EFFECTS ON HELICOPTER DYNAMICS IN CASE OF ENGINE FAILURE DURING INTENDED SINGLE ENGINE OPERATION

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Abstract

Helicopters that are equipped with two or more turboshaft engines for safety reasons, mostly operate in part load conditions. As the specific fuel consumption is reduced with increasing engine load, shutting down one engine in suitable flight envelope areas would cut down fuel consumption significantly and reduce engine operating hours. To account for safety in case of failure of the active engine, the inactive engine is required to restart fast enough to minimize the altitude lost until a stationary flight condition is recovered. Thus a quick start system concept for turboshaft engines has been developed and tested on a test bed in preceding studies. In order to evaluate intended single engine operation during mission flight an Allison 250-C20B engine equipped with a quick start system has been coupled to a helicopter flight simulator. The research simulator replicates BO 105 flight physics, which are validated against flight test data. Pilot-in-the-loop tests were performed to evaluate the effects on the helicopter dynamics during engine failure until the inactive engine is quick-started. It was shown that a quick start enabled altitude hold flight controller can greatly reduce pilot workload and optimize the height loss while maintaining sufficient rotor speed compared to the manually piloted engine failure.

NOTATION

EOC	Engine Operation Controller
FADEC	Full Authority Digital Engine Control
ISEO	Intended Single Engine Operation
KIAS	Knots Indicated Airspeed
MSL	Mean Sea Level
N1	Engine Gas Generator Speed
OEI	One Engine Inoperative
ROSIE	Rotorcraft Simulation Environment
SAS	Stability Augmentation System
TOT	Turbine Outlet Temperature

1 INTRODUCTION

According to the certification specifications a category A class helicopter is required to fly with a minimum of two engines. In case of an engine failure the remaining engine is required to have a sufficient power margin to continue flight with one engine inoperative (OEI) [1]. Thus, modern medium sized helicopters are usually equipped with two engines which operate at equal partial load in a large range of the flight envelope. However, the specific fuel consumption of an engine is rising with lower load.

One approach to reduce fuel consumption is to shut down one engine while the remaining one is operating in a more efficient range. Nevertheless in case of failure of that engine the inactive engine is required to start fast enough to minimize the altitude loss to an acceptable level until power is regained. The start up time to ground idle of common turboshaft engines, such as the Allison 250-C20B used in this study is about 28 s. The altitude lost in an autorotation maneuver of this time span prohibits the use of regular engines from an intended single engine operation (ISEO). Recent modifications to an Allison 250-C20B engine [3] have shown, that the time to ground idle can be reduced to less than 2.4 s and sufficient power of 60 kW can be provided less than 9 seconds after the engine quick start.

In this paper, pilot operated engine-in-the-loop tests are examined. In order to investigate the application of the ISEO system during mission flight the test bed of the quick start engine has been integrated into a helicopter flight simulator. Manual as well as controller assisted recovery from failure of the active engine was analyzed. Simulated engine performance was com-

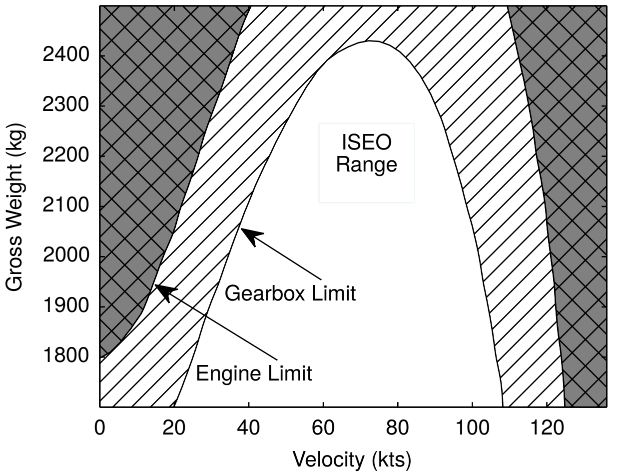

Figure 1: ISEO boundaries for BO 105 including 10 % maneuver reserve (at sea level, ISA standard atmosphere)

pared with measurement data to further improve the simulation models.

