FLIGHT SIMULATOR TESTING OF A VARIABLE SPEED HELICOPTER DRIVETRAIN USING ELECTRIC VARIATORS

Jonas Koch Research Associate
Bastian Bauer Research Associate
Andreas Reiser Research Associate
İlkay Yavrucuk Professor
Institute for Rotorcraft and Vertical Flight
Technical University of Munich
Munich, Germany

ABSTRACT

This paper presents a piloted simulation study evaluating a continuously variable rotor speed drivetrain for helicopters. The objective is to assess the drivetrain's impact on handling qualities, system behavior, and pilot workload both during dynamic rotor speed transitions and at subsequent steady-state rotor speed levels. The drivetrain, based on a compound-split gearbox architecture with electric variators, enables rotor speed adjustments in flight to improve aerodynamic efficiency. Simulation scenarios include cruise flight with systematic variations in rotor speed, while pilot assessments were conducted using standard handling quality and workload rating scales. The study demonstrated that rotor speed transitions of up to 20% can be executed without compromising helicopter controllability. Power and fuel savings of up to 5% were confirmed during rotor speed reductions. The pilot reported acceptable workload levels and manageable control compensation requirements during rotor speed changes with manual collective adjustment, which were further alleviated by a collective compensation controller. The findings validate the drivetrain's potential to enhance helicopter operational efficiency without significantly degrading handling qualities.

NOTATION

*

Symbols

R Rotor radius, m

Ω Rotor speed, rad/s

P Shaft power, kW

Q Shaft torque, Nm

V_{tip} Blade tip speed, m/s

μ Advance ratio, -

θ_0 Collective pitch, °

ρ density, kg/m³

T Temperature, K

N_1 gas turbine speed, rad/s

N_2 power turbine speed, rad/s

C_T/σ blade loading, -

*

Acronyms

ARCS Advanced RotorCraft Simulation

BWR Bedford Workload Rating

CHR Cooper-Harper Handling Qualities Rating

COI Critical Operational Issue

CS Compound Split

CVT Continuously Variable Transmission

HMI Human Machine Interface

MFD Multifunction Display

MOE Measures of Effectiveness

MOA Measures of Assessment

MTE Mission Task Element

NDARC NASA Design and Analysis of Rotorcraft Software

ORCD Operational Requirements and Capabilities Document

ROSIE$^{\mathbf{X}}$ Rotorcraft Simulation Environment - Extended Version

SSQ Simulator Sickness Questionnaire

TID Test Identification Number

TSE Turboshaft Engine

VRS Variable Rotor Speed

INTRODUCTION

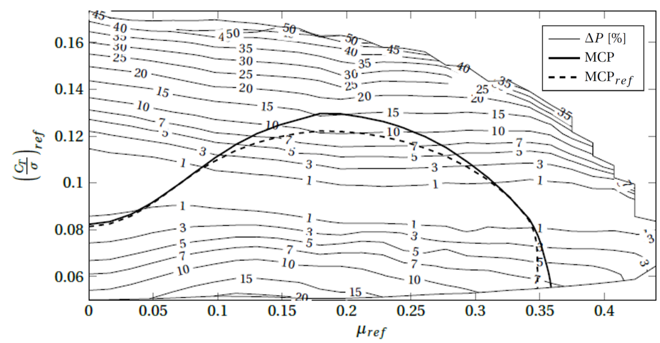
The ability to vary main rotor speed in flight offers several advantages for helicopter configurations, including reduced rotor noise and vibration, improved power efficiency, and extended mission range. By adjusting the main rotor speed to the actual flight condition, it is possible to optimize aerodynamic efficiency, thus reducing fuel consumption and environmental impact. The concept of Variable Rotor Speed (VRS) has gained significant attention as an enabler for enhanced operational flexibility and mission-specific performance optimization [1].

Recent research has shown that the optimal drivetrain architecture for enabling rotor speed variation depends strongly on the specific helicopter configuration and its operational use case. For example, dual-speed, clutched stage gearboxes have been identified as suitable solutions for tiltrotor concepts, while Continuously Variable Transmission (CVT) gearboxes offer particular benefits for utility helicopter applications, such as the UH-60 Black Hawk [2]. Prior studies have demonstrated that power savings up to 20 % are achievable through rotor speed variation in the range of $-30\,\%$ to $+10\,\%$ of the nominal rotor speed, depending on the mission profile and drivetrain architecture [3].

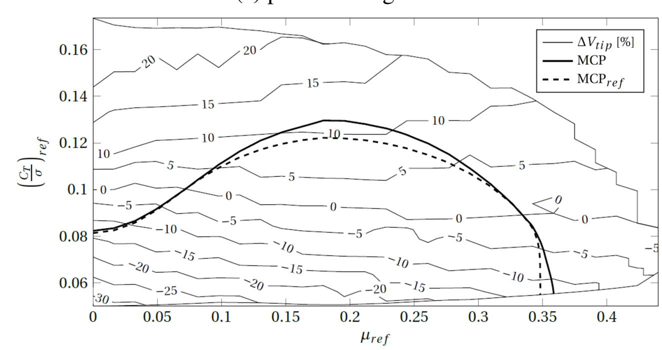
In the scope of ongoing research, a drivetrain concept based on Compound Split (CS) modules has been developed. A CS module integrates two nested planetary gear stages with electric variators arranged in a motor-generator loop. By actively controlling the variator torques, the gear ratio of the drivetrain can be adjusted continuously, allowing precise control of the main rotor speed in response to changing flight conditions [4]. The drivetrain is designed to allow operation at the design point of existing turboshaft engines, with the goal of achieving maximum efficiency.

The work presented in this paper focuses on the integration of the variable rotor speed drivetrain into a pilot-in-the-loop simulation environment. A key objective is to evaluate the operational behavior of the drivetrain in realistic flight scenarios based on mission task elements from the ADS-33E-PRF standard, and to assess the pilot's interaction with the system through a modified Human Machine Interface (HMI). This piloted simulation study represents an essential step towards validating the drivetrain's control strategies and its influence on overall helicopter handling qualities. The developed simulation environment allows for systematic testing of dynamic rotor speed variation profiles, assessment of pilot workload, and identification of potential integration challenges for future in-flight applications.

