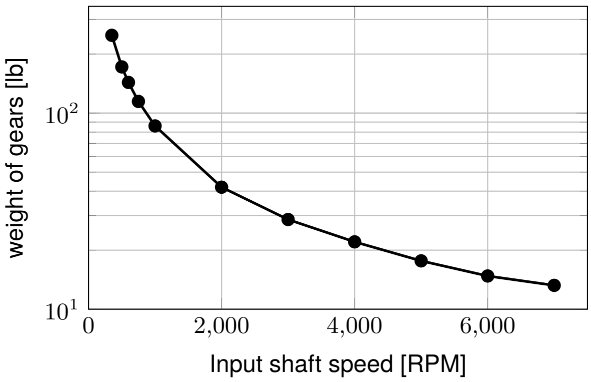


Figure 5: Weight estimation of the dual-speed shifting module depending on rotational speed.

Known CVT solutions from the automotive and industrial segment can hardly be adopted as a shifting module for a rotorcraft due to its high torque requirements. Thus, an alternative solution with a superposition of power flow seems to work best. This is schematically illustrated in figure 6. The proposed CVT shifting module consists of two coupled epicyclic gearboxes, where both ring gears are rigidly connected by a shaft. The input and output shaft are in turn connected to the sun of the first epicyclic stage and to the carrier of the second stage. The remaining carrier and sun are connected through a shaft that can be blocked or rotate, when power is superposed, at a chosen speed that determines the kinematic transmission ratio at the output.

When no power is superposed to the main flow, a ratio of i=1 is obtained. When power is added or removed from the sun-carrier shaft, every transmission ratio is theoretically achievable, getting an infinitely variable transmission. To keep the superposed power flows acceptable and unidirectional, only a maximum spread of Φ=1.75 is chosen. Using a fixed carrier train ratio of i_{12}=-2.4 the power to be superposed varies linearly

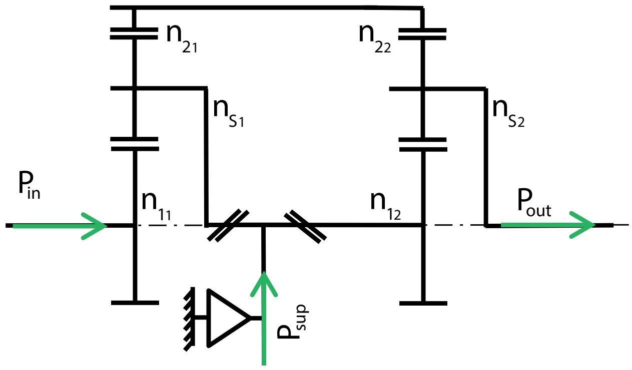


Figure 6: Schematic cross-section of CVT approach.

from 0% to 43% of the input power. For this concept and a transmission power of 2682hp (associated to the UH-60A), an additional mass for the superposition drive has to be considered with m_{SG}=243lb. The superposition drive train can be either electrical or hydraulic with an estimated weight of m_{SE}=595lb according to state of the art hydraulic components. The two stage planetary gear has an weight of m_P=485lb. So the concept has a total mass increase of m=1323lb.

In the first instance the configurations with no pusher device are investigated in a mission context. This distinctions allows to separate particular high-speed mission profiles, that still incorporate hover segments, from conventional helicopter missions. Tilt-rotor and compound configurations are designated in related research programs like Clean Sky 2 [6], FVL [7] and Russia's PSV project to perform equivalent missions. Similar programs focusing on conventional configurations (main/tail - rotor, tandem, coaxial) are rare.

Except for the considered CH-47D supply mission and the XH-59A rescue mission, mission profiles are derived from the helicopters performance. For the UH-60A a maritime SAR mission, a high altitude external transport mission and a troop transport mission are chosen. Yamakawa et. al. [15] reveal UH-60A mission requirements and Johnson [14] reveals the UH-60A performance. The maximum external cargo hook load is assumed to be 8000lb. The maximum UH-60A SAR mission radius is assumed to be 275km, while hover duration is 45min. The SAR mission is expected to require a 4 person crew. Additionally, 6 people are expected to be rescued at a maximum.