Single engine operation limits

Single engine operation is primarily restricted by two constraints: The maximum gearbox torque limit and the power available from the engine. The power required for helicopter flight is in turn mainly dependent on the flight state, the take-off weight, and environmental conditions. In order to evaluate the boundaries where single engine operation is feasible, parameter studies have been conducted. The maximum continuous power for the Allison 250-C20B at standard atmosphere and sea level is 313 kW, a shaft torque of 521 N m is provided at its reference speed of 6016 rpm. However, for the BO 105 helicopter the main gearbox limits the transmissible torque to 407 N m.
For practical application of ISEO the main gearbox would most likely need redesign. Besides an increased torque limit, it is necessary to adapt the design to its asymmetric load conditions. Thus the engine can be considered as the limiting factor. If a torque margin of 10 % is regarded as maneuver reserve, single engine operation is thus possible up to a maximum torque requirement of 469 N m (366 N m at the main gearbox). The research simulators flight physics model was used to calculate single engine operation limits for the BO 105 helicopter, which is typically equipped with two Allison 250-C20B engines. Figure 1 depicts these limits based on the power required at standard atmosphere and sea level plotted against take-off weight and forward speed.

2 TEST SETUP

The test environment consists of a helicopter flight simulator (the rotorcraft simulation environment, ROSIE, developed at TU München) coupled with an engine-in-the-loop test bed. Both were connected bidirectionally via local area network as shown in Figure 2. This allows to fly a piloted mission in the simulator while the real engine is running at the test bed. Due to these fast and low cost tests, with a minimum of safety requirements compared to regular flight tests, it is possible to instantly characterize the influence of system changes on performance, fuel consumption and system dynamics. The design of subsystem parts of the helicopter as well as the engine can easily be changed and tested further.

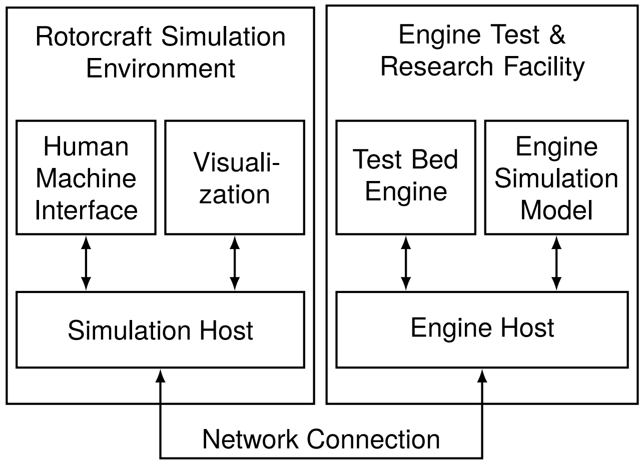

Figure 2: Scheme of simulator / test bed coupling

2.1 Rotorcraft simulation environment

The ROSIE flight simulator was developed as a multipurpose research simulator. Besides engine coupling tests, current applications are handling quality assessments for flight control system development, evaluations of pilot assistance systems such as helmet mounted displays as well as the improvement of simulation fidelity especially considering real time brown out simulation.

2.1.1 ROSIE hardware architecture

The simulator is controlled by a simulation host computer which links the cockpit input and output signals as well as the visual display system with the flight physics model. In combination with the engine test bed it also handles network traffic to the test facility. The output of the flight physics model is broadcasted to six image generator computers that render the data displayed on a six channel projection system. The image is projected to a spherical screen which has a field of view of 190° horizontal and +30°/−50° vertical on a diameter of 5 m (Figure 3). The projected image is generated employing a terrain and navigation database with a digital elevation model overlaid by high resolution aerial images. The pilot sits in a former BO 105

Figure 3: Helicopter cell and visual display system

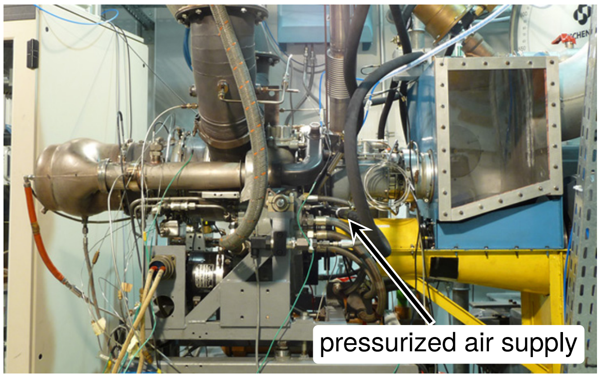

Figure 4: Allison 250-C20B at the engine test bed

helicopter cockpit with its original controls and seats. The BO 105 instrument panel has been replaced by four touch panels to emulate different cockpit designs and evaluate visual cue systems. Two human machine interface computers are used to handle the control input signals and to drive the cockpits instrument panels.

