ENGINE QUICK START IN CASE OF EMERGENCY - A REQUIREMENT FOR SAVING FUEL BY MEANS OF ENGINE SHUTDOWN

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Abstract

Poor gas turbine part-load performance can be one reason for high helicopter operating costs. Shutting down one engine during flight can save up to 30 % of kerosene in a twin-engine helicopter - depending on its operating point. However, if the running engine fails, it generally takes about 25 s for the second engine to start. This case of emergency is not acceptable. In order to be able to use the fuel-saving potential and to maintain safety standards at the same time, a new emergency engine quick-start system has been designed and experimentally investigated for the Allison 250-C20B, now Rolls Royce M250.

1. NOMENCLATURE

CO	Carbon Monoxide
EI	Emission Index
FADEC	Full Authority Digital Engine Control
GG	Gas Generator
GI	Ground Idle
NCP	Normal Cruise Power
NOx	Nitrogen Oxides
N1	Gas Generator Spool Speed
N2	Power Turbine Spool Speed
OEI	One Engine Inoperative
PT	Power Turbine
SFC	Specific Fuel Consumption
TUM	Technische Universität München
UHC	Unburned Hydrocarbons

2. INTRODUCTION

Helicopter performance calculations prove that the engine power required for cruise flight is significantly lower than for hovering or high-speed flights. Figure 1 (green line) shows the engine power required for the twin-engine helicopter BO 105 at SL ISA with a gross weight of 1800 kg [15]. The dotted blue line illustrates the maximum available Normal Cruise Power (NCP) of one Allison 250-C20B engine. It shows a field in the flight envelope in which one engine alone delivers sufficient power for the helicopter. Hirschkron and Russo analysed helicopter missions in [5]. They state that both engines are operated at less than 40 % of nominal power for more than 50 % of the whole mission time.

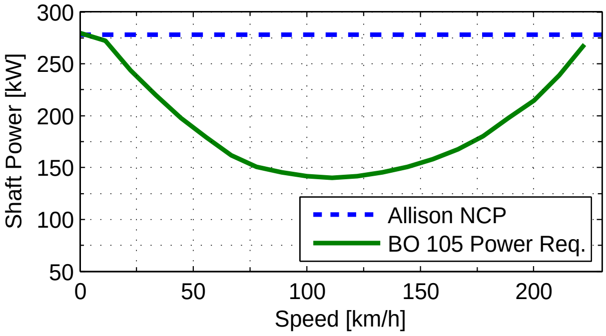

Figure 1: BO 105 power req. against flight speed [15]

Today the power required in a twin-engine helicopter is split equally among both engines. This implies that both gas turbines operate at part load over a wide operating range. At part load two major effects lower the overall efficiency of a gas turbine. The thermodynamic cycle runs at lower pressure ratio thus reducing thermodynamic efficiency. Furthermore, turbo machineries operate at a significant distance from their most efficient working point, deteriorating cycle efficiency even more. Several methods are available to counteract these effects. Bringhenti and

Barbose [3] suggest running the engine at constant pressure and temperature but reduced mass flow. This requires variable geometry in case of [3] on both compressor and turbine. In their simulations they managed to significantly improve part-load performance. In a similar case, Karstensen and Wiggins proved this concept experimentally [7].

Another – more costly – option of improving the part-load performance of gas turbines is the integration of a heat exchanger. This alters the engine characteristics significantly. Simulations with real helicopter mission data showed that fuel burn can be reduced by up to 15 % at the cost of higher engine price and weight [2].

However both modifications require a complete redesign of the engine cycle. As an alternative this paper presents a method based on a changed operational strategy, which leaves the gas turbine cycle unchanged.

3. ENGINE: ALLISON 250-C20B

Figure 2 shows a schematic diagram of the Allison 250-C20B engine. The engine is usually started with an electric starter generator which is connected to the gas generator (GG) shaft via the gearbox. In the BO 105 not only the starter but also ignition is operated manually by the pilot during an engine start.