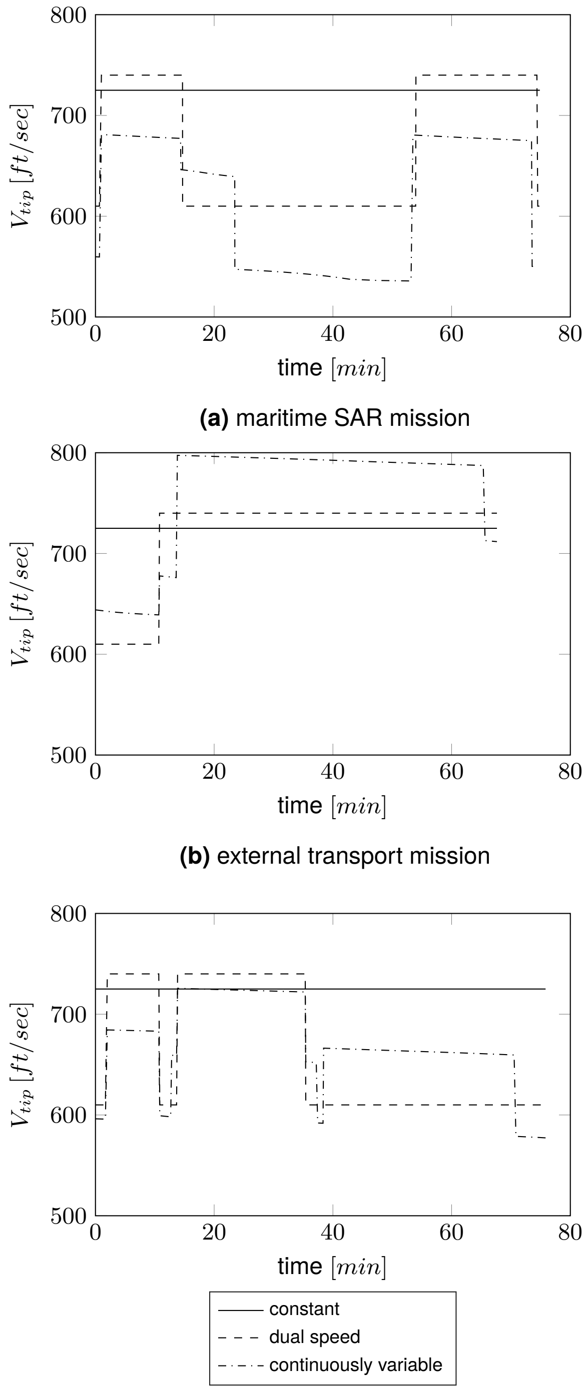
Trasana [16] contains a full CH-47D mission profile but its range is halved, because the description exceeds the considered MTOW. The second tandem mission is a high altitude external transport mission. The maximum cargo hook load is assumed as 20000lb. Additional data regarding the CH-47D is obtained from [14] likewise for the XH-59A. The passenger transport mission of the XH-59A is derived from Clean Sky 2 transport mission requirements. The XH-59A rescue mission profile was adapted from a German Federal Police rescue mission by adjusting the flight speed. Even if the XH-59A was not designed for rescue purposes, the gross weight of the helicopter matches the mission's characteristics in terms of weight. The resulting missions are illustrated in table 3.

The Future Vertical Lift (FVL) program asks for a small, agile configuration among other heavier helicopters. The related requirements are a mission radius of 424km, at a cruise speed of at least 200kts, a hover ceiling of 6000ft at 95°F and a payload capacity of 2010lb. Naturally, the configurations from the 1970's do not meet the latest mission requirements. Thus the mission requirements are diminished to enable the XV-15 and the Compound helicopter to perform the missions successfully. Especially, the hover ceiling is reduced to 4000ft/ISA. The altitude of the cruise flight segment is assumed to be 1000ft. The mission radii are resulting from maximum fuel capacity. In addition to the performance characteristics of the XH-59A Compound and XV-15 from [14] the requirements are leading to the missions illustrated in table 2.

The european Clean Sky 2 objectives regarding helicopters are a reduction of CO_2 emissions up to -17% by drag efficiency, noise reduction up to -7% (-13% until 2030) by optimized trajectories and rotor design. The european Clean Sky 2 project aims to build two demonstrators incorporating both high-speed and hover capabilities. The 'LifeRCraft' program aims to develop and built a single rotor compound configuration that is requested to perform both passenger transport and rescue operations. The main requirement of the transport mission is to fly 550km at 220kts. The rescue mission is not considered within this study.

The 'NextGenCTR' program intends to achieve a mission radius of 463km in 105min including a hover segment at a cruise speed of at least 300kts and and altitude of 25000ft [6]. These requirements and the XV-15 performance are considered within the mission definition in table 2. The mission radius is adopted and resulting from maximum fuel capacity. The payload is taken from FVL. The cruise flight altitude is slightly reduced and represents the maximum calculated altitude. The hover segment represents operations at the destination in helicopter mode.