2.1.2 Software architecture

All input and output signals of the flight loop are processed by a Simulink model on the simulation host which acts as a wrapper for the flight physics model and coordinates data management as well as time scheduling of the simulation. Different environmental conditions such as clouds, fog, wind, gusts, and temperature can also be controlled from the simulation host. The proprietary flight physics model written in FORTRAN is integrated into the Simulink model as external S-Function block. It simulates a helicopter in conventional main and tail rotor configuration fitted and validated with flight test data of the BO 105 helicopter. The rotor model calculates the flap, lag and pitch motion of the blades with piecewise uniform inflow. The helicopter motion results from force and momentum balance of the rotor, fuselage, tail plane, fin, and landing gear etc.

2.2 Engine test bed

The engine test bed comprises an Allison 250-C20B turboshaft engine which was formerly installed in a BO 105 helicopter of the German armed forces. The engine delivers 313 kW maximum continuous power that is dissipated by an electrical dynamometer. The breaking torque of the dynamometer can dynamically be adjusted to emulate the helicopter rotor loads. As the engine is object to several research activities it is equipped with various additional sensors. All measured values are recorded with a continuous data acquisition system by a sampling rate of 2 Hz [4] and if greater resolutions are required with a dynamic data acquisition system with a sampling rate of 1 kHz. In order to influence the engine operating behavior a new fuel flow controller was developed replacing the original hydro-mechanical fuel flow governor. This controller, based on the principles of a Full Authority Digital Engine Control (FADEC), is implemented in Simulink and runs on a real-time system. The FADEC controls an electro-mechanical valve control unit which meters the fuel flow according to the controller. Therewith, manipulation of the fuel flow as required is possible. The original bleed valve was additionally replaced with an independently controllable bleed valve. This allows additional control of the engine behavior, especially at idle and low gas generator speeds. In 2011 a quick start system was implemented for the Allison engine. The quick start system utilizes about 1.2 MPa compressed air to expand via five Laval nozzles and uses these gas impulses to drive the radial compressor of the Allison engine (Figure 4). Due to integration of the Laval nozzles into the radial compressor casing a new casing was designed to meet the requirements of nozzle integration. In addition, the FADEC was updated to meet the altered engine start-up requirements.

2.3 Coupling of the flight simulator with engine test bed

The flight simulators helicopter model is capable of using different engine models. It receives the engine torque and power turbine speeds (N2) from the test bed. The torque powers the main gearbox, the N2 turbine speeds are used for free wheel mode calculations in the flight physics model. For cockpit visualization purposes the test bed computer also transmits the gas generator speed (N1), fuel flow and turbine outlet temperature to the simulator. The backlink from the ROSIE simulator sends the breaking torque, the main rotor speed, the collective input as well as some environmental data to the engine. Furthermore engine operating mode signals are send, including Off/Idle/Flight, quick start switches and a signal to start ISEO mode for a selected engine. Additionally the test facility receives motion data of the simulated helicopter for remote visualization.

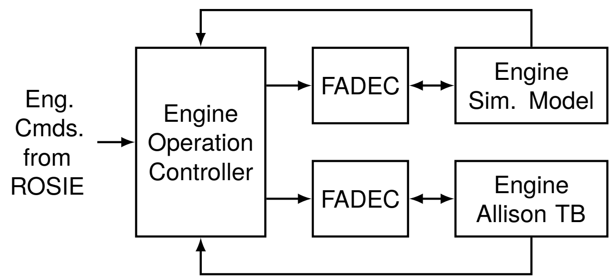

Figure 5: Integration of the EOC in the engine host

The engine test bed is coupled with the simulator via UDP network connection. Switches in the overhead panel of the flight simulator activate the link between the simulation models and determine the engine operating modes. Thus the pilot has full control of the engine while running the simulation. However, backup switches in the simulator and at the test bed can disengage the link between both sides in case of unexpected events.
At the engine test facility a Simulink model running on the engine host computer processes all incoming and outgoing network data. This can either be the output of the engine simulation model or the measured data of the engine in the loop test bed. In the regular setup one engine of the helicopter is simulated, while the second one is the engine-in-the-loop coupled Allison 250-C20B which runs in parallel. The Simulink model of the engine host computer contains an Engine Operation Controller (EOC) to reduce the workload of the helicopter pilot during any ISEO state (Figure 5). The EOC receives all the pilot commands related to the engine and transmits the appropriate signals to the FADECs. If an engine failure is detected by the EOC during ISEO it consequently quick-starts the inactive engine without any pilot interaction. Therewith, valuable response time can be saved and the engine management optimized.