A mechanical control unit offers two control modes for engine operation. In “idle” the speed of the gas generator (N1) is maintained at a prescribed rotational speed. In “flight” the power turbine (PT) spool is maintained at 100 % speed. This mechanical control unit does not offer any flexibility for modifications. At the TUM test bed it has therefore been replaced by a flexible FADEC system developed by Preiß [10]. The core of the FADEC is a SIMULINK model which controls all inputs to the engine. Using this setup the control parameters can be accessed and easily modified even during an engine run. It also offers a high amount of flexibility for academic research.

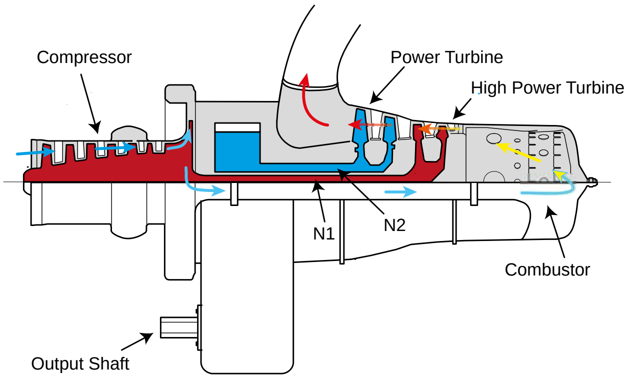

Figure 2: Schematic diagram of the Allison 250-C20B engine

3.1. Engine performance

For a proper comparison of different engine operating strategies, a validated engine characteristic e.g. fuel flow over N1 is required. While the speed range 68 % - 100.4 % N1 can be derived from manufacturer reference data, the sub-idle region was recorded at the TUM test bed. The lowest operating speed was defined at 35 % N1 by the minimum oil pressure. The resulting fuel flow diagram is shown in Figure 3, which will be the basis for the following examinations.

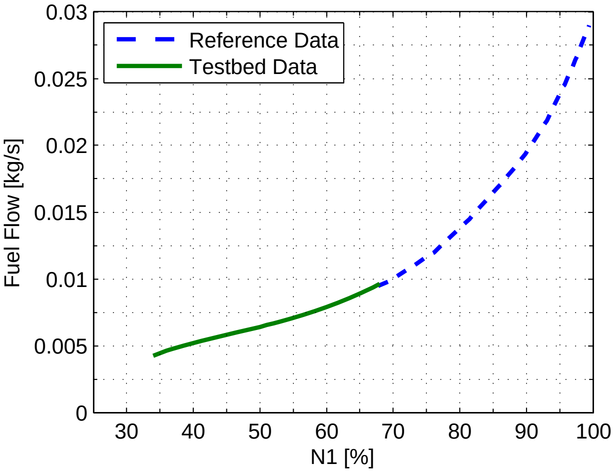

Figure 3: Fuel Flow versus N1 for the Allison engine

4. OPERATIONAL STRATEGIES

The simplest solution to reduce the fuel consumption problem at part-load is to shut down one engine in flight – if power requirements allow. This introduces a significant safety concern, as the spare engine requires about 25 s to be back in operation at idle.

Stone and Eberhardt [13] proposed to motor the GG of the inoperative unit via a 2:1 reduction drive and a clutch system which is connected to the GG of the running engine. An alternative is to connect the GG spool of the non-operating engine to the PT spool of the running unit via a gearbox. As the PT spool speed (N2) is kept constant at 100 % a fixed sub-idle speed can be selected for the shut-down engine. In both cases the compressor is not thermodynamically throttled, which lowers its pressure ratio and consequentially compression power.

Another approach without additional clutch systems etc. is to actively operate the spare engine in a sub-idle mode, which means N1 is below ground idle (GI). As the engine is not completely shut down, a faster acceleration to high power is expected.

4.1. Fuel Saving Potential

The following part-load operating scenarios are compared regarding fuel flow. The first engine is delivering full power demand while the second engine is:

1. shut down,
2. shut down, but its GG is connected to the GG of the running engine,
3. shut down, but its GG is connected to the PT of the running engine,
4. running at ground idle,
5. running at sub-ground idle conditions.

