HARDWARE-IN-THE-LOOP EVALUATION OF A QUICK-START SYSTEM FOR HELICOPTER GAS TURBINE OEI OPERATIONS TESTED IN SIMULATED FLIGHTS

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Abstract

This paper first outlines a hardware-in-the-loop environment for helicopter flight simulations with a real turboshaft engine. The setup uses an Allison 250-C20B engine equipped with a pneumatic impingement system, named as Quick-Start System (QSS). The hardware-in-the-loop engine and the QSS are connected to the Rotorcraft Simulation Environment (ROSIE), a fixed-based pilot-in-the-loop rotorcraft simulator. In parallel, a visual and audio augmentation system based on a standard helicopter head-down instrumentation and a future-proof multimodal cueing concept is used for pilot workload and handling qualities investigations. Next, the paper covers the design and proceeding of a hardware-pilot-in-the-loop simulator flight test campaign along ADS-33 PRF flight test standards conducted together with five helicopter test and fleet pilots from German Armed Forces. Finally, the paper reports the results of piloted simulation tests of different mission task elements (MTE), embedded to a wide spectrum of helicopter Intended Single Engine Operation (ISEO) and One Engine Inoperative (OEI) operations, where different levels of the QSS and the augmentation concepts had been evaluated by the participating pilots. Results indicate a pilot workload level of Bedford rating level 1 and an enhanced situational awareness with the assistance of visual and audio augmentations. Moreover, the QSS enabled all pilots to recover the helicopter with acceptable loss of altitude at acceptable handling qualities and pilot workload.

NOMENCLATURE

AEO	All Engine Operative
AGL	Above Ground Level
ASL	Above Sea Level
ECB	Eddy Current Brake
ERA	Engine Recovery Assistance
FADEC	Full Authority Digital Engine Control
FLI	First Limit Indicator
HDD	Head-down Display
HIL	Hardware-in-the-loop
ISEO	Intended Single Engine Operation
KIAS	Knots Indicated Airspeed
MFD	Multifunctional Display
MTE	Mission Task Element
OEI	One Engine Inoperative
PFD	Primary Flight Display
PID	Pilot Identifier
N1	Engine Gas Generator Speed, [%]
N2	Engine Power Turbine Speed, [%]
NR	Main Rotor Speed, [%]
QSS	Quick-Start System
RER	Real Engine Recovery
ROSIE	Rotorcraft Simulation Environment
SA	Situational Awareness
SART	Situational Awareness Rating Techniques
SER	Simulated Engine Recovery
TOT	Turbine Outlet Temperature, [K]
TRQ	Torque, [Nm]
TUM	Technical University of Munich
UDP	User Datagram Protocol

1. INTRODUCTION

Helicopter intended single engine operations (ISEO) continue to pose operational challenges even for experienced pilots. Such alternative operating strategies for helicopter missions hold a major potential in fuel saving and thus in reduction of emissions and operating cost [11] [3]. Furthermore, the reduced fuel consumption can permit to enlarge the operational envelope of the rotorcraft.

The goal of the current research at the Technical University of Munich (TUM) is to investigate a novel air impingement system, which can reduce the startup time of the engine by about 60 % to 80 % for hardware-in-the-loop one engine inoperative (OEI) missions and which could be fitted to existing

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helicopters. The OEI operations affect as well pilot workload, the performance of the QSS, and the restart time of the gas turbine of the helicopter in flight.

Previous and current work provided the proof of functional operability of the QSS [7] [9]. However, the QSS has not yet been evaluated by professional pilots. In this paper, professional pilots operated the engine with the QSS to handle ISEO and OEI situations in a hardware-in-the-loop environment embedded to a fixed-based rotorcraft simulator. Moreover, a novel multimodal cueing concept, named as Engine Recovery Audio Assistance (ERA), had been integrated to the rotorcraft simulation environment ROSIE for aspects of distributed situational awareness (SA) [13] within pilot-in-the-loop investigations.

1.1. Prior Work

A hardware-pilot-in-the-loop environment based on the coupling of ROSIE and the Allison 250 engine had been introduced by Spieß et al [19]. The authors proposed an altitude hold controller which can limit the altitude loss after engine failure to around 90 m, which was about 50 m less than in manually controlled flight by a non-professional operator. The present work describes the connection, in-flight evaluations and results using the quick-start capabilities of the engine in the case of an engine failure in an OEI situation with the ERA system being activated on top. The QSS is supplied with pressurized shop air. So far, the gas turbine had used an ordinary shaft connection to the eddy current brake (ECB). Substantial changes had been made on the QSS and the configuration of the test bed compared to the equipment used by Spieß et al [19]. The updated hardware components enhance the capabilities of the test environment with a more accurate presentation of a helicopter powertrain, see section 5.

The performance of the QSS in combination with and without the engine had been investigated in previous studies, see [9] and [10]. The results had been used to design an updated version of the impingement system which has been tested for the first time with test and fleet pilots, as described within this paper.

1.2. Multimodal Cueing Aspects for OEI Operations

Different levels of visual and audio augmentation systems extend previous experimental work on multimodal cueing concepts [2] for helicopter operations [5] and adapt the head-down display (HDD) instrumentation with an assisting audio augmentation concepts for critical phases of flights, see [7] and [21]. The visual and audio augmentation system is composed as follows:

Helicopter glass cockpit: A standard state-of-the-art helicopter Head-down Display (HDD) approach was used during flights subdivided into a Primary Flight Display (PFD), and a digital moving map visualized on a separate Multifunctional Display (MFD) below the PFD. While the PFD visualized BO-105 PFD information, the digital moving map showed helicopters position on a typical aeronautical map (Scale 1:100.000), see Figure 1.

Figure 1 Configuration of the cockpit displays during experiments

In order to provide a realistic cockpit environment, main rotor and engine sounds, that are modulated based on the respective rotational speed, are played from speakers in the cockpit. A low-RPM acoustic warning is not included but for our study the Engine Recovery Audio Assistance (ERA) was introduced: A basic “Beep” sound represents the OEI case in flight. The sound indicates that the engine restart process is initialized. The following “Beep Beep” audio signal gives the pilot in command the information, which the engine is fully operational again, meaning the engine’s gas generator has reached a shaft speed of 73 %.