In the scope of the research project VARISPEED, a power efficiency study regarding variable rotor speed over the whole flight envelope of the UH-60 was performed using the preliminary design tool NASA Design and Analysis of Rotorcraft Software (NDARC). Possible power savings at corresponding optimal rotor speed were investigated at discrete flight states in the flight envelope, spanned by the advance ratio μ and the blade loading (C_T/σ) (cf. Figure 1). The plots clearly show the trend of decreased rotor speed at low blade loading and increased rotor speed at high blade loading for optimum efficiency. Detailed background information on the optimum rotor speed concept is provided in [3].



(a) power savings ΔP



(b) optimum tip speed ΔV_{tip} respectively rotor speed $\Delta\Omega$

Figure 1: possible power savings *(a)* and corresponding optimum rotor speed *(b)* within UH60 flight envelope, taken from [1]

The findings from these preliminary simulations have laid the foundation for the drivetrain design and control strategies implemented in this work. However, a pilot-in-the-loop evaluation is necessary to understand the practical implications of rotor speed variation on handling qualities, pilot workload, and overall system integration. The present study builds on these mid-fidelity simulation results by implementing the drivetrain model in a reduced real-time simulation environment and conducting piloted evaluations of rotor speed adaptation in operationally relevant flight scenarios.

FLIGHT DYNAMICS AND DRIVETRAIN ARCHITECTURE

The previous developed drivetrain model, consisting of a compound split transmission, electric variators, and the turbine, was adapted in such a way that it can be integrated into the development environment of the helicopter simulator ROSIE^X while maintaining real-time capability (see Fig. 2). A mathematical model of the GE T700-701C turboshaft engine, as used in the UH-60 helicopter, is applied for turbine modeling [5]. It essentially describes the dynamics of the compressor spool and the power spool using the principle of angular momentum and incorporates a fuel flow controller to maintain the power spool's shaft speed across different torque loads.

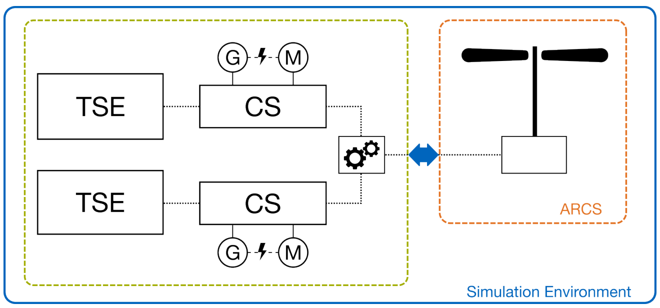


Figure 2: Coupled Drivetrain Scheme

A linear state space model was derived in MATLAB/SIMULINK [6] to describe the kinematics of the compound split gear using the Lagrange formalism [3]. Fig. 3 shows the complete transmission system, from the turbine power spool to the collecting gear stage and the main rotor shaft. The derived model captures the dynamics of the two planetary gear stages (shown in the middle of the figure) and the electric machines of the two variators (not shown).

The flight physics model used in the simulator was built within the Advanced RotorCraft Simulation (ARCS) software, which is developed at the Institute of Rotorcraft and Vertical Flight. ARCS is based on the multibody simulation framework Simbody [7], and extends its rigid-body functionality with aerodynamic components. Rotor and blade forces are computed using blade-element-momentum theory combined with 2D airfoil polars, and the dynamic inflow is modeled using the Pitt-Peters method. A UH-60 helicopter model was established within this development environment. The main rotor parameters were derived from the existing UH-60 Dymore model at the Institute of Rotorcraft and Vertical Flight [8]. The aerodynamic forces of the fuselage, the vertical stabilizer, and the movable horizontal stabilator were implemented according to [9].

Since the flight physics code was implemented in the C++ programming language, the drivetrain model developed in MATLAB/SIMULINK was translated into C++ code using Simulink Coder. A seamless integration of the drivetrain model into the flight physics code allows the required real-time capability for operation in the simulator. The synchronization between the powertrain model and the flight physics model is performed internally in the code with a fixed time step size $\Delta t = 0.001\,\mathrm{s}$. The speed of the output shaft calculated in the CS model is applied to the main rotor shaft. The resulting torque of the main rotor is returned to the CS gear. As additional parameters, the current air density and temperature are transferred to the turbine, which are calculated from the ISA standard atmosphere within the flight physics model. Due to the modeling approach of the compound split gearbox as a resource-saving linear state space model, the real-time capability of the coupled drivetrain model is guaranteed. All relevant model parameters can be output and logged from the C++ code and, if necessary, visualized accordingly in the flight simulator cockpit. In addition to the display of conventional engine parameters from the turbine model, such as speeds N_1 and N_2, additional information about the speeds and power flow of the electric variators is also available.

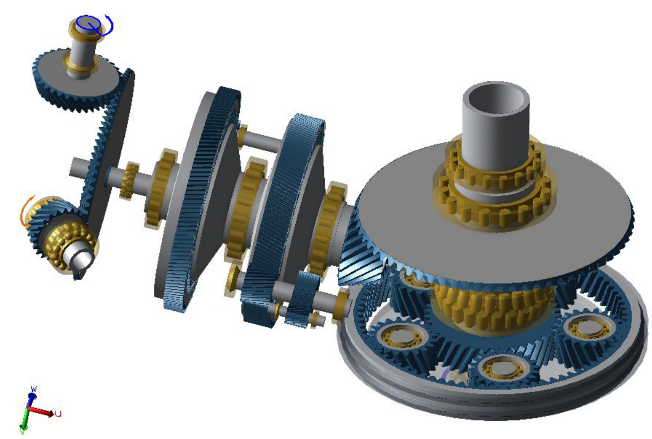


Figure 3: Model of the transmission system including the compound split gear, modeled within FVA-Workbench [10]

SIMULATOR HARDWARE ENVIRONMENT AND HMI

The piloted evaluation was conducted using the ROSIE^X fixed-base helicopter research simulator at the Technical University of Munich. ROSIE^X features a high-fidelity visualization system with a hemispherical dome spanning a 200° horizontal and +30°/-50° vertical field of view, combined with an original BO-105 cockpit fuselage. This environment enables realistic Pilot-in-the-Loop testing for rotorcraft research applications.