Except for the high-speed mission profiles the missions consist of a variety of different flight conditions. This requires a permanent adaption of the optimal rotor speed. Figure 7 illustrates the progression of the UH-60A optimal rotor speed compared to the reference rotor speed and the dual-speed approach during the maritime SAR mission, the high altitude external transport mission and the troop transport mission. The optimal rotor speed shows discrete steps at the beginning of each mission segment. This



(a) maritime SAR mission

(b) external transport mission

(c) troop transport mission

Figure 7: Optimal continuously variable UH-60A rotor speed in contrast to constant rotor speed and dual.speed approach. The missions are defined in table 3.

results from discrete loading events and altitude steps, because climb and descent are not simulated. The continuously decrease of optimal rotor speed at each mission segment results from fuel consumption. The rotor speed of the dual-speed approach is not optimal in most cases, as figure 7 reveals, because the two rotor speeds are selected with respect to all three considered UH-60A missions.

The rotor speed approximately ranges from 535 ft/sec (-26%) to 800 ft/sec (+10%). The dual-speed approach provides the rotor speeds of 610 ft/sec (-16%) and 740 ft/sec (+2%). For each isolated mission the difference in rotor speed minimum and maximum is $\Delta V_{tip} \approx$145 ft/sec ($\pm$10%). The external transportation mission requires the highest rotor speed, the maritime SAR mission requires the lowest rotor speed. The difference between optimal and reference rotor speed is small for the troop transport mission. The mission durations are comparable. For all other configurations the main rotor speed development during the missions is illustrated in figure 9. Those reveal that the XV-15 requires the widest rotor speed reduction. Especially for the high-speed the dual-speed approach covers the optimal rotor speed well.

The mission advantages of the UH-60A using both a dual-speed approach and a continuously variable rotor speed are depicted in figure 8b. The figure is divided into three areas, representing the three calculated UH-60A missions. All other helicopters consist of two areas, related to the calculated missions. The most relevant mission performance measures are illustrated individually for each mission. The fuel improvements take into account that saving fuel, requires less initial fuel. Calculated improvements of endurance, range and payload consider an equal initial amount of fuel and the same burned fuel at the mission ending. Each measure is depicted along its own axis, six measures in total for each helicopter. The results do not consider additional transmission weight.

Regarding the UH-60A SAR mission, the hover segment endurance rather than flight speed can significantly be improved by up to 9.7% using a continuously variable rotor speed. Fuel savings of 6.3% or payload improvements of 18% are obtained during the external transport mission. Relatively, the improvements of the troop transport mission are small. The dual speed approach is always less efficient.

Equivalently, the other configurations and related mission advantages are illustrated in figure 8. Except for payload improvements during the CH-47D supply mission, the advantages of the XH-59A and CH-47D are small for both dual-speed approach and continuously variable rotor speed. As the considered passenger transport missions are equivalent for both XH-59A and the compound configurations, twice as much improvements are approximately obtained using the auxillary propeller device and a main rotor speed reduction of -8%. In both missions, the XH-59A compound is not able to maintain the FVL speed requirement of at least 200kts. However, a continuously variable rotor speed provides no additional benefits. This is true for the XV-15 as well. During the XV-15 long range transport mission range and speed improvements of 9% are obtained using the dual-speed approach and a rotor speed reduction of -43%. These are related to 8% of fuel savings. The XV-15 is able to fulfill the speed requirement from the FVL program.

In table 1 the additional empty weight for each mission is shown that compensates the achieved fuel savings by variable main rotor speed. The additional weight correlates with the fuel savings in relation to the single reference rotor speed. The UH-60A tolerates nearly 1000lb additional weight during the maritime SAR mission. But the maximum additional weight is strongly depending on the mission. The troop transport mission only allows additional 424lb. The compound and tiltrotor configurations tolerate the most additional weight. That is due to the high fuel savings gained with respect to the constant reference rotor speed. During the long range transport mission up to 27% empty weight increase are acceptable in terms of burned fuel. In comparison, the UH-60A tolerates up to 9% addtional transmission weight during the maritime SAR mission.

DISCUSSION

Five different helicopter configurations are investigated with two different drive train concepts in the context of individual missions. The results suggest that both variable speed drive train concepts are reasonable, but one of them is typically preferable depending on the configuration. The transmission weight investigations reveal that the high-speed configurations provide acceptable margins towards additional weight.