2. HARDWARE-IN-THE-LOOP SETUP

The investigations of piloted flight simulations with five helicopter pilots from German Armed Forces were conducted at the TUM Rotorcraft Simulation Environment (ROSIE). The simulation environment therefor takes three main elements into account: ROSIE, the hardware-in-the-loop turbine with full authority digital engine control (FADEC), and the QSS.

ROSIE is a pilot-in-the-loop fixed base rotorcraft simulator with a realistic cockpit and a high-fidelity visual system, see Figure 1 and [1]. The environment consists of a BO-105 cockpit and a wide field of view visual cueing system, see [20] and [21], as shown in Figure 2. Helicopter dynamics of the BO-105 and the EC135 models can be simulated using the software package GenSim [6] hosted in a Matlab/Simulink framework. GenSim simulates aerodynamic effects of the main rotor, tail rotor, fuselage, vertical fin, and horizontal stabilizer. It uses a rigid blade assumption and simple analytical downwash models to simulate rotor dynamics up to the first harmonics of the flap, lead-lag, and torsion modes [19].

Figure 2 TUM Rotorcraft Simulation Environment

The engine test facility consists of three main subsystems which can be identified in Figure 3: The Allison 250-C20B engine (left), which is controlled by a FADEC developed at TUM, the pneumatic QSS (bottom), which allows to accelerate the engine's gas generator to idle speed in about 3 s, and the eddy current brake system (ECB, right), that is used to set the load on the engine. The air for the QSS is stored in a 300 bar air reservoir and fed the three supply tubes through a pressure regulator and the main valve. The air is then expanded in three supersonic nozzles and impinges on the outer section of the engine compressor impeller. The impingement provides torque to accelerate the gas generator up to idle speed but also supplies the combustor with an airflow to start the combustion process.

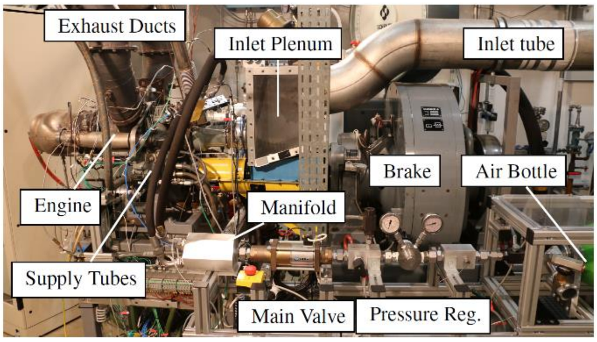

Figure 3 TUM Engine Test Facility with pneumatic QSS

In contrast to common turboshaft test facilities, the TUM test engine facility includes features which enable a realistic representation of the helicopter powertrain as depicted in Figure 4: The engine's (ENG) output shaft, which is run by the power turbine (PT) via the internal gearbox (GB), is coupled to the ECB via a freewheel (F1) which allows the ECB to overrun the engine's output shaft. Furthermore, the ECB can be run by an electric motor (M) that also features a freewheel (F2) between the motor shaft and the belt drive (BD). Figure 3 only shows the upper part of the schematic representation in Figure 4. With this setup an OEI situation, where the HIL engine represents the inoperative engine, can be simulated in a realistic scenario, since the ECB is run by the electric motor synchronously to the helicopter main rotor when the inactive engine begins the startup procedure.

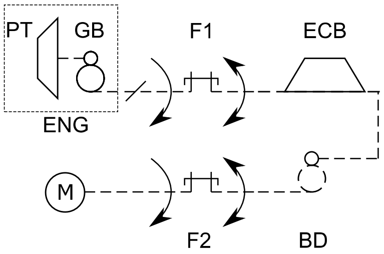

Figure 4 Scheme of TUM Engine Test Facility

The rotorcraft simulator and the engine test facility communicate via a network connection using the User Datagram protocol (UDP), as first presented in Ref. [19]. The engines' torque and power turbine speeds are sent to GenSim for the power generation calculation. In return, ROSIE communicates the required power, the main rotor speed and the atmospheric conditions in order to set the load of the engines including the correction of the different ambient conditions of the helicopter and the test facility. In the cockpit, the pilot can control the operation mode (Off, Idle and Flight) of each engine and whether an engine is set to ISEO mode. Furthermore, he can switch the starting mode between normal and quick-start. These commands are also transferred to the engine test facility. There, a real-time model implemented in the MATLAB® Simulink framework manages the communication, provides the engine FADECs and the engine state-space models. Engine 2 is always simulated by the software whereas the representation of engine 1 can be chosen between the model and the HIL engine. Although, the pilot is responsible for the operation mode of the engine, the ISEO mode features an automated sequence to decide whether the shutdown of an engine in AEO is allowed and to safely stop the engine. The restart of an engine in ISEO mode will occur automatically and immediately in case of an engine failure or can be commanded by the pilot in regular ISEO flight.

More details about the fixed-base simulator, the FAEDC engine, and the QSS can be found in [2], [7], [9], [12] and [19].

3. SIMULATOR FLIGHT TEST CAMPAIGN

Five professional test and fleet pilots from German Armed Forces within sum 14.915 flight hours (fh), mean 2.983 fh (SD 2.405 fh) participated in the simulator flight test campaign. Participating pilots hold several ratings on actual helicopter types such as BO-105, Bell 407, CH53, EC120, H135, H145, and experimental helicopters. While pilot with PIDs PID1 (2.400fh on real helicopters, 400 fh on helicopter simulators) and PID3 (5.300 fh, 1.000 fh) are test pilots with basic single engine education, PID11 (800 fh, 100 fh), and PID12 (700 fh, 400 fh) are fleet pilots with basic multi engine rating. PID2 (5.715 fh, 600 fh) is also grouped as a test pilot (1000 fh in test) but is mainly experienced on single engine helicopter types. PIDs nomenclature goes along with completed ROSIE simulator flight test campaigns, see [6] and [12].

The simulator flight test campaign had been conducted along ADS-33 PRF standards [1]. The focus was set on pilot workload, handling qualities, situational awareness [23], and motion cueing [22] during OEI operations. In parallel, the performance of the QSS with a focus on the FADEC system had been investigated. Each pilot was instructed to fulfill seven Mission Task Elements (MTEs) in a critical scenario [14] according to Figure 5:

1) MTE1: ISEO Cruise flight.
2) MTE2: Simulated OEI event for ISEO engine recovery using the simulated engine (SER), the HIL engine (RER), or regular single engine operation (SEO) using the simulated engine.
3) MTE3: Recovery of the helicopter with or without the ERA system during the OEI event.
4) MTE4: Continuation of the flight after the event.

