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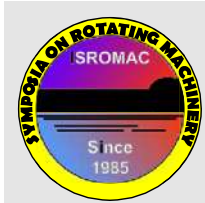
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# Experimental Investigation of an Engine Quick-Start System with Compact Air Supply for Rotorcraft Application

Martin Kerler<sup>1\*</sup>, Christian Schäffer<sup>1</sup>, Wolfgang Erhard<sup>1</sup>, Volker Gümmer<sup>1</sup>



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## Abstract

A quick-start system for turboshaft engines is an appropriate method to enhance safety and the flight operation range of a helicopter during intended single engine operation. Such a system was designed and successfully tested at the institute. However, the quick-start system used shop air of 13 bar(a) pressure for proof of concept. The shop air supply has to be replaced by an airworthy, compact and lightweight air supply system for feasible rotorcraft application. This comprises in first case general identification of adjustable system parameters by numerical studies and experimental tests in consideration of certain system constraints. Therewith, the ideal nozzle count is determined to 3 and the required nozzle entry pressure has to be about 19 bar(a). Based on these findings the final air supply system for rotorcraft application is designed and simulated with ESPSS. This system is built up at the engine testbed with some modifications for experimental testing. Gas generator acceleration tests as well as engine starting tests to idle speed are performed with the new system. A final engine start-up time of 2.8 s was achieved. Finally, further advice is given for feasibility.

## Keywords

Turboshaft, Engine, Quick-Start, Helicopter, Air Supply

<sup>1</sup>Institute for Turbomachinery and Flight Propulsion, Technical University of Munich, Garching, Germany

\*Corresponding author: martin.kerler@tum.de

## 1. INTRODUCTION

Future challenges in rotorcraft and propulsion design are diverse. Governmental regulations are tending to achieve a reduction in carbon emissions of engines and lowering the noise level of rotorcrafts. More strict regulations will apply in the future [1]. Then, rotorcraft operators claimed the development of efficient engines with significant lower fuel consumption a few years ago, due to high fuel prices. In addition, lowering other direct operational costs as well as maintenance and repair costs is crucial for the success of future rotorcrafts [2]. An entire new development of a complex system like an engine or rotorcraft is often usually risky and costly in terms of time and money. Some objectives can be partially achieved due to evolution of available and reliable technologies.

### 1.1 Potential of Intended Single Engine Operation

On account of this, a flying technology demonstrator was introduced by Airbus Helicopters in 2015. This rotorcraft called Bluecopter [3] (see Fig. 1) should comprise besides aerodynamic improvements also a modified operational usage strategy of the installed turboshaft engines for fuel saving. The helicopters original powertrain design is mainly driven by safety reasons. Thus, two engines are installed to cover an engine failure during flight and avoiding autorotation mode. Due to this requirement, the installed maximum engine power exceeds by far the usual required power during ordinary helicopter flight missions. The engines are loafing most of the mission time at part load at worse specific fuel consumption (SFC) [4]. To resolve this predicament, a modified operational usage strategy can be an intended shutdown

of one engine at appropriate helicopter flight states. Then, the shut off engine does not burn any fuel and the remaining running engine has a better SFC by means of higher power loads.



Figure 1. Bluecopter Demonstrator of Airbus Helicopters. (Image: Airbus Helicopters, Charles Abarr)

This can be observed in Fig. 2 in the power required range in which ISEO mode is possible. Here, a sample engine with max. 500 kW output power is used. Overall, this results in significant fuel savings up to 20% depending on the flight mission [5]. The savings can be used either for extending mission range and mission time or overall fuel burn. However, if this intended single engine operation (ISEO) strategy is applied on current powertrain designs, neither low and high speed flights nor steep climb flights are possible during ISEO. The required power of these flight states exceeds the available maximum continuous power (MCP) of one engine. The fuel advantage of ISEO is also a drawback for flight safety.