Especially the UH-60A missions in total require a continuously variable rotor speed adjustment. That does not directly result from considering one additional mission compared to the other helicopters, but instead from the large variety of mission segments covered by all missions. As a multi-purpose helicopter, it is reasonable to improve its versatility by a continuously variable main rotor speed. The considered dual-speed approach significantly narrows the improvements. The advantages of the troop transport mission are small with respect to the other UH-60A missions, because

mission	dual speed	continuous
UH-60A		
maritime SAR	550 lb	980 lb
external transport	315 lb	915 lb
troop transport	16 lb	424 lb
CH-47D		
external transport	390 lb	483 lb
supply	1615 lb	1850 lb
XH-59A		
passenger transport	313 lb	373 lb
rescue	417 lb	440 lb
XH-59A Compound		
transport	1689 lb	1689 lb
passenger transport	1073 lb	1073 lb
XV-15		
transport	1554 lb	1554 lb
long range transport	2688 lb	2688 lb

Table 1: Maximum additional empty weight (transmission weight) until design gets uneconomic. MTOW transgression disregarded.

the optimal rotor speed of that mission is close to the reference rotor speed as illustrated in figure 7c. Treating that mission as a standard reference mission of the UH-60A the particular advantage of a continuously variable rotor speed is elucidated. The efficiency of contrary types of missions can be improved and the portfolio of missions enhanced respectively. The maritime SAR (low payload) mission's efficiency and the external transport (high payload) mission's efficiency are distinctly improved. Using a dual-speed approach would not satisfy the large differences of all three missions. This is in contrast to the considered high speed missions, because they consist explicitly by two dominating, distinct flight regimes.

The more contrasting the mission segments and the related optimal rotor speeds considered with comparable proportions of time are, the more a continuously variable rotor speed gets interesting. If a configuration is equipped with a continuously variable rotor speed, it is capable of being adjusted towards a new specific mission. Considering only one specific mission segment narrows the advantages from variable rotor speed.

A drawback of the main-/tail-rotor configuration is the tail rotor. It needs to be driven by an additional variable gearbox, because its speed is required in contrary to the main rotor speed. Regarding this point the coaxial and tandem configurations are favorable because of no anti-torque device. Nevertheless, the XH-59A equipped with either a continuously variable gearbox or a dual-speed gearbox offers minor improvements, limiting the additional weight that can be carried in terms of overall efficiency. Equipped with an additional pusher, the improvements, for example maximum flight speed, are more than doubled. Based on this investigation, the coaxial configuration without a pusher is not a promising configuration.

The CH-47D mission advantages are low except for the payload capacity improvements of the supply mission. The high additional payload primarily results from fuel savings during the flight segments with no payload. The other mission improvements are low compared to the UH-60A.

R&D programs like Europe's Clean Sky 2 - Fast Rotorcraft program, the U.S. Future Vertical Lift program or Russia's Kamov Ka-92 focusing on high speed, usually prefer compound and tilt-rotor configurations. According to the earlier distinction, configurations featuring a propeller device or propeller mode are meant to meet fast forward flight requirements. As expected, these configurations reach the highest flight speed, while still incorporating hover capabilities. A wide rotor speed range is necessary to maintain operativeness in hover OEI conditions and to provide high speed capabilities and efficiency.

The two considered high-speed concepts approximately profit from a continuously variable rotor speed and dual-speed gearbox technology in a same way. This results from the specific mission profiles that only require a high rotor speed for excellent hover performance and a slow rotor speed for high flight speed. Whereas all high speed missions are dominated by the high speed segment. There is no justification to implement a continuously variable gearbox stage that is expected to have a higher additional weight. The XV-15 requires the widest rotor speed range of all considered configurations, besides providing the biggest range extensions of 9.5%. Fuel savings by up to 8.4% and speed improvements of 9.3% are achievable during the long range transport mission. In this case a more powerful engine should be considered to achieve even higher speeds. The most promising configuration equipped with a dual-speed gearbox stage is the tilt-rotor concept.

The dual-speed solution is the most efficient from the weight and internal-consumption point of view. The main drawback is represented by the shifting process: in fact, torque and sliding time would be too high to result in a clutch of reasonable dimensions. As a power reduction is not a feasible solution, the only way to reduce torque – i.e. weight – is to locate the shifting module at a more convenient stage that is at higher speeds. To meet the requests in terms of ratio spread, also the design of the shifting module has to be carefully taken into account.