The calculated fuel flows for these cases are displayed in Figure 4. The 100 % line represents normal operation mode with two engines, which is regarded as the reference. For all scenarios, the benefit increases with decreasing power demand.

Scenario 1 with one engine fully shut down delivers the highest reduction in fuel flow, but by current means is not certifiable. A quick start system as presented in chapter 5 and 6 bears the potential of overcoming this obstacle.

The following scenarios aim at reduced acceleration times by holding the engine in rotation, which additionally maintains some mass flow through the engine and especially through the combustor.

In scenario 2 the N1 of the motored engine depends on the N1 of the running engine. At 50 % N1 this engine consumes about 33 kW. This limits the remaining available power of the running engine, which influences the helicopter´s operation significantly. The percentage of fuel flow saved at high power in relation to the reference is about 17 %.

Scenario 3 requires an additional gear in the system, which reduces the constant speed N2 of the running power turbine to a suitable N1 of the second engine. For the calculations in this paper, this N1 was chosen to 35 % N1. The required power extraction is 11 kW which results in an overall fuel flow reduction of 20 % at high power.

Only up to 4% of fuel flow at high power can be saved by setting one engine to GI (60 % N1), shown in scenario 4. Scenario 5 is based on sub-ground-idle conditions with e.g. N1 equal to 35 % N1. This promises a benefit of 15 % fuel flow reduction at high power. In contrast to scenarios 2 and 3, this potential can be realized without implementing additional gears and clutches, but the acceleration time back to full power remains a concern.

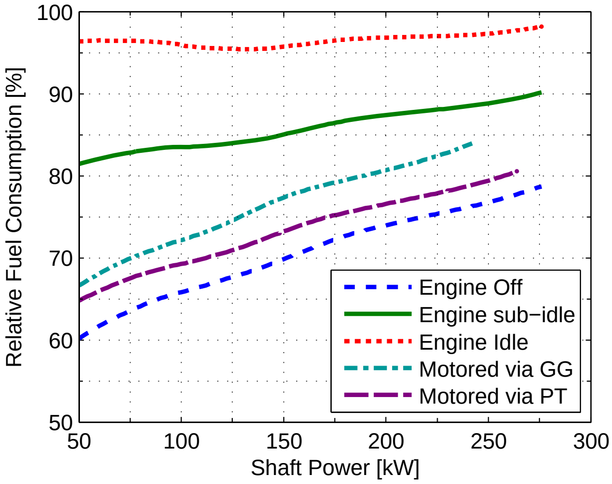

Figure 4: Relative fuel consumption in different operating strategies compared to normal engine operation

4.2. Influences on Maintenance and Life

The economic benefit of changes in engine operation is also determined by life considerations and by maintenance costs. Hirschkron and Russo specify that engine maintenance costs account for about 20 % of the overall engine costs, including acquisition [5].

The components of the gas turbine are subject to both, limits in operating hours and limits in accumulated cycles. An example is given in Table 1 for the Allison 250 engine. The number of allowed cycles is about double the number of allowed running hours. In practice the relation between hours and cycles varies in a wide range depending on the usage of the helicopter. Based on statistical data from a maintenance company, the ratio is about 1:1 for helicopters operated under normal conditions, while engines operated in rescue helicopters consume ten times the number of cycles per hour due to the dynamic usage.

Part	Hours	Cycles	C/H Ratio
Impeller	3550	9150	2.58
GG Turbine	1750	3000	1.71
LP Turbine	4550	6000	1.32

Table 1: Examples of life-limited parts of the Allison engine [12]

The five scenarios influence the relation cycles to hours in different ways. Shutting the combustor of one engine down (scenarios 1-3) reduces the number of operating hours on that engine, but necessitates additional starts, which are accounted as additional cycles. As most engines have spare cycles when they hit the limit of allowed maximum hours, this would not significantly reduce maintenance time, but on the contrary reduce operating hours. Thus these modes have the benefit of longer maintenance intervals, which can even be elongated further by alternative use of the engines. In scenarios 4 and 5, the accumulated number of cycles is not changed. These procedures may be advantageous, if the idling time can be accounted with a reduced weight in the overall operating time - e.g. by using an engine monitoring system. In general all proposed operational modes show potential for economic benefit.