The modularized ROSIE^X simulator's IT architecture allowed seamless integration of the UH-60 flight dynamics model, including the variable speed drivetrain. Key components of the simulator hardware architecture include a high-performance Flight-Model PC hosting the real-time capable flight physics model with drivetrain integration, achieving a computation time of approximately 9 ms to ensure compatibility with the 60 Hz refresh rate corresponding to a timestep of 16.7 ms. It additionally features an overhead control panel equipped

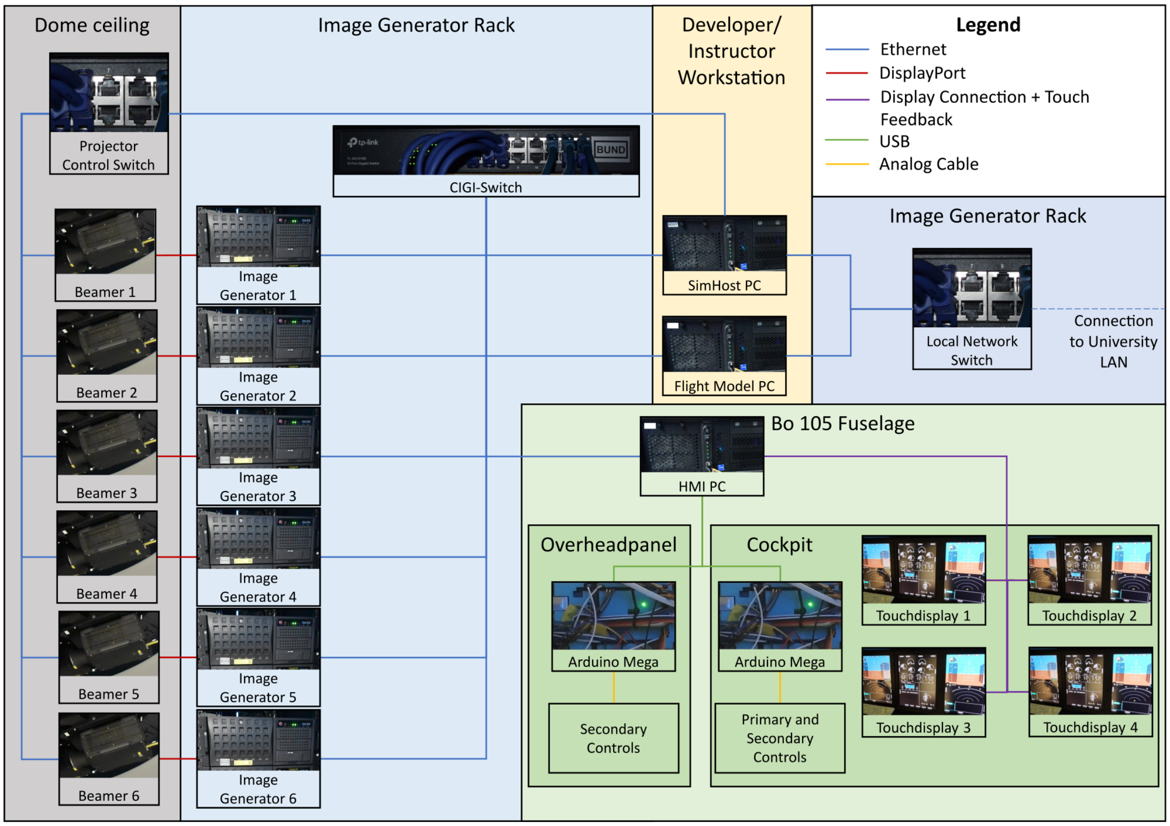


Figure 4: IT hardware structure of the ROSIE^{X} simulator [11]

with dedicated switches for toggling variable rotor speed modes and activating control logics, and multifunction displays (MFDs) retrofitted to replicate the avionics layout of the S-70A Black Hawk fleet based on the ACE Deck VL-60 configuration with the Garmin G5000H flight deck [12].

Communication between simulator modules is established via protocol buffers using the gRPC protocol, ensuring real-time data exchange between control interfaces, visualization systems, and flight dynamics computation. Pilot control inputs, including cyclic, collective, pedal positions, and overhead panel switch states, is transmitted to the flight model, while aircraft state parameters are fed back to the simulator's visual system for image generation (see Fig. 4).

Regarding the glass cockpit of the Human-Machine Interface (HMI), a mockup avionics suite was developed using the software Air Manager with Lua scripting, enabling a modular display structure [13]. The cockpit interface was retrofitted to present rotorcraft primary flight parameters alongside drivetrain-specific data (see Fig. 6). Enhancements include the extension of the engine page to display real-time parameters of the electric variators such as torque, rotational speed, and electrical power, the addition of rotor speed indicators showing the current target rotor speed directly on the primary flight display, and dynamic limit indications that adjust to the selected variable rotor speed operating point.

Due to the portrait aspect ratio of the displays installed in ROSIE^{X}, the instrument layouts were adapted while maintaining operational fidelity with the reference avionics configuration. The flexible and modular architecture of the developed avionics system enables its reuse and further customization for future simulator studies on this topic.

METHODOLOGY AND SCENARIOS OF PILOT TEST CAMPAIGN

The simulation campaign is structured to systematically evaluate the operational behavior and pilot interaction with the variable speed drivetrain under representative flight conditions. The primary objective is to assess the system's ability to dynamically adjust main rotor speed during flight while ensuring stable helicopter control and maintaining acceptable pilot workload.