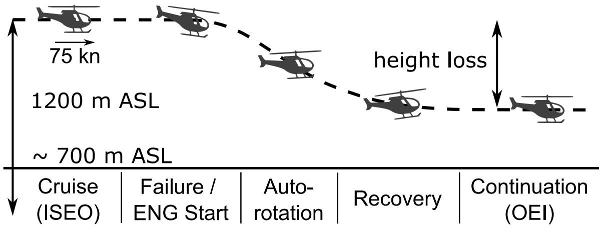

Figure 5 Side view of the helicopter recovery mission (SER and RER), figure not to scale

A general overview of the simulated mission and exemplary recorded flight paths is given in Figure 6. The picture presents the data of the four test flights of PID2 including information about the flight altitude starting at 1200 m ASL heading north over a lake. The different patterns result from variation in the time of the failure of the operating engine ENG2 (black triangle), which was commanded manually by the operator of the engine test facility at any moment in stable ISEO cruise. After having recovered the helicopter from autorotation with the help of ENG1 started by the QSS, the pilot had to continue to the landing site.

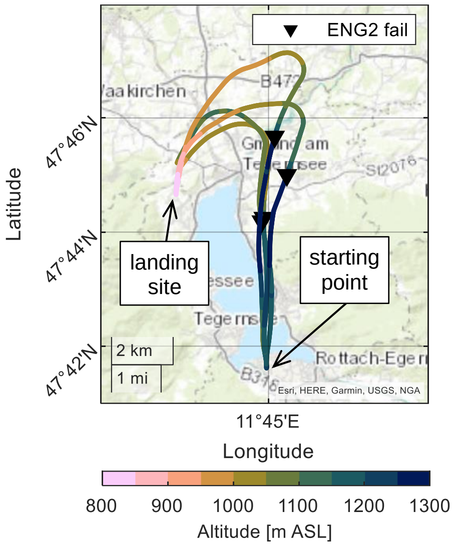

Figure 6 Top view of the flighpaths of the four test flights of PID2

For the simulated test flight missions, the BO-105 helicopter had a takeoff weight of 1700 kg and the pilot was requested to fly at a constant altitude of 1200 m ASL (~ 500 m AGL depending on terrain) with a speed of 70-80 KIAS in the ISEO cruise flight segment (MTE1) prior to the OEI event (MTE2). The chosen speed is just above the speed of minimum power requirement ("bucket speed", ~ 60 KIAS) of the present configuration and therefore represents a realistic condition for a cruise flight that aims to minimize the fuel consumption. To establish similar and reproducible conditions among all pilots and flights, the pilots were not allowed to leave their left hand on the collective but on their left leg to simulate the unawareness about the upcoming engine failure event in trimmed flight. Furthermore, they were not informed about the exact moment of the engine failure. After the simulated failure of the active engine (ENG2), the inactive engine (ENG1) automatically begins the start-up procedure. The pilot needs to initiate autorotation and wait for the starting engine to be operational. As soon as the pilot recognizes the readiness of the engine, he can start to recover the helicopter from the autorotative descent (MTE3). When a stable flight condition – respectively horizontal flight - is achieved, the flight is continued to the landing site. Although not used in the real helicopter, the PFD of ROSIE allows the use of a state of the art First Limit Indicator (FLI), see bottom right in Figure 1. The pilots were constrained not to exceed the yellow regime of the FLI to avoid to heavy loads on the HIL engine. In a real emergency event, the pilot would be allowed to access the OEI contingency of the engines and the main transmission.

Bedford workload, Cooper-Harper handling qualities (HQRs), and Situational Awareness Rating Techniques (SART) ratings for all phases of flight using different levels of visual and audio augmentations had been evaluated after each flight, except for PID3. Prior investigations showed a potential for such pilot assistance systems, see [7] and [21]. Aside from the workload and HQ questionnaires, each pilot also reported on the simulator sickness questionnaire upon completion of the simulation exercises. The questionnaire provided in Ref. [8] was used for this purpose. The responses indicate that none of the pilots faced motion sickness or vertigo, except for slight fatigue and sweating. Finally, Likert scaled questionnaires had been offered to the pilots to discuss and rate the QSS and ERA system for further development work.

4. RESULTS AND DISCUSSION

In the following sections, the outcomes of the pilot and hardware-in-the-loop study are presented and discussed. Section 4.1 focusses on the performance of the engine and the QSS before the performance of the pilots and the impact of the ERA is evaluated by objective criteria in section 4.2 and 4.3. Finally the results of the assessment of workload, HQR and SART are presented.

4.1. Engine Quick-Start Performance

Based on an exemplary test flight with the HIL engine, Figure 7 shows the sequence of events in case of an engine failure (MTE2) during ISEO cruise flight (MTE1) and the subsequent recovery of the helicopter (MTE4) during the RER mission. At $t = 0\,s$ the failure of the active engine with sudden loss of power is simulated which is indicated by the drop of the helicopter's transmission torque (TRQ, orange) and the start of the decrease of the main rotor speed (NR, light green). The failure triggers the quick-start of the other engine and the gas generator (N_1, blue) starts to ramp up. The output shaft (N_2, dark green) follows shortly after. About at the same time, the pilot reacts to the failure and starts to reduce the collective pitch (COLL, pink) to initiate the autorotation. The first vertical dashed line marks the point where the gas generator reaches $N_1 = 60\ \%$ and the QSS is cutoff. At the second dashed line, the gas generator reaches the threshold for the triggering of the ERA signal in the cockpit ($N_1 = 73\ \%$). Just before this event (at about $t = 5\,s$), the engine output shaft reaches the speed of the main gearbox, the freewheel is engaged and now allows the torque transmission from the engine to the helicopter, which is indicated by a step in the torque curve. The engine accelerates the rotor until it eventually levels of at 100 %. After the successful restart of the engine, the pilot starts to increase the collective input again to recover the helicopter from autorotation dive and reach a stable flight condition. In the here presented example, the engine runs faster than the main rotor between $t = 5\,s$ and $t = 10\,s$ which would not be possible in an actual helicopter powertrain. This difference occurs because the engine and the main rotor are not mechanically coupled but only by the power or rather the torque requirement, which is transferred over the UDP interface. The provision of torque by the ECB has a certain degree of sluggishness and therefore can lead to deviations from the ideal behavior especially when additional torque to equalize the different inertia of the helicopter's lifting system and the testbed assembly is required.