4.3. Helicopter Safety

Shutting one engine down during flight raises significant safety concerns and requires careful certification consideration in case of failure of the running engine. In normal twin engine operation, the remaining engine will immediately enter an OEI mode delivering emergency power almost instantly. In single engine operation significant time is required to get the second engine back to power. Even if the emergency is detected automatically, the start-up to idle requires about 25 seconds. This interval can slightly be reduced by improved fuel flow control or reduced inertia of the rotors. The acceleration from idle to full power consumes about 4 seconds. Some details are discussed in [9]. During this interval the helicopter operated in autorotation will lose 15 – 20 meters of height per second [1], which accounts for an overall loss in height of 400-550 meters. Yet all these considerations do not include typical reaction times of the pilot, which has been investigated in [14], thus the real event will be even more critical.

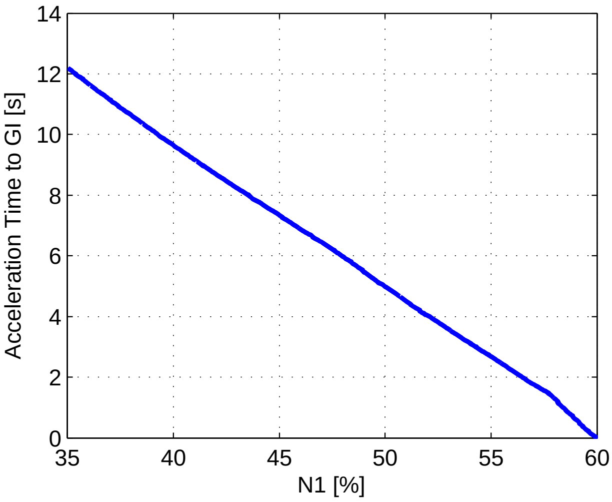

Figure 5: Measured engine acceleration time to GI

Shorter acceleration times are to be expected for the engines in idle or sub-idle operation, as the combustor is still running. For engines in idle mode, just the above mentioned 4 seconds are required. For sub-idling machines, measurements have been made on the TUM test bed. The results are displayed in Figure 5. There exists a nearly linear relation between reduced N1 and acceleration time. Up to 12 seconds are required to restore the normal idle speed, which again results in a significant loss in height.

All these aspects underline the necessity for a quick start mechanism of the engine to ensure full power operation in as little time as possible. A suitable system is introduced and investigated in chapter 6, which will even enable scenario 1 to approach certification.

4.4. Emissions

The operational strategy of the engines will change the overall emissions. This has been investigated for scenarios 1 – 4. For sub-idle operation (scenario 5) no emission data were available. Running the engine in an idle or sub-idle manner will increase the overall emissions, as negligible power is delivered with notable emissions.

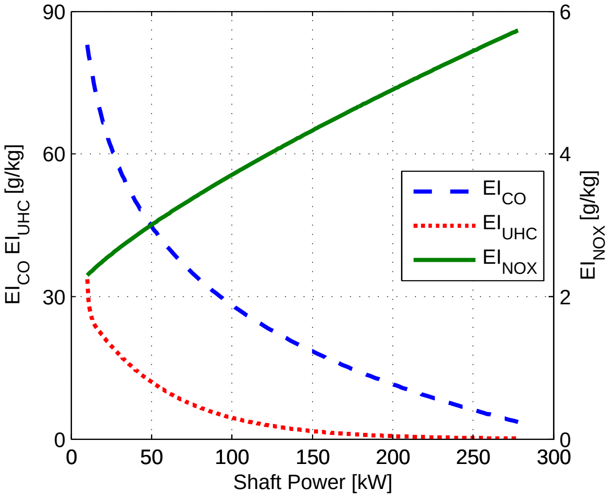

Figure 6: Emission Indices of the Allison engine [8]