The test scenarios are designed based on an Operational Requirements and Capabilities Document (ORCD), defining technical and operational target criteria. A key requirement is the ability to vary the main rotor speed dynamically between 73% and 110% of the reference speed during flight without compromising controllability. Additionally, it is specified that the pilot workload should not increase due to drivetrain operation and that the rotor speed adjustments should integrate seamlessly into the overall flight dynamics.

For systematic evaluation, an assessment framework is established based on Critical Operational Issues (COIs), which are translated into measurable Measures of Assessments (MOAs).

Figure 5: ROSIE^{X} flight simulator at the Institute of Rotorcraft and Vertical Flight at Technical University of Munich

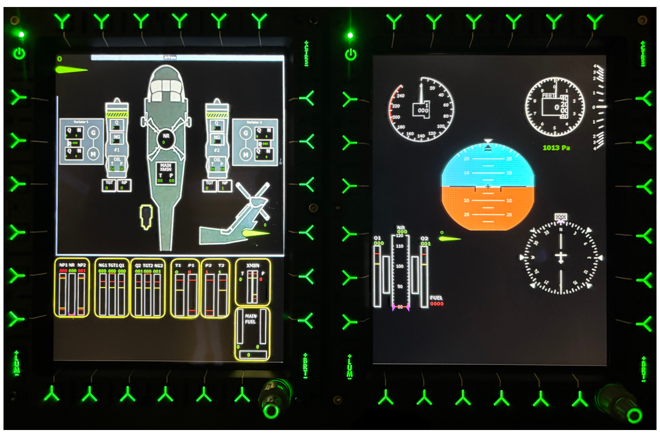


Figure 6: PFD and VEMD panels based on the G5000H Glass Cockpit developed at TUM [13]

The following MOAs were defined to capture the essential performance and usability aspects of the developed system:

- MOA 1.1: Subjective pilot evaluation of handling qualities at fixed rotor speeds deviating from reference speed.
- MOA 1.2: Objective analysis of system parameters under these fixed-speed conditions.
- MOA 2.1: Subjective pilot evaluation of handling qualities of dynamic rotor speed adjustments during flight without additional controller
- MOA 2.2: System behavior analysis during these dynamic rotor speed transition maneuvers.
- MOA 3.1: Subjective pilot evaluation of handling qualities of dynamic rotor speed adjustments during flight with additional collective controller
- MOA 3.2: System behavior analysis during these dynamic rotor speed transition maneuvers with controller

Corresponding targets are formulated to verify technical performance, including criteria such as maintaining controllability during cruise at reduced rotor speeds, executing standard turn maneuvers within defined tolerances, and ensuring that the rotor speed transitions do not exceed permissible engine torque limits or induce excessive pilot workload. The transition profiles are defined to achieve target optimum rotor speeds within five seconds, following a cosine-shaped acceleration/deceleration profile to minimize excitation of drivetrain resonances.

The test procedures are based on the Aeronautical Design Standard ADS-33E-PRF [14] and structured as a parcours of standardized flight maneuvers. The parcours includes stabilized cruise flight, climb and descent at constant vertical speeds, and standard rate turns, ensuring a comprehensive assessment of the helicopter's handling qualities at different rotor speed levels. Particular focus is placed on the transitions between different rotor speed settings, as these represent critical phases where increased control effort by the pilot might occur. Additionally, variations in helicopter loading conditions are considered to evaluate the robustness of the system under different blade loadings and advance ratios within the flight envelope. The test campaign is executed in a sequential flight schedule, starting with a familiarization flight, followed by flights under variable rotor speed without an additional control mechanism, and concluding with test flights featuring active rotor speed adaptation including an open-loop controller to compensate for the collective pitch change to maintain trim condition.

Subjective pilot evaluations are conducted using the Cooper-Harper Handling Qualities Rating (CHR) and the Bedford Workload Rating (BWR) scales. The CHR is a ten-level scale ranging from 1 (excellent handling qualities, no corrections needed) to 10 (aircraft is uncontrollable), and is widely used in flight testing to assess the controllability of an aircraft from the pilot's perspective [15]. The BWR is similarly structured in ten levels and measures the pilot's perceived mental workload, with 1 indicating minimal workload and 10 representing an unacceptable level of workload that prevents task completion [16]. These scales provide structured feedback on the pilot's perception of handling qualities and workload during steady-state and transition phases of rotor speed adaptation.

A Simulator Sickness Questionnaire (SSQ) is presented to the pilot after several flights to capture any simulator-induced symptoms systematically [17]. The questionnaire assesses various factors including general discomfort, nausea, eye strain, and disorientation, ensuring that the simulator environment does not adversely affect pilot performance during the evaluation.

The pilot and co-pilot communicate throughout the test flights using an intercom system. While the pilot maintains primary control of the helicopter, the co-pilot operates the overhead panel switches for activating and deactivating the variable rotor speed mode based on the pilot's commands. Activation of the optimal speed mode results in an automatic adjustment of the rotor speed to the most efficient value based on current

flight conditions. The system continuously calculates the target speed using a lookup table derived from the aerodynamic simulations referenced in the introduction section, which considers the current normalized blade loading and advance ratio. In emergency or special maneuver scenarios, the pilot can override the system and restore the rotor speed to the reference value by toggling the switch.
The collective pitch open-loop controller can also be activated via an overhead panel switch. It is designed to automatically compensate thrust variations caused by rotor speed changes. It incorporates a feedforward approach based on a lookup table derived from mid-fidelity Dymore main rotor simulations. This lookup table provides the required collective pitch adjustment $\Delta\theta_0$ for any given combination of the three flight condition variables advance ratio μ, blade loading C_T/σ_{ref}, and current rotor speed Ω_{var}. The precomputed pitch offset $\Delta\theta_0$ is applied as a feedforward control input to preserve the trim condition during rotor speed variations.
An instructor station supervisor monitors the flight parameters in real-time and ensures that the test procedures are followed correctly.