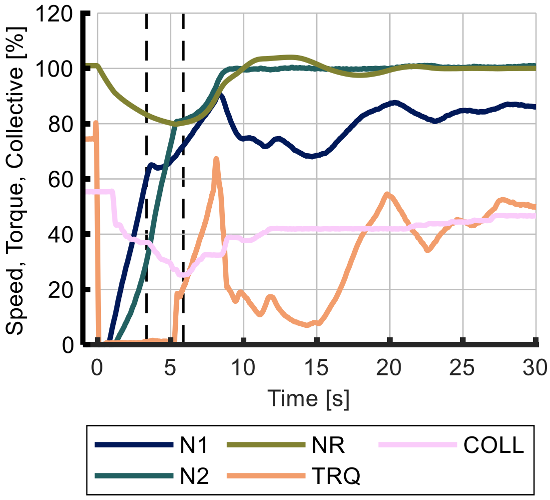

Figure 7 Engine quick-start and helicopter recovery after engine failure during OEI flight

Figure *8* depicts the quick-start performance of all test runs in terms of time needed to accelerate from stop to ground idle N1 (60 %) and to 73 % by grouping them into experiments with the HIL engine and flights with the engine model. For the time to 60 % the median for the HIL engine is 3.30 s with a standard deviation of 0.03 s while the engine model has a median of $(5.32\ \pm 0.08\,s)$. The plot shows that the engine accelerates to 60 % reliably with a maximum difference of 0.11 s. The continuing acceleration of the HIL engine up to 73 % is subjected to more fluctuations and the time mainly varies between 5 and 6 s $(5.41\ \pm 0.78\,s)$, although some outliers can be observed at values up to 7.5 s. Considering the plot, one could conclude that the variation of the 73 %-time is caused by the engine behavior after the cutoff of the QSS at 60 %. But closer evaluation revealed, that in fact small differences in the combustion process during the active phase of the QSS develop their effect not until the QSS is deactivated and especially the transition is a sensitive moment. A more robust behavior could be obtained by adjustments on the FADEC settings for the quick-start process. The engine model's time to 73 % varies less ($5.99\ \pm 0.19\ s$) and the median is closer to the HIL engine than for the time to 60 %. The differences between the HIL engine and the model suggest that the model is not fully capable of representing the quick-start process in detail and thus shows the need for further improvement of the simulation. For the pilot however, only the time to 73 % will have a perceptible influence on the handling qualities since it is the point where the engine reaches full operability and the ERA signal is triggered. In the study's questionnaire, this topic was addressed, and all candidates reported that they did not perceive any difference in the starting behavior between the model and the real engine. The pilots were also asked about their opinion on the restart time of the engine and all of them agreed that the achieved time is more than sufficient for mastering the recovery event (MTE3).

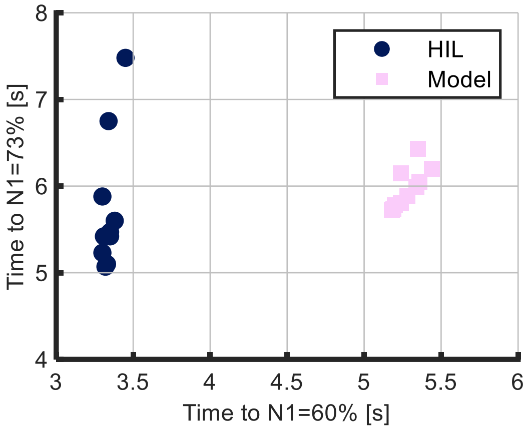

Figure 8 Gas generator ramp-up times grouped by engine mode

Along with the ramp-up time, the power output of the engine was investigated. At $N_1 = 73\,\%$, the engine delivers an output torque of 50-80 Nm, respectively a power of 30-50 kW. As depicted in Figure 7, this amount of power is enough to accelerate the main rotor during the autorotation descent and thus allows the pilot to start the recovering process of the helicopter. A power of 60 kW (20 % takeoff power), which was considered to be needed to start recovering by Spieß et al [19], can be delivered after about 6.5 s. In all investigated test flights, the engine's power output dropped after the main rotor was accelerated to 100 % since the pilots had not yet set the collective to higher level, see Figure 7 at $t = 8\ s$. Therefore, an independent series of experiments had been carried out to evaluate the achievable power output of the engine. It was found that 50 % of the engine's takeoff power, can be reached 7-8 s after restart. The time for the engine's power turbine (N_2) to reach 100 % with disengaged freewheel, thus without any braking torque and accelerated mass, is 5.5 s or less.

The fast provision of power suggests that there might be high thermal loads on the engine. Figure 9 shows plots of the turbine outlet temperature (TOT) versus the gas generator speed (N_1) for a normal start (pink) and a quick-start (blue). The temperature level in the turbine section during a quick-start is below the one of a normal start-up procedure with respect to the same gas generator speed. This is since the QSS supports the gas generator much more than the electric starter motor during normal start and the expanded cold air from the QSS bottle helps to decrease the temperature level. Having a look at the time series in Figure 10 however, it can be discovered that the engine experiences higher temperature gradients during quick-start. Right after the combustion chamber ignition at $t = 0\ s$, the normal start curve has the same gradient as the quick-start up to a temperature of 480 K. After a period of slower increase, the two curves approach each other again after 12-15 s. Here, the quick-start curve further increases since the engine accelerates to the operating point implied by the helicopter's power demand whereas during normal start, ground idle is reached at $t = 30\ s$ and the TOT does not increase until the FADEC switches to flight operating mode at $t = 35\ s$. The engine eventually reaches a similar operating temperature after 80 s, which was cut from the view in the figure, whereas with quick-start the operating condition is reached after 30 s.