3 HARDWARE-IN-THE-LOOP TESTS

The purpose of the hardware tests conducted was to determine the simulation fidelity of the engine integration into the flight physics model. In addition to that the accuracy of the engine model itself was tested at different flight states. Furthermore, the effect of engine failure on helicopter dynamics during ISEO was investigated.

3.1 The reference mission

In order to validate the behavior of the simulated engine model in flight against the test bed engine a reference mission was flown. It was set up to contain common flight stages from which other helicopter missions can be assembled. Another scope of the mission was to fly through a wide range of required power levels to analyze the engine behavior at different loads. The mission consists of hover, climb, horizontal flight, and coordinated turns. It is divided in the following phases:

1. CAT-A takeoff: Hover IGE, then rearward climb at ~300 ft/min to 120 ft AGL (ground at 2400 ft MSL)
2. Climb with ~1000 ft/min at 50 KIAS to 4500 ft
3. Climb with ~500 ft/min at 0 KIAS to 5000 ft
4. Hover at 5000 ft
5. Straight and level low speed flight at 25 KIAS
6. Level moderate speed flight at 80 KIAS including standard turns at 3 °/s
7. Level higher speed flight at 110 KIAS including standard turns at 3 °/s
8. Descent with ~1000 ft/min at 50 KIAS to 200 ft/min AGL
9. Landing at 2400 ft/min MSL

As described above the reference mission was flown with one simulated engine and the engine-in-the-loop running in parallel. It is thus possible to evaluate if the simulation model outputs correlate with the measurement data in the different flight stages. Figure 6 compares the gas generator speed, the engine torque and the turbine outlet temperature. The section of the mission depicted in the figure shows a representative progression of the curves in transition from flight phase 1 to flight phase 2. It illustrates dynamic behavior of the engine during an acceleration of the gas generator due to increasing torque demand. For nearly steady-state conditions good correlation between the values of the simulated and the real engine was found. In transient operating ranges small deviations of the curves are observed. The mean relative error is 0.9 % for N1, 6.4 % for the torque provided by the engine, and 1.2 % for TOT respectively. The error mainly originates in a time delay between the values calculated by the simulation model and the engine measurements. The combination of the Simulink engine model and the real Allison engine at the test bed was found to be feasible for further investigations, particularly simulated mission flights.

3.2 Engine fail during single engine operation

If the pilot flies within the previously stated single engine operation limits he may shut down one engine in order to save fuel and to reduce the operating hours of that engine. Therefore the ISEO command for a selected engine is send to the EOC which handles the shut down procedure. In a future development

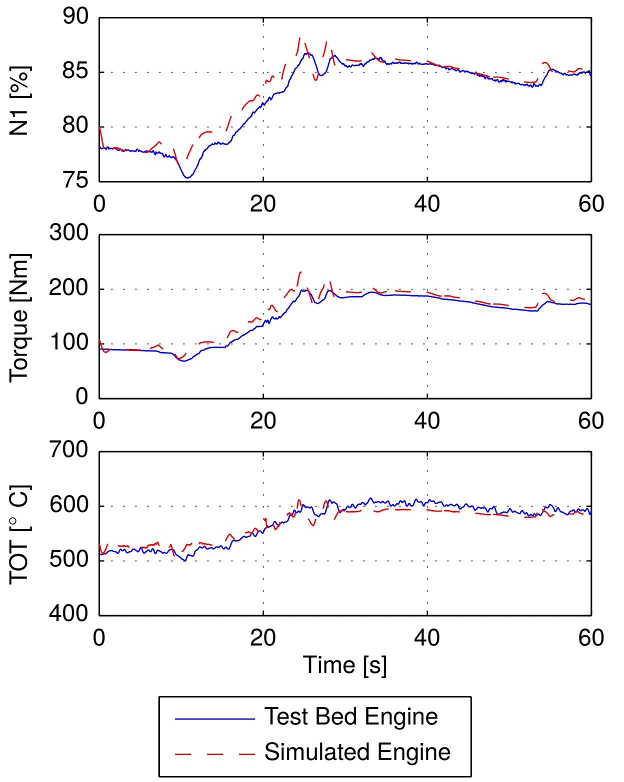

Figure 6: Comparison of engine measurements and simulation output in transient flight stages

stage the EOC may decide which engine shuts down depending on engine hours and cycles to ensure balanced engine usage. The engine selected by the pilot changes its state from flight mode to idle mode by slowly fading down fuel supply and thus its delivered power. Meanwhile the second engine receives the information to change into continuous OEI mode to deliver more power than in AEO MCP mode (all engines operative, maximum continuous power). Though AEO MCP mode is sufficient for ISEO flight, it was decided to switch the active engine to OEI mode in order to account for unexpected peak loads. After a certain time the first idling engine is shut down completely and the power required is entirely provided by the second engine.