To ensure comprehensive data collection, all flight dynamics parameters, control inputs, and drivetrain state variables are logged at a sampling rate of 1000 Hz. Additionally, a wide-angle camera records both the external view and the pilot's control movements during the flights. The combination of high-resolution flight data and standardized pilot rating scales, including the CHR and the BWR, provides a robust methodology to evaluate both the technical performance and the human factors implications of the variable speed drivetrain system.

Figure 7: VARISPEED flight test campaign in the ROSIE^X simulator

RESULTS AND DISCUSSION

The following section presents the results of the pilot test campaign, focusing on the data from a single helicopter pilot in the simulator.

The evaluation of the flight characteristics during rotor speed adaptation is exemplified by the test flight Test Identification Number (TID) 1. This flight sequence consists of the following Mission Task Elements (MTEs): a climb to 2000 ft MSL, stabilized cruise flight at 85 kts and 2000 ft MSL, activation of the VARISPEED system while maintaining level flight, followed by standard rate turns to the left and right with the VARISPEED system active. During this flight, the additional controller for altitude stabilization was deactivated, requiring the pilot to manually compensate for changes in rotor thrust during rotor speed variation.

Figure 8 shows the flight parameters during the rotor speed transition in the time interval from t = 220 s to 260 s. After establishing a stable cruise flight, the pilot gave the callout to activate the VARISPEED system at t = 225.4 s. The rotor speed controller of the CS drivetrain reduced the rotor speed Ω_{MR} to the optimal value within five seconds (see Fig. 8c). For this flight condition with a gross weight of $m = 7547\,\text{kg}$ and air density of $\rho = 1.15\,\text{kg/m}^3$, the optimal rotor speed was calculated as $\Omega_{opt} = 92.9\,\% \cdot \Omega_{ref}$.

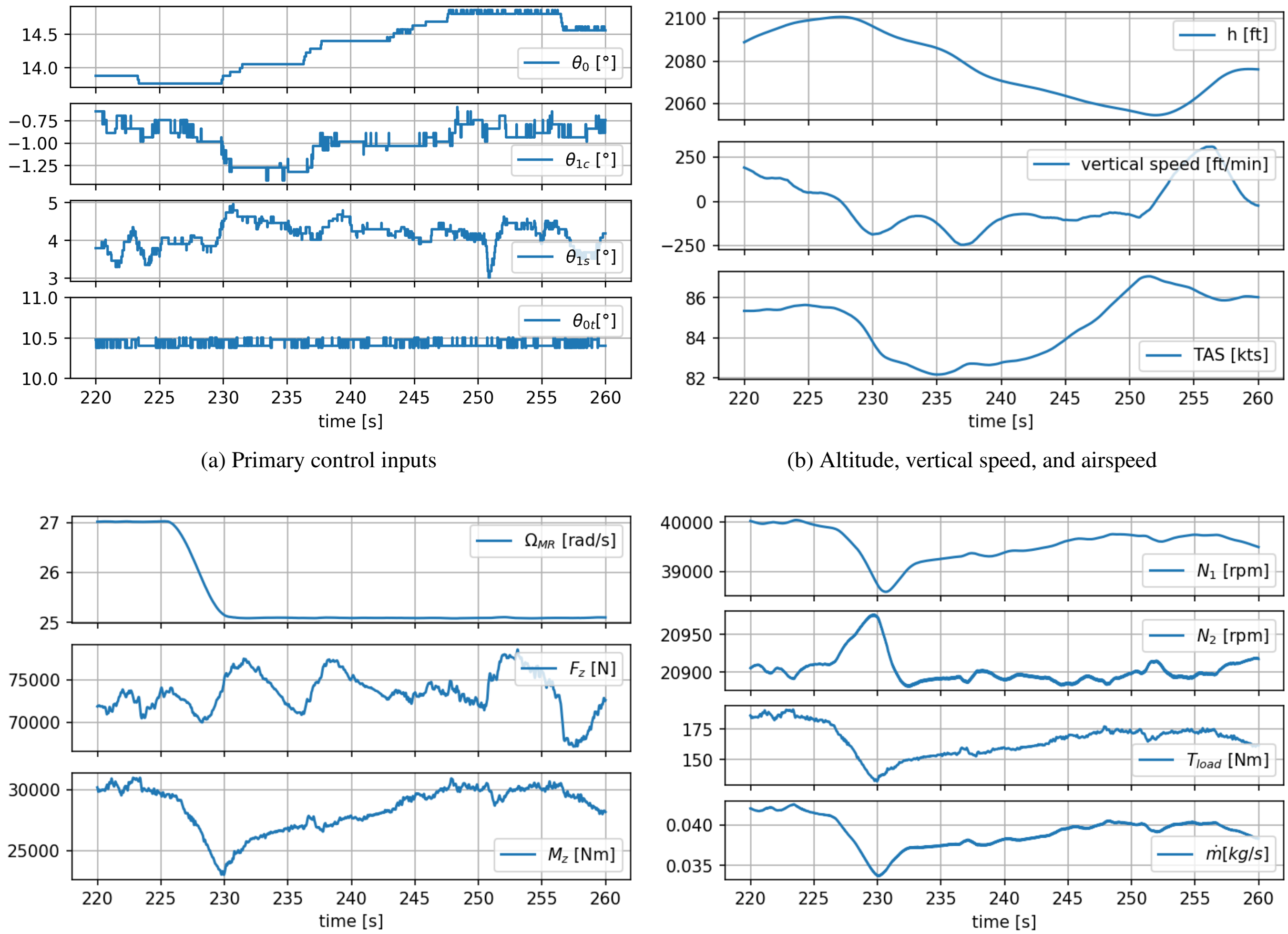
As shown in Figure 8b, the pilot maintained flight within the prescribed limits of vertical speed ($v_z = \pm 250$ ft/min), altitude ($h = \pm 100$ ft), and true airspeed ($TAS = \pm 5$ kts) during the rotor speed reduction. Initially, the reduced rotor thrust caused a slight altitude loss, which the pilot corrected by increasing the collective pitch by $\Delta\theta_0 = 1.0°$ (see Fig. 8a). This maneuver resulted in a minor decrease in airspeed of $\Delta TAS = -3.5$ kts.