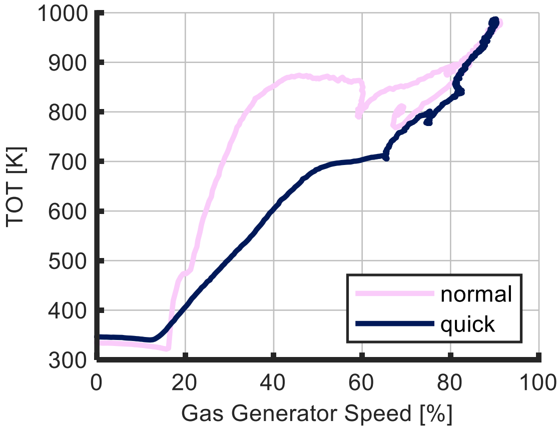

Figure 9 Comparison of turbine outlet temperature (TOT) between normal engine (pink) restart and QSS (blue)

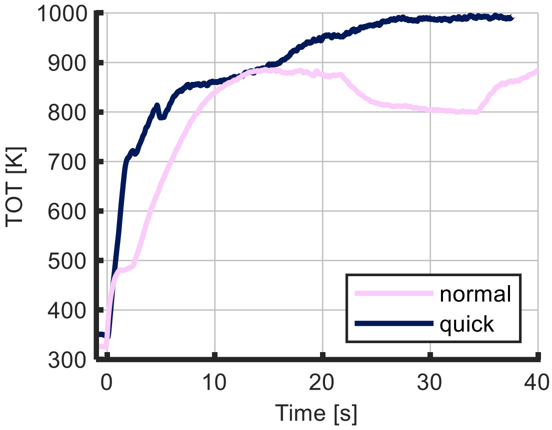

Figure 10 Comparison of turbine outlet temperature (TOT) between normal engine (pink) restart and QSS (blue)

4.2. Observations during the Helicopter Recovery Missions

As described in section 3, the pilots' task was to recover the helicopter without exceeding the yellow FLI limit at any moment. The pilots fulfilled all missions well within the engine's operational limits. The maximum measured output torque of all flights was 310 Nm, which corresponds to a power of about 200 kW, respectively 72 % of the normal cruise power (64 % takeoff power) and was reached about 13 s after the engine failure event during the recovery phase (MTE3). The turbine outlet temperature also remained in an acceptable range with a maximum level of below 1000 K whereas the normal cruise limit of the engine is at 1011 K. However, in four of the 20 flights the main rotor speed dropped below the critical value of 85 %, the minimum value observed was 80 %, see Figure 7. Furthermore, in three scenarios, the maximum rotor speed of 110 % was exceeded.

To evaluate the pilots' performance during the OEI emergency, the altitude changes between the moment of the engine failure and the moment when a stable flight condition was reached has been assessed as an important parameter. In Figure 11, the altitude loss of all 20 OEI emergency test flights is plotted grouped by pilot (PID). After an initial familiarization and training phase, each pilot performed four test flights: two were done with the engine model (SER, squares) and two with the HIL engine (RER, circles). Each engine configuration was used once without (orange) and once with support of ERA (blue). The purple diamonds mark the median of each PID. The altitude loss has a range from 80 to 230 m with a median (dash-dotted line) of 130 m across all flights. In three flights, the pilot was able to recover the helicopter with an altitude loss of 100 m or less. In general, it took the pilots 15 to 20 seconds to recover the helicopter. The results underline that there is no evidence for an influence of the engine mode on the handling qualities and the performance of the helicopter. The effect of the ERA will be discussed in section 4.3. As mentioned in section 4.1, the engine is able to produce more than 50 % of its take-off power within 10 s but in most flights the pilot controlled the situation in a way that didn't push the engine close to its limit. The difference in the PID medians and the scattering of the results of each pilot give an idea about how differently the pilots handled the event. The performance in terms of altitude loss can be influenced by the initial reaction time of the pilot, the entry into autorotation, the maintained rotor speed, which is a result of the descent rate and the angle of attack of the rotor blades, and the intercepting of the descent.

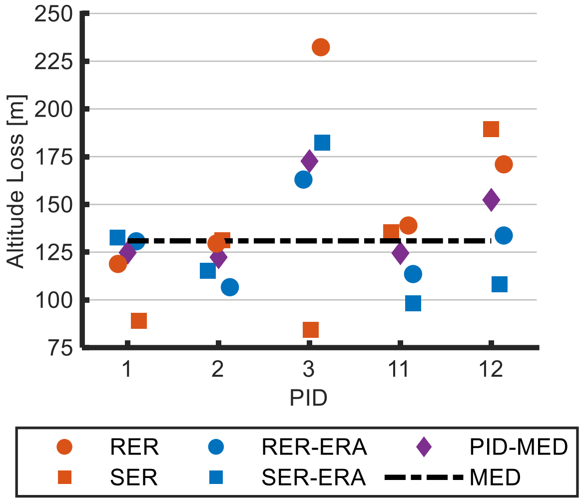

Figure 11 Altitude Loss of all test flights grouped by PID (abscissa), engine mode (symbol) and ERA mode (color)

The reaction time of the pilot had been defined as the time between the engine failure and the moment when the pilot reduced the collective pitch. For all except one test flight, the reaction time was in the range of 0.7–1.4 s with a median of 0.97 s, which is in between two similar investigations in Ref. [18], where it was found to be $(1.18 \pm 0.31\,s)$, see and in Ref. [17], where almost all pilots stayed below 1 s. The differences in the reaction times that we observed in our study were not able to reflect the differences in Figure 11 since e.g. the reaction time of PID12 only varied by about 0.15 s between all flights. The flight condition prior to the event was reproduced in the simulator without a pilot and predefined flight control inputs were applied to evaluate the helicopter's behaviour. Without any reaction of the collective level, the rotor speed would decrease with about 7-8 % per second which gives the pilot about 2.5 s before the critical rotor speed of 85 % is reached. An instant collective movement to zero blade pitch would lower the rate to about 5 % per second increasing the critical time to 3.75 s. In the test campaign, it took the pilots 3-