Figure 6 presents the emission characteristics of the Allison 250 engine regarding CO, UHC, NOx, based on measurements by Lang [8]. While CO and UHC reduce with power, NOx increases significantly with combustion temperature regarding of the emission indices, which weight the emission mass flow in relation to the overall fuel flow. A more adequate calculation is the absolute mass flow. It is shown in Figures 7, 8, 9 normalized with the emission flow of normal twin engine operation. The engine, which delivers the overall power, runs at high efficiency delivering low values for CO and UHC, while as expected the NOx is even higher than in normal operation. This tendency can be identified for all operating scenarios. The Allison 250 contains relatively old combustion technology, thus it can be expected, that current modern gas turbines will have lower NOx emissions. The tendency of an increase in NOx with power is natural chemistry and cannot be changed.

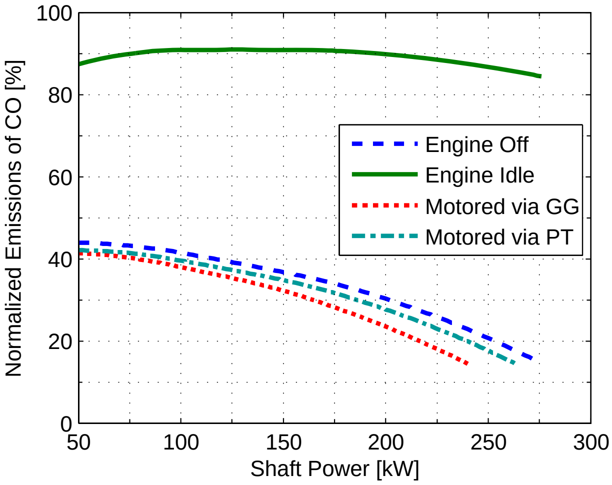

Figure 7: Normalized Emission of CO

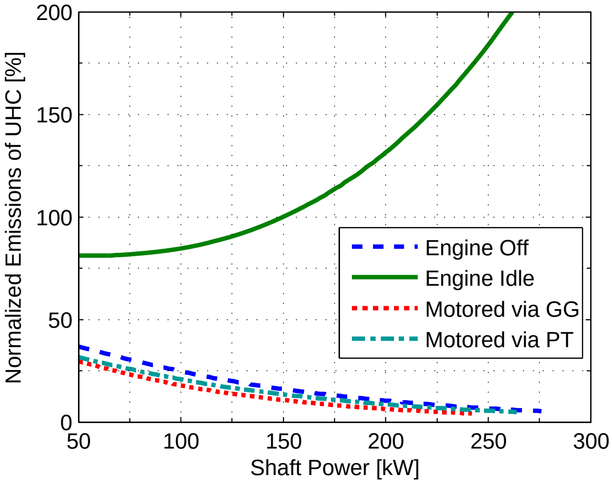

Figure 8: Normalized Emission of UHC

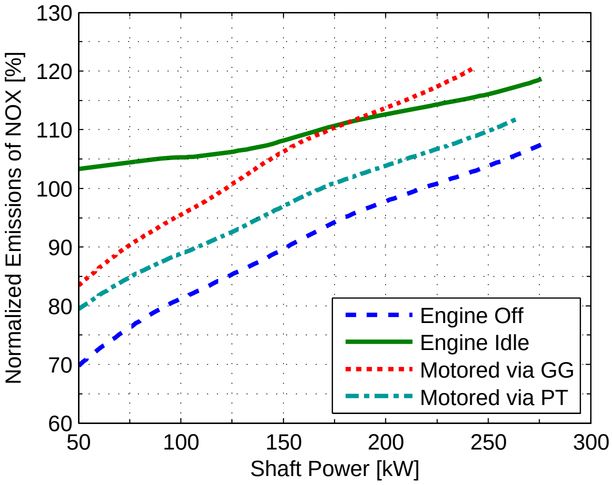

Figure 9: Normalized Emission of NOX

5. ENGINE QUICK START

To significantly improve safety of a helicopter, which runs with one engine shut down during low power operation, the acceleration time of the not operated engine to full power needs to be shortened. Major time is lost for the start-up to idle, which accounts for up to 25 seconds.