The reduction in main rotor torque due to the decreased rotor speed led to an imbalance in the anti-torque effect since the tail rotor continued operating at constant reference speed. Consequently, a slight yaw drift to the left developed, resulting in a ground track offset of $\Delta\chi = 2.0°$. The pilot did not perceive this deviation as critical and thus did not apply corrective pedal input (see Fig. 8a, bottom row).

Turbine parameters during the rotor speed reduction are shown in Figure 8d. Both turbines operate synchronously, sharing the load equally. Therefore, only one turbine and its corresponding CS train are considered. The CS gearbox allowed the power turbine speed N_2 to remain at its design point of 20900 RPM with a maximum deviation of $\Delta N_2 = 0.3\%$. The turbine load torque decreased by $\Delta T_{load} = 5.4\%$, corresponding to a turbine power reduction of $\Delta P_{turbine} = 5.4\%$. This result aligns with prior simulations predicting a power saving potential of 3-5% for this flight condition. Consequently, a fuel flow reduction of $\Delta\dot{m}_{turbine} = 4.8\%$ was recorded for that condition.

MOA 1.1 and MOA 1.2 are evaluated based on these results. Subjectively, the pilot rated the handling qualities at fixed rotor speeds (MOA 1.1) as level ③ on the Cooper-Harper scale, indicating minor deficiencies requiring small compensations but without impact on task performance. Objectively (MOA 1.2), the system maintained the commanded rotor speed precisely, with stable flight parameters and no significant oscillations, validating the ability of the drivetrain to maintain performance under steady rotor speed variations.

Test flight TID5 is considered to evaluate the effect of rotor speed increase. Analogous to TID1, the relevant flight parameters during the rotor speed transition from t = 160 s to 200 s are depicted in Figure 9. The gross weight for this flight



(a) Primary control inputs

(b) Altitude, vertical speed, and airspeed

(c) Main rotor speed, thrust, and shaft torque

(d) Turbine parameters

Figure 8: Flight log TID1 - Rotor speed reduction during level flight at $\mu = 0.2$ and $h = 2000\,\text{ft}$

was increased to $m = 11\,500\,\text{kg}$, resulting in a blade loading of $(C_T/\sigma)_{ref} = 0.115$. After VARISPEED activation at t = 167.2 s, the rotor speed was increased to the optimal value of $\Omega_{opt} = 108.3\% \cdot \Omega_{ref}$ (see Fig. 9c).

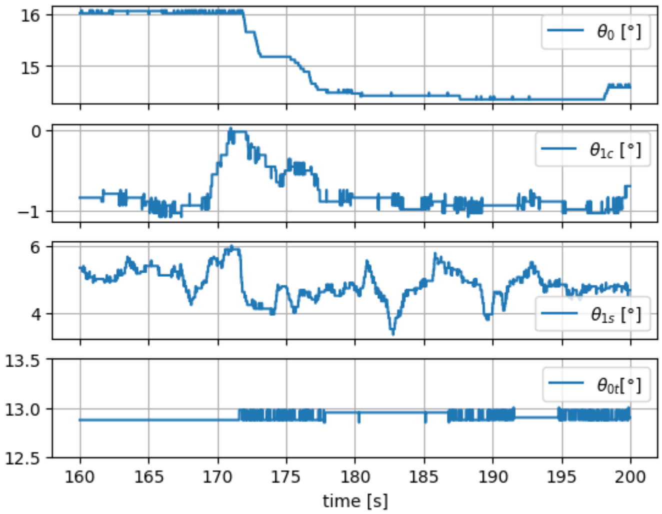
Following the rotor speed increase, the helicopter initially gained altitude and airspeed (see Fig. 9b). The pilot counteracted this by reducing the collective pitch by $\Delta\theta_0 = -1.5°$ and applying a nose-down longitudinal cyclic input of $\Delta\theta_{1s} = -1.9°$, successfully re-establishing level flight within the specified limits.

The increased main rotor speed resulted in an anti-torque imbalance, producing a positive yaw rate. The pilot compensated this with a pedal input, resulting in a ground track offset of $\Delta\chi = 6.1°$ to the right. The CS drivetrain maintained the power turbine speed at the design point of 20900 RPM, with a maximum deviation of $\Delta N_2 = -1.0\%$. Unlike during the rotor speed reduction, no reduction in turbine load torque or fuel flow was observed, despite prior simulations predicting a power saving potential of 4-6% for this flight condition.

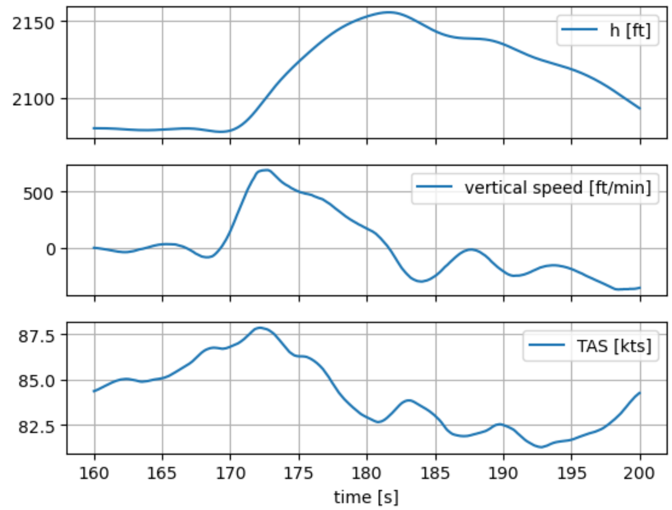
MOA 2.1 was assessed through subjective pilot feedback during dynamic rotor speed transitions without collective control assistance. The CHR ratings for these transitions were level ⑥, indicating that while compensation was required, the tasks remained achievable. MOA 2.2, the objective system behavior analysis, confirmed that dynamic rotor speed transitions followed the prescribed trajectories accurately, with stable flight dynamics within the specified limits.