A continuously variable transmission has many advantages against the dual-speed solution. Among them, especially the absence of friction-based elements, such as clutches, and the ability to achieve every possible speed ratio within the limits of the system are very important. Moreover, the possibility to vary from a ratio to another smoothly and over a longer time period allows the rotor to accelerate and avoids the turbine to abruptly change its velocity. Thus, especially the CVT solution seems to be promising. Unlike the dual-speed solution, in this case an important contribution to the overall weight is given by the second epicyclic gearbox and the motor system for the power superposition. To keep components small - and thus achieving a better lightweight design -, the least power possible has to flow through the generator/motor system itself. Simulations confirm that smaller absolute values of the epicyclic transmission ratio lead to lowering superposition power. The concept also has good potentiality, as the shifting module can be merged with the epicyclic set findable as a last stage in many helicopter gearboxes. The additional weight would therefore come from one epicyclic gearbox only. Hence, a reduction of about 35% of the initially estimated weight could be achieved, which would lead to a total mass increase of m=860lb. This would be acceptable for the UH-60A. The designed gearboxes are a first approach and they are designed to be added to an already existing system. The calculated weights show that a transmission variable gearbox system could be used in rotorcraft. The additional weight of the gearbox is assumed to be smaller, if such a system is designed within a new main gearbox- and rotorcraft-design.

CONCLUSION AND OUTLOOK

Rotor speed variation technology enables an efficiency increase for any rotorcraft configuration. The variation of rotor speed with turbine technology is suitable when only a small range of speed variation is required. The limiting factor is not the turbine itself but the gearbox afterwards because of the increased torque and the attached auxiliary units which will lose power with decreasing RPM. It seems to be possible to use variable gearbox technology close to the rotor to overcome this problems. The weight increase for the speed variation unit is higher because of higher torque but it could be in an acceptable region. Dual-speed transmission systems are suitable for configurations and missions with two explicit working areas, like a tilt rotor configuration. An additional continuous speed variation in a small range done by the turbine could make sense to minimize SFC.

In the context of missions the variable rotor speed is a promising technology to enhance fuel consumption and mission performance. But the improvements are strongly depending on the diversity of mission segments notwithstanding the number of missions considered. Especially, utility and multi-purpose helicopters, in this case represented by the UH-60A, benefit from a continuously variable rotor speed. The CVT technology can also be used to operate the turbine in the optimum operation point independent of the required rotor speed. In contrast, the tilt-rotor concept especially benefits from a dual-speed gearbox stage to adjust the rotor speed according to the airplane and helicopter mode respectively.

Both, utility and tilt-rotor configurations are most promising and the high-speed configurations additionally provide an appropriate margin towards additional transmission weight and thus benefit from variable rotor speed despite related weight drawbacks. However, particular missions may not benefit from variable rotor speed, if the reference rotor speed is equivalent to the related optimal rotor speed.

By additionally taking medium speed mission segments into account, the compound helicopter may benefit from a continuously variable rotor speed, because the mission requirements are less complementary. In all cases a redesign will raise the variable rotor speed efficiency by a reasonable rotor and drive-train design. It's the aim of subsequent investigations to demonstrate the feasibility and to reinvestigate the efficiency in detail after both an appropriate rotor system and a drive train system are designed for one distinct configuration. The selection of the configuration is based on the presented results. The design gross weight will be derived from the related mission requirements, whereas the design missions itself are inferred from lessons learned. Furthermore, stability, controllability, feasibility, etc. are intended to get investigated. In the future, it should be considered to reduce the rotor speed, even beyond the power optimum, to significantly reduce noise radiation.

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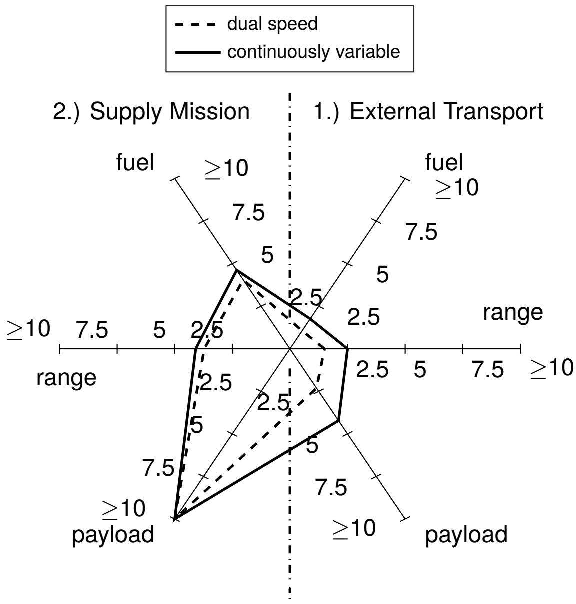
APPENDIX