Several systems have already been presented [6], [11]. Some of the proposed systems apply higher torque via the starter drive to the GG spool. This can be realized by several means:

1. a stronger starter motor,
2. an additional hydraulic motor,
3. an additional pneumatic motor.

However, the maximum allowable torque is very often limited by the gearbox itself or by the relevant drive. For the Allison 250 a value of 60 Nm is given [4]. Therefore concepts are to be sought, which apply additional energy independently of the gearbox. Examples are:

1. Connecting the GG spool of the inoperative engine to the helicopters main rotor via a clutch system,
2. Installing a cartridge starter which provides hot pressurized gas for the HPT of the engine,
3. Integrating impingement nozzles at the compressor impeller, which are bled through by external pressurized air.

Careful evaluation of these systems revealed, that the impingement nozzles offer the highest potential for quick start at most reasonable cost. This concept has been implemented into the TUM test engine. First results are presented in the following.

6. ENGINE MODIFICATIONS

6.1. Design

The engine Allison 250 provides an axial compressor combined with a last radial stage. Mostly, modern helicopter engines use a two stage radial compressor. The modification presented here is only introduced within the area of the radial impeller and thus is thought to be applicable for modern engines too. The aim of these first investigations is the proof of concept.

The newly introduced nozzles are positioned at a radius and an angle, providing highest effect onto the acceleration of the impeller and thus onto acceleration of the complete GG. As a side effect the injected pressurized air immediately increases the mass flow through the combustion and through the turbine, supporting the acceleration even further.

First design investigations were based on the original casing of the radial compressor unit. It turned out to be highly complex to modify this steel part, which belongs to the structural main path of the engine, but only offers a material thickness of up to 3 mm. As a compromise, a newly designed aluminum casing was used, in which the nozzles were integrated. Whereas the inner contour was maintained, it goes without saying, that the changes in material and wall thickness significantly influence the thermal behavior of the casing and thus the compressor tip clearance. While this will change high power efficiency, it is thought to have a minor effect onto the starting behavior, which is in the focus of these investigations.

The nozzles were distributed asymmetrically around the circumference to avoid both, collision with accessories and resonance excitation of the blading. The principal design is shown in Figure 10. The modified compressor casing is shown in blue, the nozzles in orange and the impellor blades in red. The unchanged original parts are colored in brown.

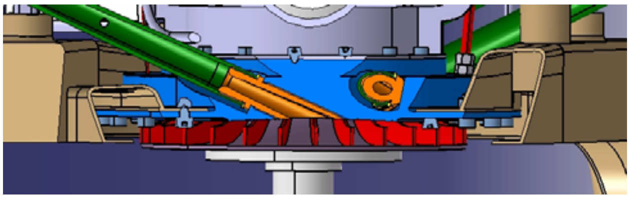

Figure 10: Rendering of the compressor casing

The overall setup at the test bed is shown in Figure 11. The axial compressor part is at the right. The centre of the picture shows the modified impellor casing, which is provided with the required quick start air via a simple high pressure tube. The rectangular pipe on the lower left is one of the two original and unchanged channels connecting the exit of the compressor to the combustor. The high pressure reservoir is not shown. A simple diving bottle (length: ~ 0.6 m, diameter: ~ 0.14 m) is satisfactory for one start. This underlines the weight advantage of this system over the introduction of any clutch system.