In addition to the transient effects of rotor speed transitions, the performance during standard rate turns at reduced and increased rotor speeds was assessed in flights TID1 and TID5, respectively. The data logs showed that the rotor speed variation did not compromise controllability in these flight conditions, and the turns were successfully flown within the specified limits.

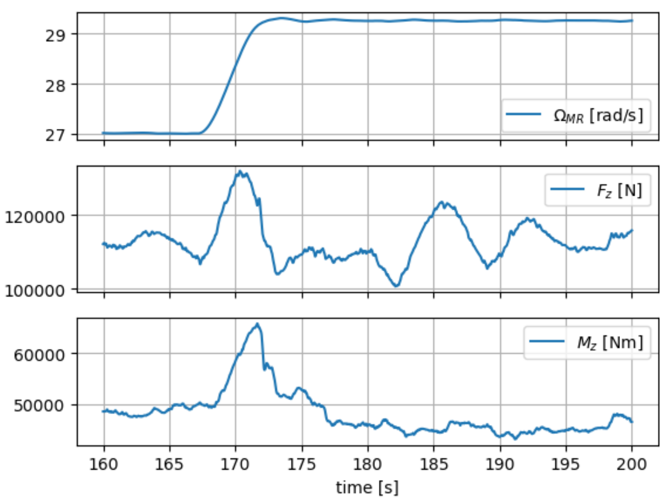
Similarly, vertical maneuver requirements in flights TID2 and TID6 were met at adapted rotor speeds. Sufficient collective control margin was available to maintain the required climb rates. The control margin inherently adjusts with rotor speed variation; at high blade loading (high collective input), rotor speed increases, reducing the required collective pitch for the same thrust, thereby providing additional control margin. Conversely, at low blade loading, rotor speed decreases, re-



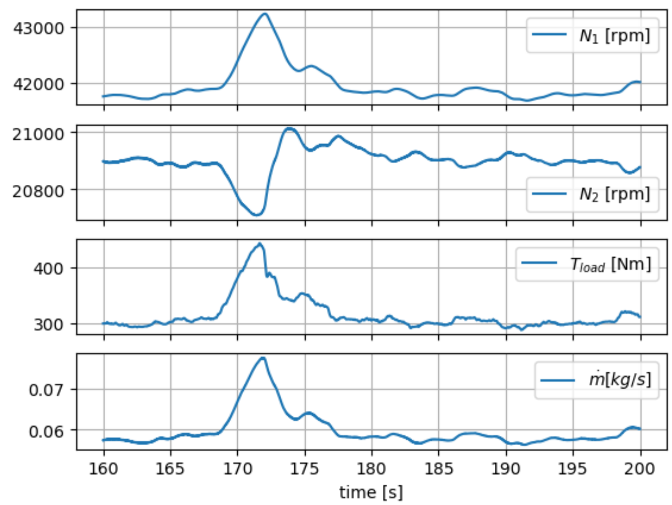
(a) Primary control inputs



(b) Altitude, vertical speed, and airspeed



(c) Main rotor speed, thrust, and shaft torque



(d) Turbine parameters

Figure 9: Flight log TID5 - Rotor speed increase during level flight at $\mu = 0.2$ and $h = 2000\,\text{ft}$

quiring increased collective pitch. However, the low blade loading ensures that there is sufficient control reserve up to the upper limit.

In addition to objective flight data analysis, the pilot's subjective evaluation of the VARISPEED system was conducted using the BWR and CHR scales. After the initial familiarization flight at reference rotor speed, the flight model was rated at BWR level ④ and CHR level ④, indicating acceptable but elevated workload. The subsequent test flights at modified rotor speed levels were rated at BWR level ④ and CHR level ③, regardless of payload. During rotor speed transitions without active control assistance, handling qualities were rated at CHR level ⑥ due to the manual compensation required. However, the pilot noted that the workload remained manageable, largely due to the awareness provided by explicit callouts prior to rotor speed changes.

By the end of the first part of the study, after eight flights, pilot ratings improved likely due to a habituation effect, with BWR ratings improving to level ③ and CHR ratings to level ② in steady conditions, and CHR ratings during rotor speed transitions improving to level ⑤.

In the second part of the study, the collective pitch open-loop controller to compensate thrust variations caused by rotor speed changes was evaluated based on subjective CHR and BWR ratings (MOA 3.1) and flight log data (MOA 3.2). Four test flights were conducted, two with rotor speed reduction similar to TID1 and two with rotor speed increase similar to TID5, each pair performed once without and once with the controller activated.

The flight log shows that without the controller, rotor speed transitions led to altitude deviations of about $\Delta h = 40\,\text{ft}$ in both rotor speed increase and decrease cases, with delayed manual compensation by the pilot of $\Delta\theta_0 = 2.5°$ and $\Delta\theta_0 = 1.2°$ collective input respectively. With the controller active, the altitude deviation was significantly reduced. During rotor speed reduction, the sink was limited to only $\Delta h = 4\,\text{ft}$, compensated automatically by a $\Delta\theta_0 = 2.5°$ collective increase by the controller, while during rotor speed increase the helicopter gained about $\Delta h = 15\,\text{ft}$, driven by a $\Delta\theta_0 = 1.5°$ collective increase commanded by the controller.

These results indicate that the controller improves the delayed manual pilot collective compensation and effectively suppresses large altitude deviations due to rotor speed changes.

To address MOA 3.1, the CHR and BWR ratings from the two flights without the controller are compared to those from the two flights with the controller activated. For rotor speed decrease, activating the collective pitch controller consistently improved CHR ratings by approximately one level and also improved BWR ratings for some MTEs, indicating improved handling qualities and reduced pilot workload compared to flights without the controller. For rotor speed increase, CHR ratings remained largely unchanged, while BWR ratings showed notable improvements for some MTEs, demonstrating that the controller is capable of reducing pilot workload during transition to increased rotor speed levels. Overall, the controller effectively mitigates the effects of rotor speed variations, enhancing handling qualities and reducing pilot workload.