In the unlikely event that the active engine fails during single engine operation, the inactive engine needs to recover as fast as possible immediately upon detection of the failure, in order to minimize altitude loss of the helicopter. Hence the engine that was previously shut down will instantly be started to flight mode to deliver torque. Within 2.4 s the engine is capable of reaching ground idle from “Off”; 9 s after “Off” state sufficient power is provided.

In case of total loss of power with conventional engines the rotor speed decreases rapidly. However, aerodynamic and structural limitations result in constraints on the rotor speed, typically between 85 % to 100 % of the reference speed during autorotation. To keep the main rotor within its operating range the pilot needs to lower the collective and hence the angle of attack of the rotor blades. Thereby the profile drag is reduced and sufficient rotor speed can be maintained. However reducing the angle of attack reduces the rotor thrust and thus results in loss of altitude. The helicopter will descent with a glide path depending on its velocity and rotor speed.

In contrast to fixed wing aircraft the helicopter has—besides the kinetic and potential energy of the cell—an additional source of energy in the rotor. If the active engine fails in intended single engine operation the rotational energy of the rotor can be utilized to reduce the loss of altitude while no power available by the engines. Accepting a decrease of rotor speed the collective pitch can be lowered less and consequently the altitude loss is reduced. When the inactive engine is quick-started and delivers power, the collective can be lifted according to the power available and the initial altitude as well as rotor speed can be regained. Since the resulting helicopter dynamics are strongly coupled to the power required in a particular flight state, the loss of height and rotor speed mainly depends on the takeoff weight, flight speed and air density. Consistently those losses are also reduced by fast engine recovery and—in manually operated flights—by fast pilot reaction.

In initial tests of engine failure during ISEO in simulated mission flight, the quick starting engine failed to deliver the torque required. It was found that the Allison 250-C20B successfully starts to ground idle. Though, shortly afterwards it stops operating due to deep surge and reaches its TOT limit as the gas generator tries to accelerate for further power generation. Former tests of the quick start system proved safe engine quick starts with a brake torque of 100 N m applied [3]. However, the flight tests conducted showed that a step input of 300 N m can not be handled properly by the engine after a quick start is performed. Preliminary analysis revealed a shift of the operating line as well as the surge line due the modifications off the compressor case, which might cause the unexpected engine behavior. In an experimental study it was found that the maximum rate of change in torque was reduced from 150 N m/s to 75 N m/s. Thus a torque rate limiter was implemented into the EOC and the engine simulation model. For safety reasons the limit was set to a conservative value of 65 N m/s in further tests.

3.3 Pilot-in-the-loop tests in single engine operation

Different pilot-in-the-loop tests have been conducted with simulated failure of the active engine during ISEO. The purpose was to find the best operating strategy until the remaining engine is restarted. The recorded flight data was used to estimate the average loss of height and rotor speed in manually operated missions. In Figure 7 a selected flight test is depicted which represents the recovery from ISEO engine failure with typical height loss. The simulated helicopter BO 105 in this evaluation has a takeoff weight of 1700 kg and advances at 70 KIAS during the recorded maneuver.

It was found that special procedures are required to recover the helicopter. As described before the collective input needs to be adjusted in accordance to the downwards velocity, the rotor speed and the power available. This leads to an increased workload for the pilot and might result in non-optimal control inputs. To facilitate this maneuver and to further minimize the loss of altitude a flight controller has been developed.

3.4 Quick-start enabled altitude hold controller

To enhance the handling qualities of the simulated helicopter a full authority controller has been developed. The altitude hold mode of this controller has been extended to support power loss in ISEO. In case of failure of the active engine the controller can thus autonomously minimize the loss of altitude of the helicopter while limiting the decrease of rotor speed accordingly. Furthermore the controller eliminates the pilot reaction time.