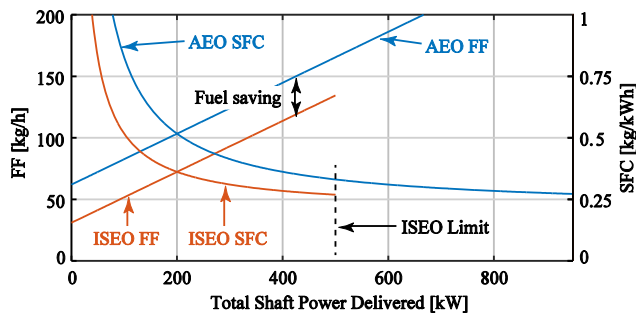


Figure 2. Fuel saving potential due to use of ISEO at appropriate flight operation. (similar to [3])

## 1.2 Flight Safety and Capability Enhancement with Engine Quick-Start

During ISEO flights, the twin-powered helicopter is just like a single engine powered helicopter. In case of an engine failure, flight cannot be maintained and autorotation has to be initiated. A solution to ease this emergency situation is a re-start of the engine which was shut off before due to switching in ISEO mode. Regular starts to idle of turboshaft engines of 500 to 1000 kW class are up to 30 s. Further time is elapsing until sufficient shaft power can be provided. A helicopter has sink rates of about 8 to 15 m/s which means in worst case the helicopter has lost about 700 m of altitude until engine power is available again. Thus, sufficient altitude margin must be available during active ISEO. This cuts the flight envelope of the helicopter and the reasonable usage of ISEO. A solution to overcome this drawback is a reduction of the turboshaft engine's start-up time.

### 1.2.1 Evaluation of Engine Quick-Start Methods

An engine quick-start (QS) can be achieved by additional acceleration torque for the gas generator GG provided by a technical device. Pascoe [6] gives a general overview of common gas turbine start devices. Hull and Santo [7] made an evaluation of suitable devices for high torque demands, too. One system comprises a hydraulic motor with an appropriate hydraulic system of high pressure. Experimental tests of the system were promising but the prerequisite of a hydraulic system for proper operation may not apply for a helicopter due to excessive additional weight. Another method is Hydrazine impingement or cartridge impingement. This is realized by directing a hot gas stream of high velocity onto the blades of a GG turbine stage. However, the hydrazine solution has many drawbacks like costs, complexity and health hazards and is thus, not really a practical solution. The cartridge impingement requires for operational usage

too much installation space and has to be replaced after each use [7]. Since the required system for quick starts should be an emergency system, the replacement after use is not an issue. But installation space is restricted at helicopters. Thus, this variant seems not really applicable for a compact and lightweight quick-start system (QSS). Rodgers [8] picks up the basic idea of impingement nozzles but utilizes high-pressure air or hot-gas as propellant at the turbine. The hot-gas was of approximately 533 K and the gas generator was accelerated just to 4770 rpm. Due to radial turbine design and its operational principle, a less nozzle expansion efficiency [8] and therewith lower acceleration rates were achieved. Another problem which cannot be satisfactorily resolved is the required proper long term storage of pressurized air at temperatures above 500 K. A gas impingement at the compressor section was also investigated by Rodgers [8]. Utilization of pressurized gas seems feasible and compressor shroud impingement was the most convenient method for GG acceleration with impingement nozzles [8]. QS tests of a gas turbine with 260 kW power output were conducted with compressed nitrogen at several operating conditions. Start times could be reduced by 55%. More results of this investigation can be found in [8] and [9].

### 1.2.2 Design of a Quick-Start System for the Allison 250

Based on these findings, a QSS comprising impingement nozzles directing a gas jet onto the trailing edge of a radial compressor rotor seems to be a proper solution. However, the use of compressed nitrogen seems not feasible, since it cannot be used for combustion during QSS operation. This would not be an issue if the compressor is regularly operating during QS. But the compressor of Rodger's experiments did not. Compressor surge and backflows out of the compressor occurred. This means, the compressor does not deliver any air for combustion during QS. Thus, regular air injection instead of nitrogen would be the better case, since this air can be used for combustion. For proof of concept with a common helicopter turboshaft engine, the institute's Allison 250-C20B was chosen. The engine is fully functional as well as instrumented for further performance analysis. The modular design of the engine enables an easy replacement of engine modules. MCP is about 300 kW and the compressor has a radial last stage. Thus, this engine is similar to the engine modified by Rodgers [8]. Hence, the Allison QSS has similar design parameters as the QSS of Rodgers [9]. The new compressor casing is equipped with de Laval nozzles which are asymmetrical positioned in circumferential direction due to available design space and to avoid harmonic excitation (see Fig. 3).