segment	speed [kts]	(Δ)GW [lb]	altitude [ft]	time / range
Compound - transport and return				
1.	hover	12327	500	120 s
2.	max.	+ 0	1000	290 km
3.	hover	- 2010	4000	600 s
4.	max.	+ 0	1000	290 km
5.	hover	+ 0	500	120 s
Compound - passenger transport				
1.	hover	12327	500	120 s
2.	max.	+ 0	5000	550 km
3.	hover	+ 0	500	120 s
XV-15 - transport and return				
1.	hover	14112	500	120 s
2.	max.	+ 0	1000	210 km
3.	hover	- 2010	4000	600 s
4.	max.	+ 0	1000	210 km
5.	hover	+ 0	500	120 s
XV-15 - long range transport				
1.	hover	14112	500	120 s
2.	max.	+ 0	24000	410 km
3.	hover	- 2010	500	240 s
4.	max.	+ 0	24000	410 km
5.	hover	+ 0	500	120 s

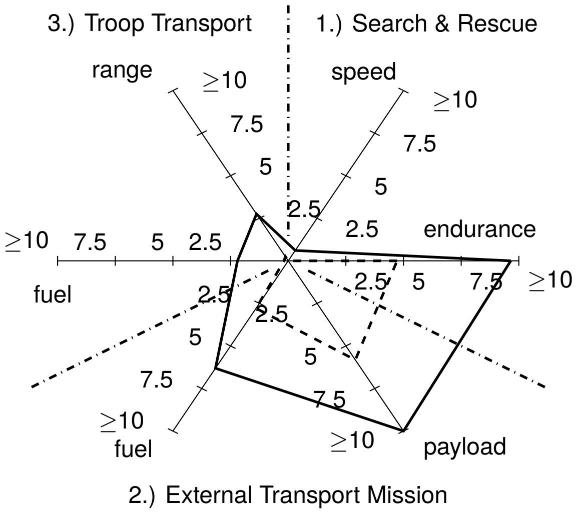
Table 2: Mission definition for high-speed configurations with propeller device.

segment	speed [kts]	(Δ)GW [lb]	altitude [ft]	time / range
UH-60A - maritime SAR				
1.	hover	15543	50	60 s
2.	max.	+ 0	300	60 km
3.	range	+ 0	300	30 km
4.	hover	- 220	50	1800 s
5.	max.	+ 1100	300	90 km
6.	hover	+ 0	50	60 s
UH-60A - high altitude external transport				
1.	90	15065	2800	30 km
2.	hover (IRP)	+ 5500	2500	180 s
3.	75	+ 0	11000	120 km
4.	hover (IRP)	+ 0	6500	120 s
UH-60A - troop transport				
1.	hover	15685	4000	120 s
2.	110	+ 0	5000	30 km
3.	hover	+ 2915	4600	180 s
4.	120	+ 0	5000	80 km
5.	hover	- 2915	4600	180 s
6.	90	+ 0	5000	90 km
7.	hover	+ 0	4000	120 s
CH-47D - high altitude external transport				
1.	90	31683	1500	30 km
2.	hover (IRP)	+ 18000	4500	360 s
3.	80	+ 0	9000	70 km
4.	hover (IRP)	+ 0	8800	300 s
CH-47D - supply mission				
1.	70	31000	4000	65 km
2.	40	+19542	4000	74 km
3.	70	- 20458	4000	130 km
XH-59A - passenger transport				
1.	hover	12327	500	120 s
2.	max.	+ 0	5000	550 km
3.	hover	+ 0	500	120 s
XH-59A - rescue				
1.	hover (IRP)	11011	1000	120 s
2.	max.	+ 0	2969	35 km
3.	hover (IRP)	+ 176	1000	240 s
4.	max.	+ 0	2969	35 km
5.	hover (IRP)	- 176	1000	240 s
6.	range	+ 0	2969	35 km
7.	hover	+ 0	1000	120 s