3.4.1 Baseline full authority controller

As shown in Figure 8 the control law is based on a model following approach. The SAS in the inner loop stabilizes the helicopter through angular rate and vertical velocity feedback. The feedback controller in the outer loop provides different control modes depending on the forward velocity of the helicopter. At low speed and hover translational rate command (TRC) and position hold (PH) are selected respectively. In high speed flight the controller provides rate command rate hold (RCRH) mode. The model following approach provides the ability to change the aircraft response to fit a desired model, which is implemented in the command model. The inverse plant ideally cancels the aircraft dynamics such that the response on control input follows the command model [2]. The signal is fed through axis decoupling to cancel interdependencies between the control inputs. Response feedback is used to account for model inaccuracies and disturbances.

With the controller enabled the pilot controls the vertical velocity with the collective input. Disturbances in other axis which occur from changing the collective input of the uncontrolled helicopter are automatically compensated by the controller. In altitude hold mode the vertical velocity input signal is switched from pilots input to a simple PID controller loop where the altitude and its time derivatives are fed back to hold the desired

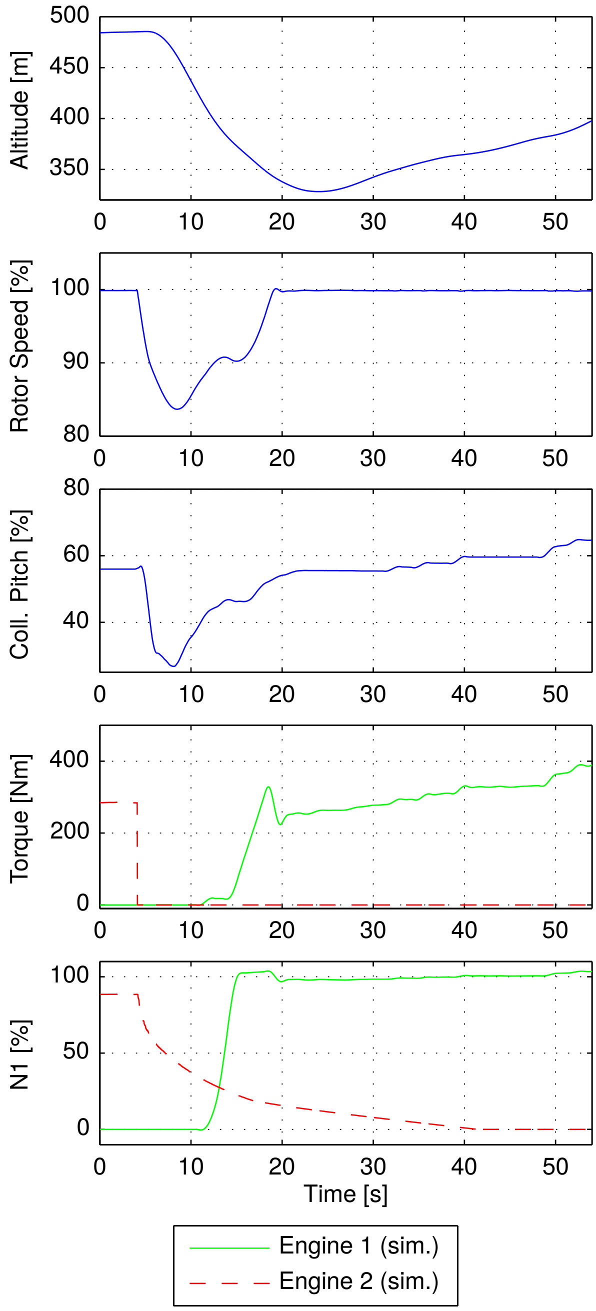

Figure 7: Simulated engine fail during manually piloted single engine operation

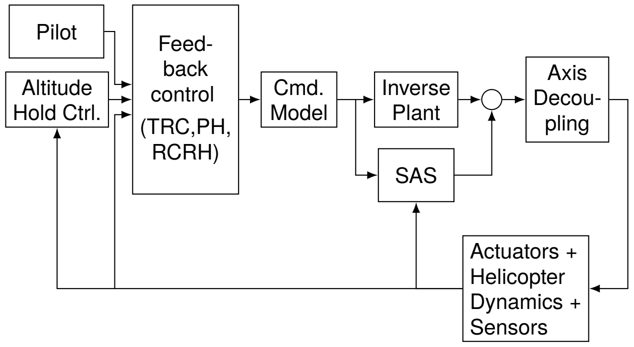

Figure 8: Model following structure of the baseline full authority controller

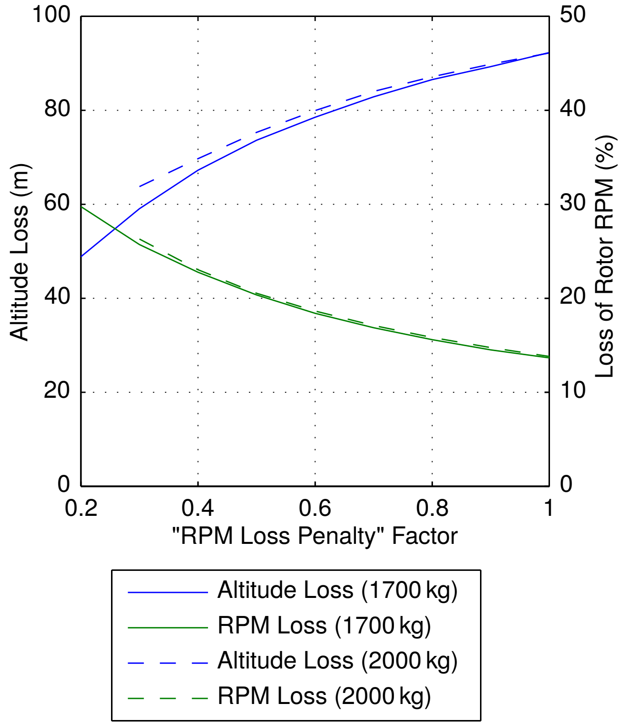

Figure 9: Loss of rotor speed and altitude

altitude.

3.4.2 Controller extension for ISEO engine failure

The altitude hold control law has been extended by the feedback of the rotor speed. If the rotor speed drops, a vertical downward acceleration will be commanded to the controller model. This control input mainly results in a collective command plus its compensations in other axis. The vertical acceleration command $\ddot{h}_{cmd}$ is described by

$$\ddot{h}_{cmd} = k_{\Omega}\Delta\Omega + k_h\Delta h + k_{\dot{h}}\dot{h} + k_{\ddot{h}}\ddot{h}$$