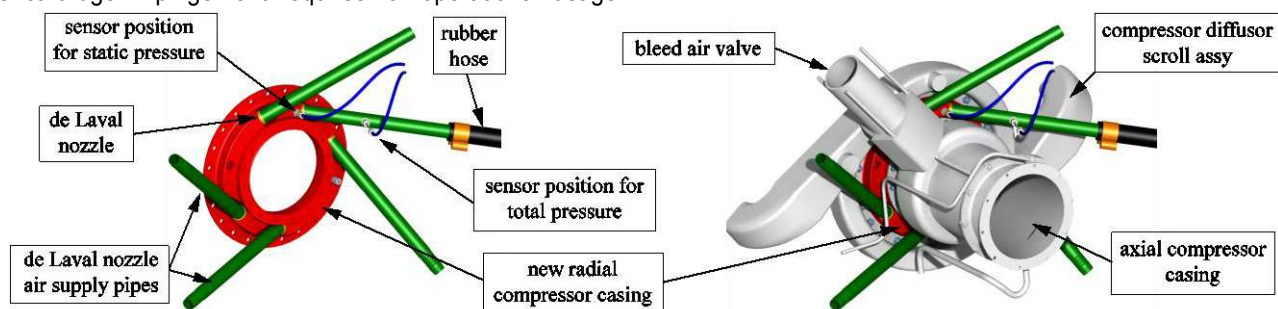
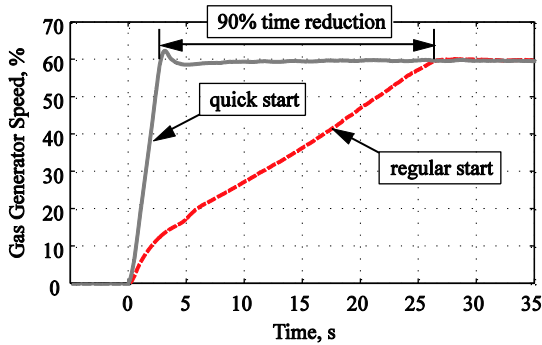


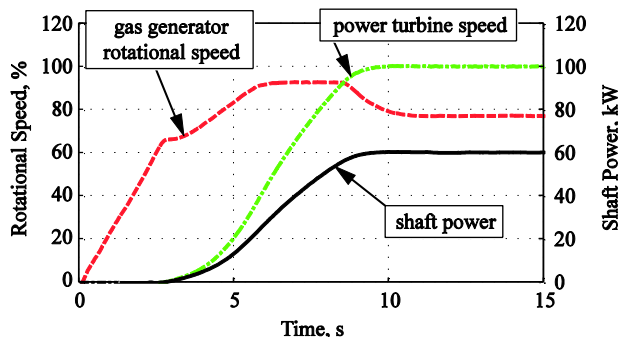
Figure 3. New radial compressor casing with 5 nozzles, supply pipes and its integration into the compressor section.

With these restrictions a maximum nozzle count of 5 is possible. The angle of the injected air is defined to provide best impulse propagation to the impeller's trailing edge and to allow proper connection to an air supply. The available shop air for nozzle supply has a static pressure of about 13 bar(a). This QSS with shop air and 5 nozzles is called Testbed Quick-Start System (TQSS). Due to total pressure losses caused by valves, pipes and hoses the nozzle entry working total pressure is about 12.3 bar(a). Based on these specifications and with a required start performance of less than 3 s from off-state to idle, the calculations revealed the following nozzle parameters. The nozzle's throat diameter is 6.6 mm which means an air mass flow of 0.1 kg/s resulting in 0.5 kg/s overall air mass flow. The design Mach number of the nozzle is 2.3. Operation time is 2.2 s. During GG acceleration, the starter motor is also working. Approximately 0.85 s from off-state, ignition of the injected fuel takes place and the high pressure turbine supports the GG acceleration. Finally, start-up time was reduced by over 90% from 26s to 2.4 s for ambient conditions close to the International Standard Atmosphere at sea level at a Standard Day (see Fig. 4).



**Figure 4.** Allison 250 ground idle start times of a regular engine start and a quick-start [10] [11].

For sufficient power delivery, the GG has to be further accelerated. Initial conservative tests were performed with 100 Nm brake torque preset at the testbed. As Fig. 5 shows, 60 kW (equals 20% of MCP) is available within approximately 8 s from off-state. Further details on design and initial testing of the Allison QSS supplied with 13 bar(a) shop air can be found in Hönle et al. [10] and Hönle [11]. These results show the successful proof of concept of a TQSS for a turboshaft engine of 300 kW power class.