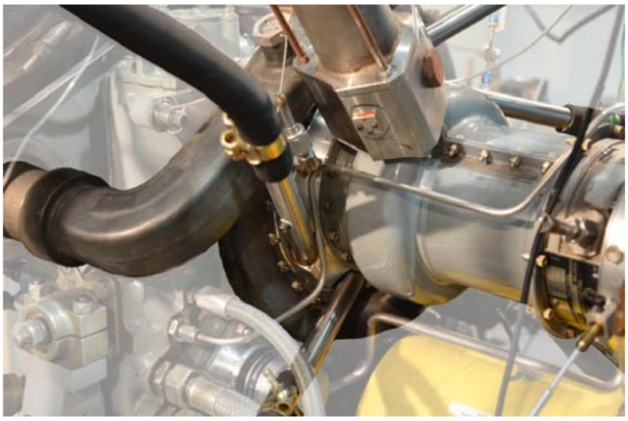

Figure 11: Integrated compressor casing

6.2. Performance of the quick-start system

The additional air in the hot engine section allows an increase in fuel flow over time during the start-up, which was implemented by simply modifying the test bed FADEC. The nozzles were provided with air at a pressure of 13 bars and with a mass flow of 0.5 kg/s. During the first test run, the engine ignited safely and accelerated to GI within 2.4 seconds, which is a reduction by 23 seconds. As during helicopter operation the quick start system will be used only once, a total mass of pressurized air of 1.5 kg is sufficient.

A typical acceleration curve N1 over time is plotted in Figure 12. During quick start, both the electric starter and the nozzle system are used.

An even more realistic setup has been demonstrated by applying a continuous brake torque of 100 Nm to the engine´s power turbine while starting. Again the FADEC was modified. The engine was directly switched from “off” to “flight” whereby “idle” was completely skipped. The N1 limiter was set to 93 %, which is equivalent to about 200 kW of power, to avoid engine damage. Typical data of this powered start are displayed in Figure 13. Starting time is increased, but significant power is available after 4 to 5 seconds. Almost full power is available after 8 seconds. This compares to about 30 seconds for an unmodified engine. Based on this data and the assumptions presented in chapter 4.3 the quick start system reduces the loss in height of the helicopter in case of engine emergency from 400 - 550 meters to 150 – 200 meters, which underlines the high potential of the system.

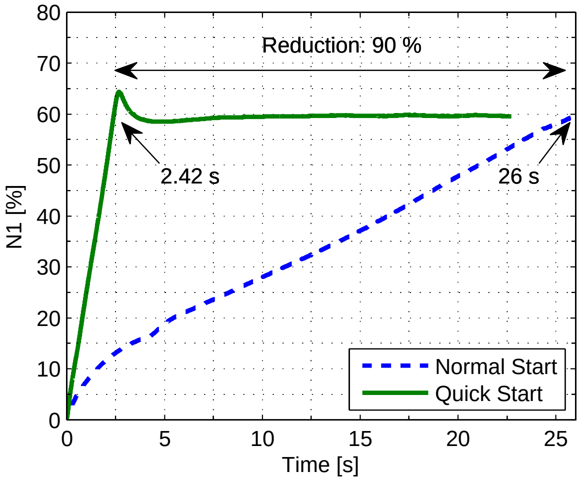

Figure 12: Comparison of a normal and a quick start

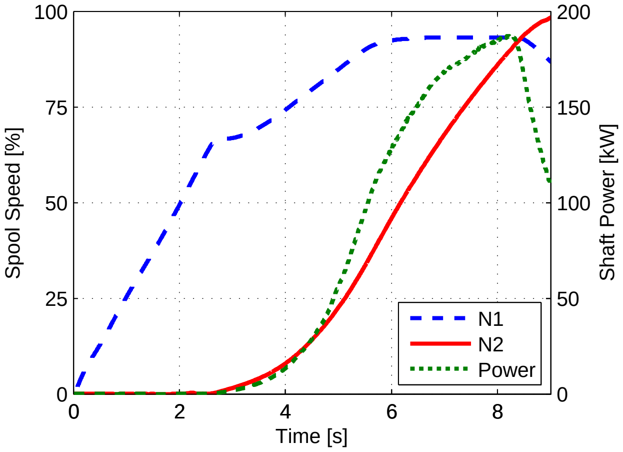

Figure 13: Engine quick start to full load

6.3. Efficiency Impact

The modified compressor casing of the TUM test engine and the implementation of the bleed nozzles will have an effect onto tip clearance and aerodynamic losses and consequently onto overall performance of the engine system. Thus comparisons of the compressor characteristics and of the overall performance levels between the engine with and without modifications have been made.