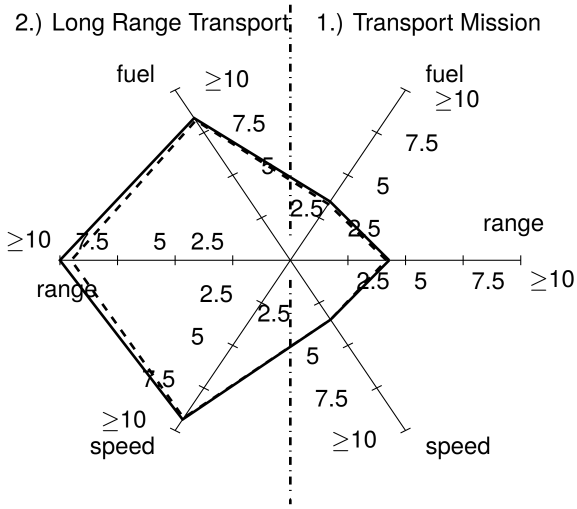
Table 3: Mission definition of configurations with no propeller device.



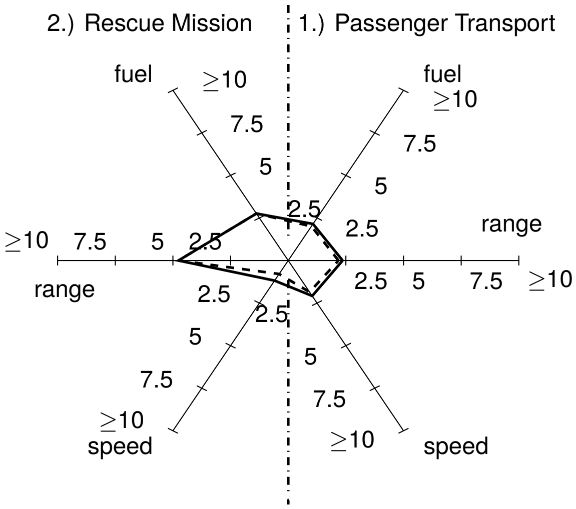
(a) CH-47D



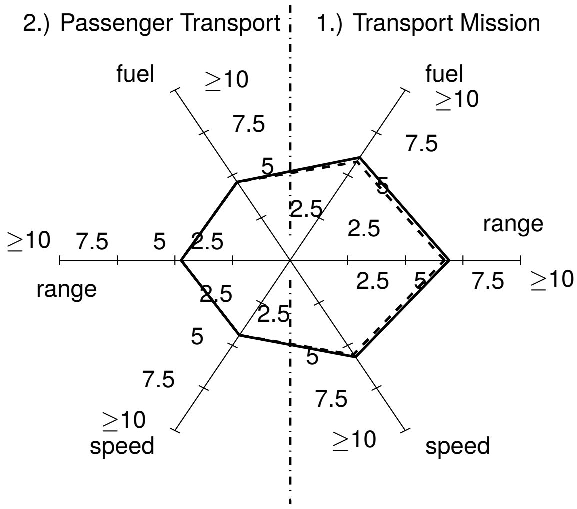
(b) UH-60A



(c) XV-15

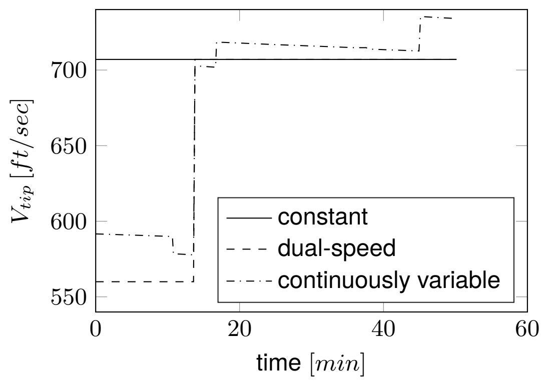


(d) XH-59A

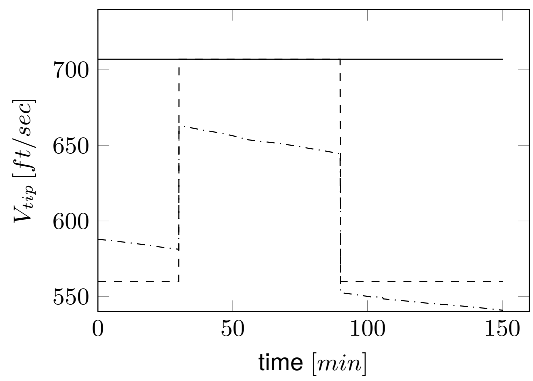


(e) XH-59A Compound

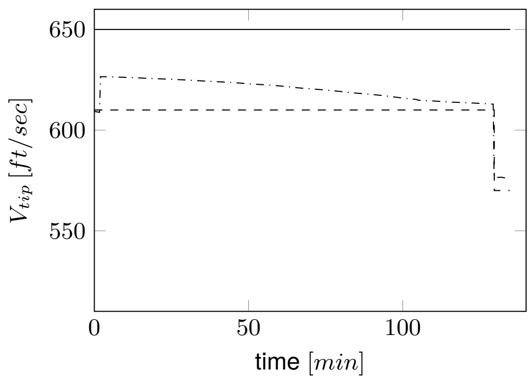
Figure 8: Mission advantages [%] using both continuously variable rotor speed and the dual-speed approach.