4 s before they were able to intercept the decrease of the rotor speed at a minimum of 82-87 % and to enter autorotation descent. A significant difference to common loss-of-power-events with subsequent autorotation is that in the OEI events conducted in this study, the helicopter didn't spend an extended period of time in a steady autorotation condition. In Ref. [17], the time to enter a steady descent in autorotation was observed to be between 10-15 s. In our experiments, it took between 5 and 9 seconds to accelerate the rotor to 100 % in most cases, depending on the pilot's actions on the flight controls. The engine didn't participate in the acceleration but after about 5.0-5.5 s, meaning that a large part of the acceleration is achieved by the autorotation descent. The quick-start enables the intercepting of the descent almost immediately after the pilot has entered into autorotation and before a steady flight configuration is achieved. However, the training of the pilots requires them to ensure that the helicopter can perform a landing in case the engine fails to start meaning that that reducing of the altitude loss has not the top priority but keeping the helicopter in a more conservative flight condition. In general, we conclude that there are two factors, which cause larger altitude loss. On the one hand, smaller pitch angle (nose-down) of the helicopter during autorotation paired with low collective input leads to a reduced inflow angle into the rotor disk and thus higher descent rate because less lift is provided. It also was discovered that the rotor speed decreases more in this configuration and thus more energy must be put into its re-acceleration. In addition, a quick increase of the helicopter pitch is necessary to reduce the height loss if the pilot performs the descent with distinct nose-down input. Flight RER of PID3 is an example for this, see orange circle in Figure 11. On the other hand, during the intercept more height is lost if the collective input is increased later and/or with a small gradient. For example, PID12 increased the collective from 0 % to 40 % in 3.5 s on flight SER-ERA (blue square) whereas it took 7.1 s on flight SER (orange circle). This resulted in an additional loss of 80 m on SER compared to SER-ERA.

4.3. Impact of the ERA System

The ERA, which has been described in section 1.2, was introduced to support the pilot during the recovery with the aim to reduce the workload and the altitude loss and therefore increase the safety of ISEO operations. The different results of the flights with and without the support of ERA indicate that the audio cueing leads to lower altitude loss, see Figure 11. Furthermore, the recorded data revealed that the recovery performance of the engine tends to scatter less when ERA is used as shown in Figure 12. With the support of ERA, 70 % of the observations were within the 100-150 m bin and no flight had a loss of more than 200 m.

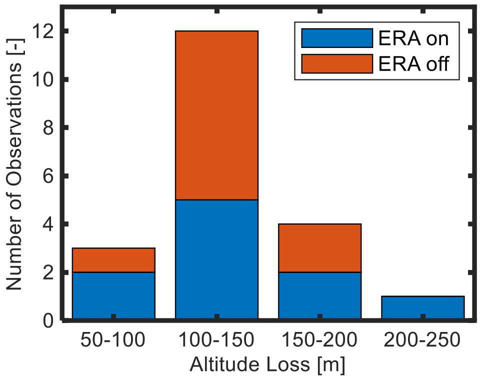

Figure 12 Distribution of the altitude loss, grouped by status of ERA

However, not all the observed results support the hypothesis that ERA helps to increase the recovery performance. PID1 had lower altitude loss on the flights without ERA, see Figure 11 (RER and SER, orange), but the difference between the runs is of minor magnitude, which is also true for PID2. To further investigate the impact of ERA on the pilots' behaviour, the questionnaire focused on their subjective perception of the audio cueing. The candidates agreed that the audio signal helped to shift their attention to the engine instruments in the cockpit when their visual cue was overloaded and also allowed them to react initially to the situation. However, they pointed out that some training with the system is essential to profit from its presence and PID1 as well as PID2 reported that they had been disturbed by the audio signal to some degree. It was criticized that the sound can be mistaken for a warning when it actually signals the pilot the proper operation of the engine. Despite two training flights, PID1 reported this misunderstanding on the SER-ERA flight, which might explain why the altitude loss of the SER flight without ERA was larger. As previously described, in the results of PID1 and PID2 no significant benefit of the ERA was noticeable. The two pilots have in common, that they, as well as PID3, belong to the group of test pilots, whereas PID11 and PID12 are fleet pilots. The candidate who profited most of the use of ERA was PID12, since both flights with ERA (blue) have significantly lower altitude loss than without (orange), see Figure 11. The difference in the pilot's behaviour is made accessible in Figure 13, where the altitude change with reference to the point of the engine failure and the collective input are plotted versus the distance travelled, also with reference to the point of engine failure. The altitude and distance axes have the same scale to give an impression about the flightpath in the side view (compare to Figure 5). The figure depicts the flights with the HIL engine (circles in Figure 11) with (blue) and without (orange) support of the. It is visible, that the initial descent rate and the collective input of both runs are similar. The point where the ERA signals the full operability of the starting engine is marked with a black, dashed line. With the ERA, the pilot set the collective to a level of about 30 % soon after the signal, whereas without ERA the level and the gradient of the initial increase were significantly lower. In consequence, more lift was generated on the ERA flight and the descent was intercepted more rapidly, although the pitch of the helicopter itself was increased less in this case. It can thus be concluded, that the ERA lead the pilot to increase the power requirement earlier and more aggressively. Here, similar pitch input as in the flight without ERA would have resulted in even lower altitude loss.

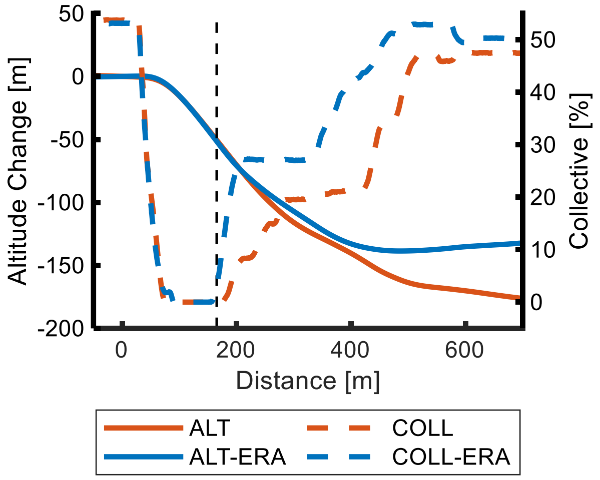

Figure 13 Altitude Change (ALT) and Collective (COLL) Input of SER (orange) and SER-ERA (blue) of PID12

4.4. Assessment of Subjective Workload and Situational Awareness

As a part of the pilot questionnaires completed after each flight, pilot workload ratings, associated SART weightings, and HQ ratings were collected. The ISEO OEI operations with activated audio augmentation and QSS partly received mean pilot workload and HQR ratings of predominantly border line level 1, while all ratings without audio augmentation only received level 2. Figure 14 and Figure 15 depict the arithmetic mean of the workload ratings for the two groups of pilots (test and fleet pilots). Due to some misunderstanding of the rating procedure, PID2 was excluded from the data captured here. The figures show that the event of the single engine operation (MTE2) during the simulated engine recovery (SER) and real engine recovery (RER) received highest Bedford ratings of predominantly level 2. In cruise flight before and after the event, pilot workloads were both on borderline level 1.