It should be noted that the CHR and BWR ratings in the second part of the study are generally higher, indicating a substantial pilot workload. This is primarily due to limitations in the UH-60 ARCS flight model, which is currently being improved. Nevertheless, relative comparisons between flights without and with the controller remain valid.

CONCLUSIONS AND FUTURE WORK

1. The integration of a continuously variable rotor speed drivetrain into the piloted simulation environment while maintaining real-time capability was successfully demonstrated. The system achieved dynamic rotor speed adjustments while maintaining flight stability and control authority.

2. Objective measurements confirmed power savings of up to 5.4% and fuel flow reductions of up to 4.8% during rotor speed reduction at low blade loading in cruise flight condition.

3. The drivetrain's transient behavior during rotor speed transitions exhibited no adverse effects on flight dynamics. The electric variator control ensured smooth torque distribution, with no significant oscillations or resonance excitations observed.

4. The rotor speed variation had no significant impact on maneuver execution, including standard rate turns and vertical climb/descent maneuvers, confirming the controllability of the helicopter under varying rotor speed conditions.

5. The pilot rated handling qualities at steady reduced rotor speeds as CHR level ③, indicating minor deficiencies requiring small compensations. During rotor speed transitions, handling qualities were rated three levels worse in the absence of an automated pitch compensation controller.

6. The Bedford Workload Ratings remained at acceptable levels throughout the test campaign. A habituation effect was observed, leading to improved ratings in later test flights as the pilot adapted to the system.

7. The implemented automatic open-loop controller for collective compensation increases handling qualities during transient rotor speed variation and improves flight path adherence, particularly altitude retention in cruise flight.

8. Integrating a Control Loading System (CLS) into the simulator could enhance pilot feedback from the collective compensation controller by automatically adjusting the collective lever.

9. An additional controller for the tail rotor pitch could be implemented to compensate for imbalances in the antitorque effect caused by changes in main rotor speed.

10. Identified flight model deficiencies, such as pitch axis oscillations at higher airspeeds, require further refinement of the baseline UH-60 flight model in ARCS to expand the validated operational envelope of the simulation environment.

Author contact: Jonas Koch j.koch@tum.de

ACKNOWLEDGMENT

This work is supported by the German Federal Ministry for Economic Affairs and Climate Action through the German Aviation Research Program LuFo VI-1 and the Austrian Research Promotion Agency through the Austrian Research Program TAKE OFF. The paper is a result of the transnational project ”Varispeed II”.

Gefördert durch:

Bundesministerium für Wirtschaft und Klimaschutz

aufgrund eines Beschlusses des Deutschen Bundestages

FFG Österreichische Forschungsförderungsgesellschaft

The authors would like to thank the pilot for participating pro bono in the simulator flight test campaign and providing valuable feedback.

REFERENCES

1. W. Garre, T. Pflumm, and M. Hajek. Enhanced Efficiency and Flight Envelope by Variable Main Rotor Speed for Different Helicopter Configurations. *European Rotorcraft Forum*, 2016.

2. W. Garre, H. Amri, T. Pflumm, P. Paschinger, M. Mileti, M. Hajek, and M. Weigand. Helicopter Configurations and Drive Train Concepts for Optimal Variable Rotor-Speed Utilization. *Deutscher Luft- und Raumfahrtkongress*, 2016.

3. J. Koch, A. Poks, and I. Yavrucuk. Active Control of a Variable Speed Rotor Drivetrain System using Electric Variators. *Deutscher Luft- und Raumfahrtkongress*, 2023.

4. T. Scheu, A. Poks, F. Donner, and M. Weigand. Dynamic Simulation of a Rotorcraft Main Transmission with Continuous Variable Ratio. *Vertical Flight Society 79th Annual Forum*, 2023.

5. M. Bischläger, C. Gross, J. Koch, A. Poks, and M. Weigand. Dynamic Simulation of a Rotor System with Variable Speed. *Vertical Flight Society 78th Annual Forum*, 2022.

6. MathWorks. MATLAB & Simulink. Software, Version R2024b, 2024. `https://www.mathworks.com`.

7. J. Schmidt, S. Delp, M. Sherman, C. Taylor, V. Pande, and R. Altman. The Simbios National Center: Systems Biology in Motion. *Proceedings of the IEEE*, 96(8), 2008.

8. W. Rex, T. Pflumm, and M. Hajek. UH-60A Rotor and Coupled Rotor-Fuselage Simulation Framework Validation and Analysis. *European Rotorcraft Forum*, 2019.

9. J. Howlett. UH-60A Black Hawk Engineering Simulation Program. Volume 1: Mathematical Model. *NASA: Contractor Report*, 1981.

10. T. Scheu, C. Gross, A. Poks, R. Willinger, and M. Weigand. Adaptive Speed Gearbox Design for the UH-60AHelicopter with Integrated Electric Variator and Frequency Investigation. *Vertical Flight Society 81th Annual Forum*, May 2025.

11. B. Bauer. Redesign and Modularization of the Hard- and Software Environment of a Helicopter Research Simulator. Master's thesis, Technical University of Munich, 2023.

12. Ace Deck VL-60. `https://aceaero.com/de/ace-deck-vl-60/`. Accessed: 2025-07-18.

13. L. Knoeppel. Development of a UH60 Avionic System for Variable Speed Rotor Operation. *Technical University of Munich*, 2024.

14. C. Blanken and E. Tobias. Evaluation of Aeronautical Design Standard-33 using a UH-60A Black Hawk. *U.S. Army Research, Development, and Engineering Command*, 2018.

15. G. Cooper and R. Harper. The Use of Pilot Ratings in Evaluation of Aircraft Handling Qualities. *NASA Ames Research Center*, 1969.

16. A. Roscoe. Assessing Pilot Workload in Flight. *Royal Aircraft Establishment Bedford*, 1984.

17. R. Kennedy, N. Lane, K. Berbaum, and M. Lilienthal. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology*, 3(3):203–220, 1993.