where $\Delta\Omega$ is the deviation of rotor speed from the reference speed in percent and Δh the deviation from the selected altitude, $(\dot{\ })$ denote the time derivatives and $k_{()}$ the controller gain respectively. By using a gain factor k_{Ω} on the rotor speed feedback the loss of rotor speed may be penalized. Different penalty factors have been tested in order to find the best compromise between loss of rotor speed and altitude. Figure 9 depicts this relation at 70 KIAS with different take-off masses. It can be seen, that a minimal altitude loss of ~48 m can be reached with 1700 kg take-off mass, if the altitude hold controller tries to hold the altitude, considering the rotor speed with a gain factor of $k_{\Omega} = 0.2$. However the rotor speed drops down to 70 %, which is out of the rotor limitations.

It was found that a gain factor of $k_{\Omega} = 0.8$ leads to good results throughout the flight envelope of single engine operation at different take-off weights. In Figure 10 the recorded data of a single engine operation with engine loss is shown. The simulated BO 105 has a take-off mass of 1700 kg and advances at 70 KIAS, the quick-start enabled altitude hold controller is enabled. The rpm loss penalty factor was set to $k_{\Omega} = 0.8$. As described before the test was conducted with the modified Allison 250-C20B engine-in-the loop running in parallel with a simulation model as second engine. The Allison 250-C20B engine (green line) is shut down to fly in ISEO and the simulated engine (red, dashed line) delivers the power required. At time $t = 4$ s the active engine fails which results in an instant drop of rotor speed. Thus the controller lowers the collective to decrease the loss of rotor speed. The lower collective input and the loss of thrust at lower rotor speed result in downwards velocity. As soon as the Allison 250-C20B is started and sufficient power is regained the rotor speed rises back towards 100 % and the controller raises the collective input accordingly. This power loss results in a height loss of ~90 m and a rotor speed loss of ~14 %. After 65 s the initial altitude is regained. As a comparison the altitude, rotor speed and collective input of the manually piloted mission engine fail (see section 3.3) is shown (orange, dashed). The graph indicates, that the controller saves valuable altitude if a comparable amount of rotor speed is lost. Tests showed, that the controller particularly outperforms the manual input even further as the time until power is regained is reduced.