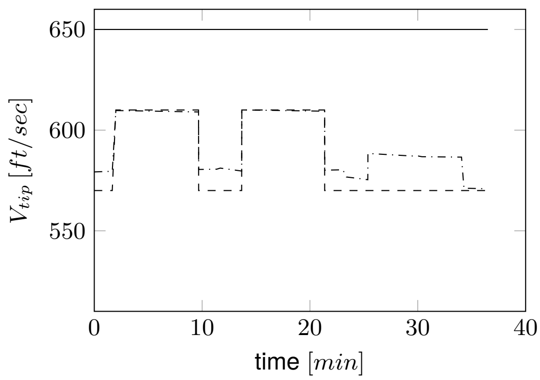
(a) CH-47D external transport



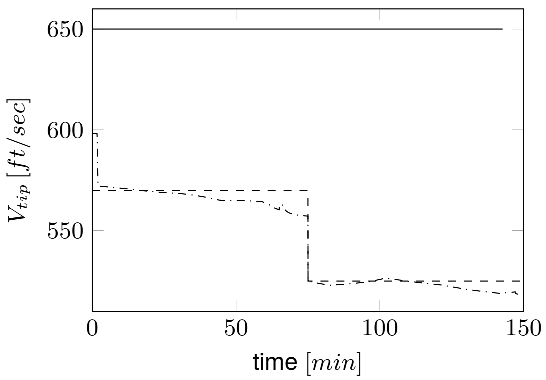
(b) CH-47D supply mission



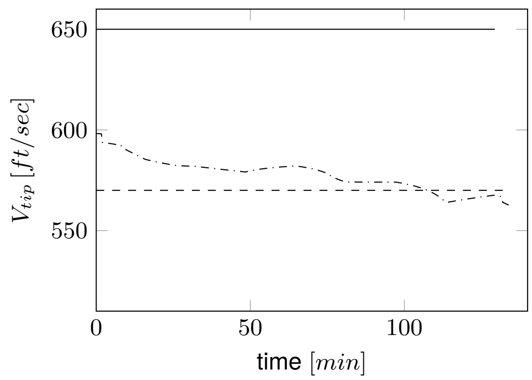
(c) XH-59A passenger transport



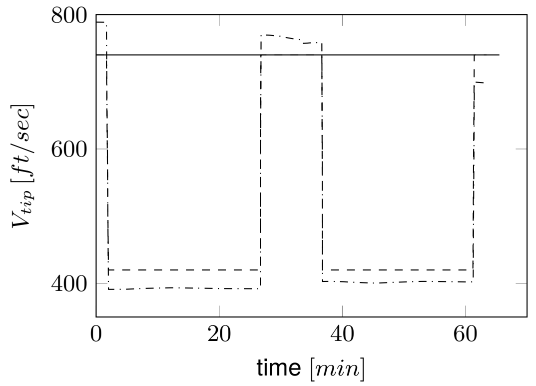
(d) XH-59A rescue mission



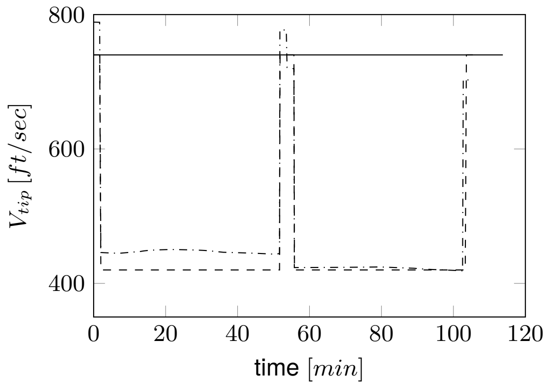
(e) Compound transport mission



(f) Compound passenger transport



(g) XV-15 transport



(h) XV-15 long range transport

Figure 9: Optimal continuously variable rotor speed in contrast to constant rotor speed and dual-speed approach. The missions are defined in table 3 and table 2.