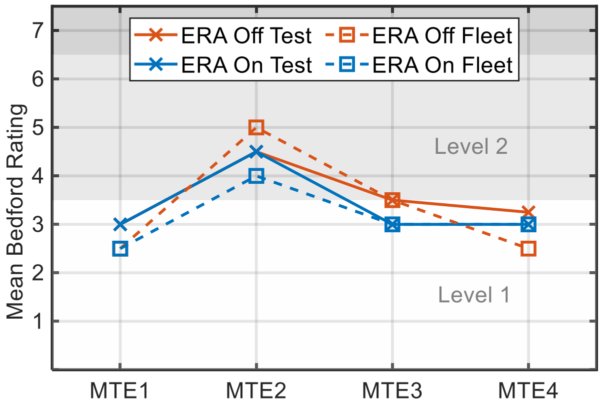

Figure 14 Pilot`s workload ratings of MTEs during operations of SER (N=2 for each group)

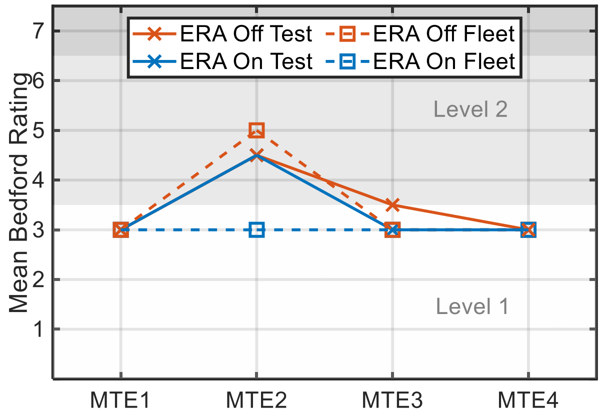

Figure 15 Pilot`s workload ratings of MTEs during operations of RER (N=2 for each group)

Due to the way the Bedford scale is structured via the questions the pilot must answer, a change in rating from 4 to 3 is a significant improvement indicating that the workload is satisfactory without reduction and that the pilot still has spare capacity to accept additional tasks. Regarding this aspect, it might be overserved that in both cases, SER and RER, the multimodal cueing concept decreased pilot`s workload to an acceptable level. This effect fits to most of the pilot`s comments: The exclusive audio guidance for the QSS allowed the pilots to more focus on the outside scenery and immediately react when the engine was available again by giving the pilot a designated audio feedback. Here, a Bedford workload rating of almost borderline level 1 was reached when the ERA system had been activated. Interestingly, fleet pilots reported bigger reduction in the workload than the test pilots. Figure 15 even shows that on the RER-ERA flight, they did not perceive higher workload during MTE2. RER-ERA was the last of a series of six flights, so that the pilots were more used to the situation than in the flights before. Future test campaigns with larger number of flights should therefore use a randomized test plan. Overall, regarding the pilot workload during operations with the ERA being activated, almost all critical parts of the mission such as the event (MTE2) and the recovery (MTE3) were rated at lower workload as without the ERA. Finally, last flights of regular single engine operation (SEO) without an engine failure event were mainly rated at Bedford workload level 1. Here pilots commented, and as for the flights before, that the very short start-up time of the engine with the QSS always allowed flights at an acceptable workload in general but is not mandatory if the restart of the engine can be anticipated.

Next, Figure 16 and Figure 17 show the pilot assigned HQRs for all flights. Both, SER and RER lie well in the level 2 HQR range. Again, the activated ERA system enhanced the HQRs, although only marginally, and resulted in borderline HQR Level 1 ratings, even during the event. Here, pilots gave feedback, that the combination of the QSS and the ERA system always allowed a controlled autorotation and flight. On top, the QSS had no negative effect to the HQ of the helicopter resulting in acceptable HQR related to ratings during simulated flights without the ERA, see Ref. [12]. Potentials of such multimodal cueing concepts with a focus on visual and control augmentation [13] had been demonstrated already in earlier simulator flight test campaigns.

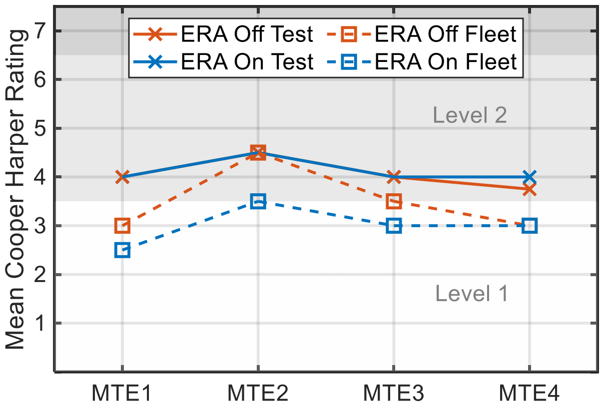

Figure 16 Pilot`s HQRs of MTEs during operations of SER (N=4)

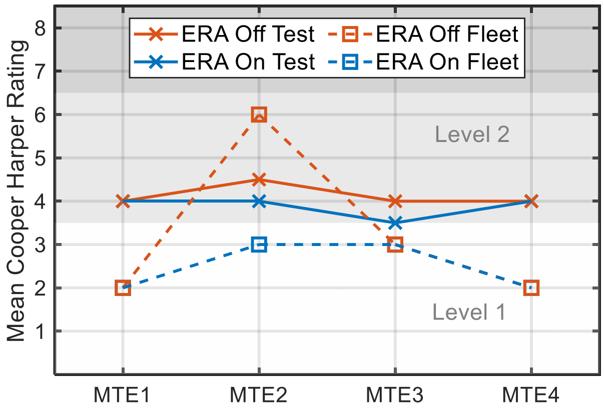

Figure 17 Pilot`s HQRs of MTEs during operations of RER (N=4)