It is shown that the quick-start enabled flight control system reduces the loss of altitude compared to human control inputs while keeping the rotor speed within the limits without pilot interaction. Since the rotor speed and engine torque is constantly measured the controller has merely no reaction time compared to a pilot after engine failure is detected.

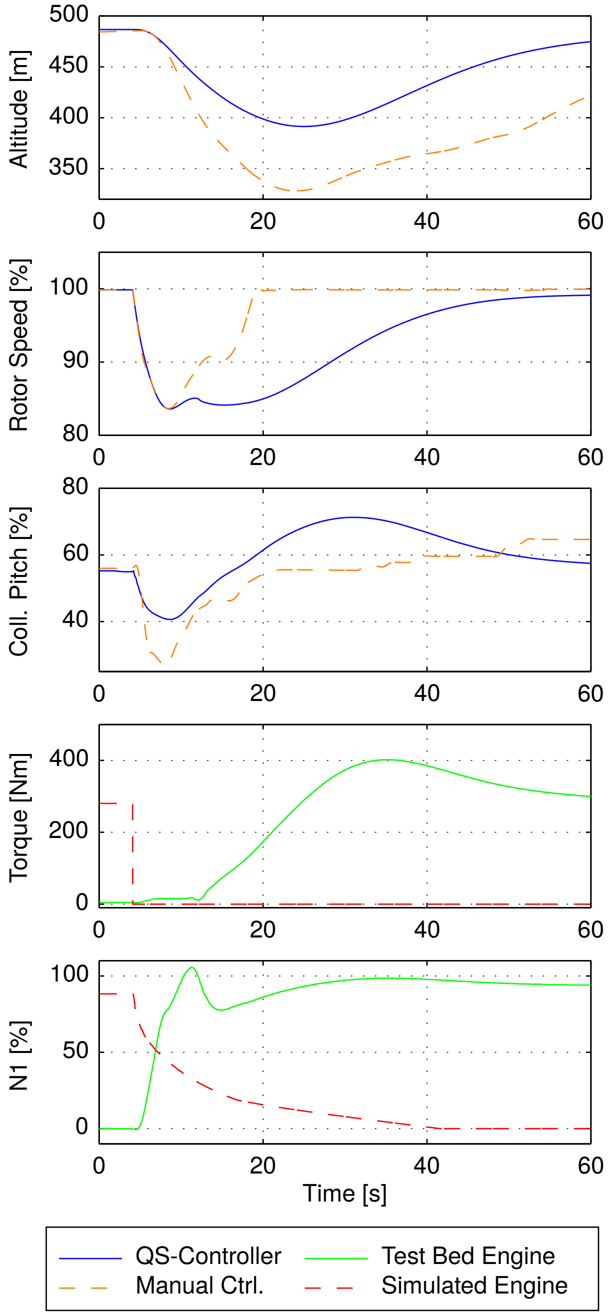

Figure 10: Engine-in-the-loop test: Power loss during ISEO with quick-start enabled flight control system and modified Allison 250-C20B

4 CONCLUSION AND OUTLOOK

The test bed of a quick-starting engine was coupled with a helicopter flight simulator. Different engine in the loop test missions were conducted to examine the accuracy of the simulation models throughout the flight envelope. The tests showed good correlation between measurements and simulation results. Pilot tests indicated the need for additional assistance during engine failure in intended single engine operation. Thus a quick-start enabled altitude hold controller has been developed which stabilizes the helicopter until power is regained. It was shown that the controller helps to reduce the altitude loss while maintaining the rotor speed within the limitations. The altitude loss which mainly depends on the required power, the loss of rotor speed, the control inputs, and the time until the inactive engine starts was evaluated at different takeoff weights and speeds. This analysis in combination with an investigation on torque requirements and engine limits indicate suitable operation limits for ISEO flights. Simulated results were validated by engine-in-the-loop mission flights with a quick-start enabled Allison 250-C20B.
Currently, the required air to quick-start the engine is provided by the test facility. Thus further research will concentrate on a mobile high pressure air system. Also the cause of the observed engine surge at high torque demand rates will be addressed in supplemental studies. To further minimize the altitude loss more sophisticated control laws will be implemented considering the rotor speed as controller state. Furthermore the effects of continuous one engine operation on the main gearbox will need to be examined. The development of a visual cueing system, possibly including tactile feedback through active controls with artificial force feedback, will help the pilot to stay within the operational limits of ISEO. For commercial application further investigations on the costs and savings of the quick start system are required.

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6 COPYRIGHT STATEMENT