Figure 14 shows pressure ratio and isentropic efficiency versus corrected mass flow of the compressors for both engine builds. Pressure ratio was maintained with a small increase at low and high mass flow. This slight increase improves the thermodynamic efficiency of the overall cycle and will balance other losses. As expected, efficiency was deteriorated over the whole operating range due to the losses introduced by the nozzles.

Figure 15 summarizes the combined effect of all alterations. The upper graph shows the absolute numbers, while the lower one shows the relative difference. At low power conditions the implemented losses predominate and up to 1 % of additional fuel flow is required. At the most relevant high power end, the increased pressure ratio improves the overall thermodynamic efficiency in such way that even lower fuel flows are required for the same power output. All in all it can be summarized that the introduction of the nozzle bleed system has not deteriorated the overall performance in any unacceptable manner.

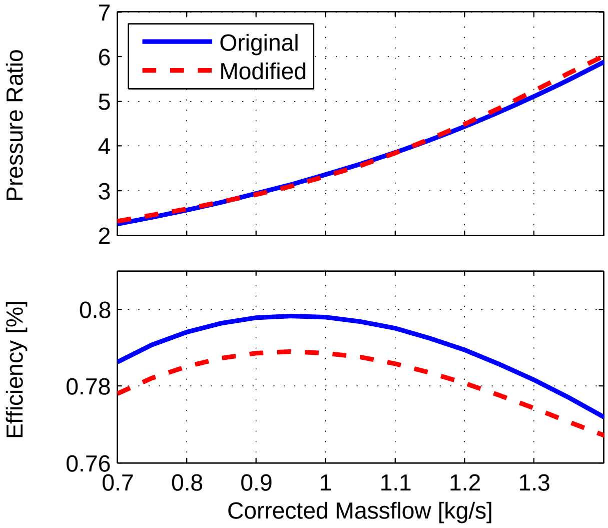

Figure 14: Compressor performance before and after the modifications

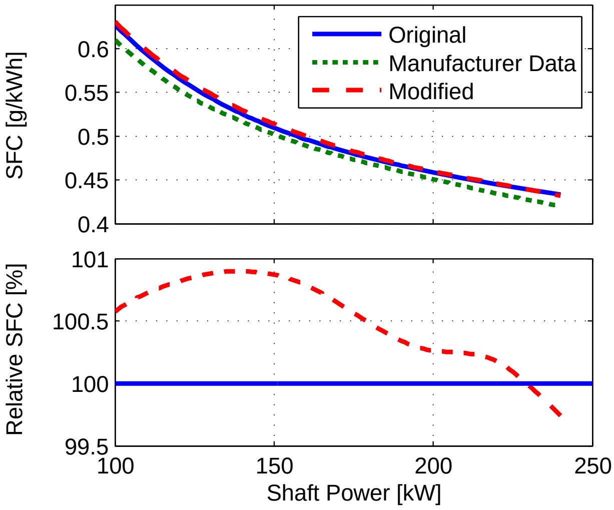

Figure 15: Engine performance before and after the modifications

7. CONCLUSION AND OUTLOOK

A significant amount of fuel can be saved by operating twin engine helicopters with just one engine during low power demand, e.g. during horizontal flight. Highest potential, which means up to 30% reduction in fuel flow can be reached by any system in which the idling engine is switched off. This introduces serious safety concerns for the case of a main engine failure.

A system has been developed and demonstrated that brings the non-running engine back to high power within 8 seconds in comparison to 30 seconds for the normal run up. The system only requires a slight modification in the radial compressor in order to introduce an acceleration system via bleed air and does not compromise overall engine performance.

Future work will optimize the nozzle design to reduce aerodynamic losses. As the system has so far only been demonstrated at one engine, it will be implemented and investigated at a more modern high power engine following current design principles. Additional aspects like temperature gradients and resulting stresses during quick start need to be considered as well.

8. ACKNOWLEDGEMENTS

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