Finally, regarding the two categories of pilots, fleet pilots seemed both to benefit from the ERA during the event. As from pilots' ratings and debriefing comments, the specific audio guidance for QSS operations allowed them to have a constant "eyes out the cockpit view to maintain stable outside visual cues and succeed to recover the helicopter within the given values at same time. This effect fits to most of pilots' comments, as they strongly recommended to have a more detailed audio guidance regarding the different states of the engine related to the QSS, which will be part of a multimodal cueing concept for OEI operations in the future. Regarding the critical MTE3 (recovery) with a detailed look on the Situational Awareness Rating Techniques (SART), see Figure 18 and Figure 19 with ratings from 1 (low) to 7 (high), the following results can be drawn in accordance with the pilots' workload ratings: Both, for SER and RER OEI operations and especially during the recovery of the helicopter, pilots benefitted from the ERA in the case of reducing the variability and complexity of the situation (VoS, CoS) by distributing their SA to the visual and aural channel. Moreover, pilots recommended to receive more quantity of information (IQ) as they were able to connect the different states of the engine provided by the ERA directly to the then expected manual control inputs. Finally, pilots emphasized to focus on the main needed helicopter parameters, such as IAS, altitude and attitude of the helicopter, resulting in a lower division of attention (DoA) and more spare mental capacity (SPC) during the critical maneuver of recovery and autorotation. However, a harmonization and tailoring of the ERA to the appropriate helicopter system, BO-105 in here, and the head-down and potential head-up instrumentation had been strongly recommended by all participating pilots. The resulting multimodal cueing concept for tailored environments will be part of the future work.

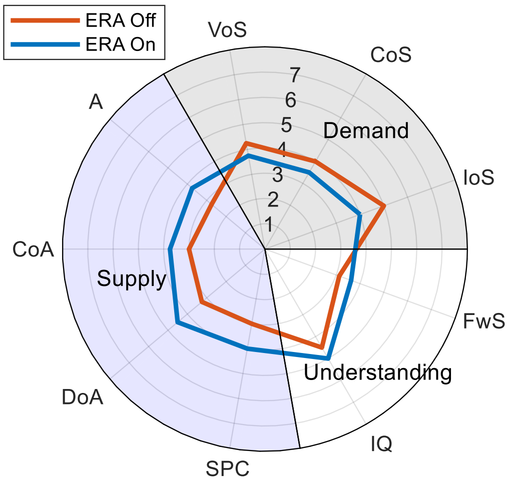

Figure 18 Pilot`s SART ratings during operations of RER MTE2 (N=4)

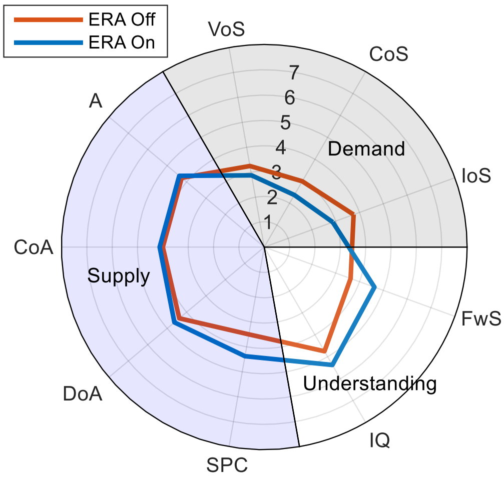

Figure 19 Pilot`s SART ratings during operations of RER MTE3 (N=4)

5. CONCLUSIONS AND FUTURE WORK

The present paper outlined the setup and the results of a professional pilot and hardware-in-the-loop study that made use of a hardware-in the-loop environment consisting of fixed-based helicopter simulator and a real turboshaft engine. The environment was used to conduct missions with Intended single Engine Operation that make use of a pneumatic engine quick-start system in case of an engine failure. Within the test campaign, a mix of five test and fleet pilots from German Armed Forces and industry performed a series of ISEO missions including the simulation of an engine failure during SEO. The aim of the study was to validate the setup, especially with the use of the HIL engine with the quick-start system, and to evaluate the pilots' performance in terms of handling behaviour and workload during the simulated event. Furthermore, the use of a multi-modal cueing system as part of the human machine interface had been integrated and evaluated during the flights. The QSS with compact air supply from a bottle reservoir was tested in a realistic environment and flight profiles for the first time after having passed several preliminary lab and integration tests.

At first, the results show that the pilots were able to recover the helicopter from the engine failure event within the defined operational limits. The observed altitude loss and other flight parameters during the simulated flights can be used to define the envelope for the future application of the ISEO. The pilots rated performance of the QSS to be sufficient for safe and comfortable handling of the engine failure event.

Second, results from the current simulator study demonstrate that OEI operations are a great challenge, increase pilot workload and the necessity for pilot performance and reduce situational awareness. The current study, however, also demonstrated that these challenges could be significantly reduced if pilots had access to a quick-start system and an engine recovery audio assistance at same time:

1. The simulated engine showed realistic behavior from pilot´s subjective perspective compared to the real engine. This effect culminated in almost similar Bedford workload and HQRs results for most of the proceeded MTEs.
2. Without any further support, pilot`s level of workload is mostly at borderline level 2 and shows a peak during engine failure vent (MTE2 here). Accordingly, handling qualities of all pilots are also at level 2 during the critical phases of the mission (MTE2 and MTE3).
3. The multimodal cueing concept, in detail the engine recovery audio assistance, decreased pilot workload and enhanced pilots SA, especially during the critical phases of the flight OEI recovery and emergency approach and landing. It some cases it was possible to reach borderline level 1 However, a pilot fitted design concept of the ERA embedded to state-of-the-art helicopter glass cockpit layouts is investigated in the future.

Future enhancements of the HMI could for example further extend the audio cueing by means of voice messages that address different phases of the recovery event. Furthermore, the range of the available visual cues can be expanded by filtering the available information and guiding the pilot's attention with the help of a coloured head-up or head-down display. After a revision of the full multimodal cueing and HMI concept, a second test campaign should be conducted to carry the ISEO concept to the next level. With the knowledge that the simulated engine is suitable for the OEI operations and with further improvements on the model as well as the interface between FADEC and cockpit, a following test campaign can be largely extended in terms of number of pilots and number of flights since experiments with the simulated engine are more time and cost effective.

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