**Figure 5.** Power delivery curve after performing a quick-start to FADEC mode "flight" [10] [11].

The TQSS is supplied at this development stage with shop air which is not available in a rotorcraft. Hence, the next step is design and test of a pressurized air supply system which can be integrated into a helicopter airframe. If an existing airframe is used, extensive structural airframe modifications have to be avoided and the system must be compact as well as of lightweight design.

## 2. DESIGN PARAMETERS IDENTIFICATION

Prior to final airworthy design, adjustable design parameters of the QSS have to be identified. Due to cost-containment and development time optimization, the components of the air impingement system (AIS) are predefined and thus the modified compressor casing as well as the nozzles cannot be modified or exchanged. Consequently, changeable parameters are on the air supply system (ASS) side. The ideal acceleration torque  $M_{QSS,id}$  is basically the result of the relative nozzle forces  $F_{noz}$  to the surface of the trailing edge of the radial compressor and the distance  $r$  from the origin of force to the shaft axis. Since the acting force of the nozzle's jet is not perpendicular to the trailing edge, the relative deflection angles  $\alpha$  and  $\beta$  have to be considered (see Eq. 1). These angles are based on design space restrictions. Further information about this can be found in Hönle [11]. Hönle sets the transfer efficiency  $\eta_{noz}$  of the force between nozzle and trailing edge for an initial TQSS design to a fixed value of 0.7 based on literature data. Later on (see section 4.1.) this value is redefined.

$$M_{QSS,id} = \sum_{i=1}^n \eta_{noz} \cdot r \cdot F_{noz,i} \cdot \sin(\alpha) \cdot \sin(\beta) \quad (1)$$

Each nozzle has the same distance to the axis as well as the same deflection angles. Thus,  $M_{QSS}$  varies with varying nozzle force  $F_{noz}$ . This force can be adjusted by changing nozzle mass flow  $\dot{m}$ , nozzle exit velocity  $v_{noz,exit}$  or the nozzle count  $n$  (see Eq. 2).

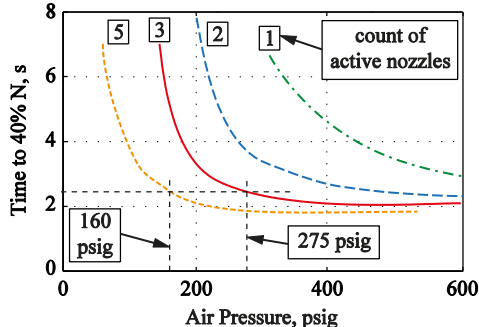
$$\sum_{i=1}^n \frac{dI_{air,i}}{dt} = \sum_{i=1}^n F_{noz,i} = \sum_{i=1}^n (\dot{m} \cdot v_{noz,exit})_i \quad (2)$$

Since weight saving is important for helicopters, QSS nozzle count reduction saves weight due to fewer parts. To keep  $F_{noz}$  at the same level, mass flow or exit velocity has to be increased. The nozzles of the QSS are basically operating at choking conditions and consequently the air mass flow  $\dot{m}$  does not depend on the ambient pressure at nozzle outlet anymore. A feasible exit velocity increase is not possible. The geometry of the nozzle and thus the critical throat cross section area  $A^*$  is fixed. Since variation of gas constant  $R$  and isentropic coefficient  $\kappa$  are negligible, an air mass flow  $\dot{m}$  change can only be achieved by change in total temperature  $T_t$  or total pressure  $p_t$ . This relationship is depicted in Eq. 3.

$$\dot{m} = A^* \cdot \sqrt{\frac{\kappa \cdot (1 + \kappa)}{2 \cdot R \cdot T_t}} \cdot p_t \cdot \left(\frac{1 + \kappa}{2}\right)^{\frac{-\kappa}{\kappa-1}} \quad (3)$$

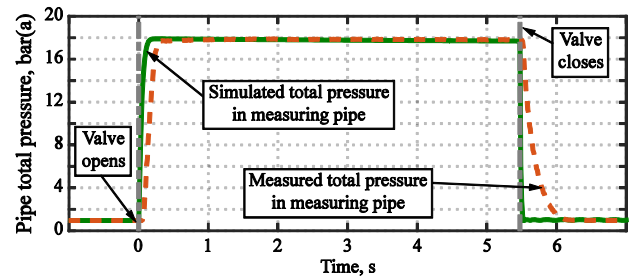
A lower gas temperature  $T_t$  results in higher mass flow. A temperature drop by approximately 30 K would increase the air mass flow in best case by only 6%. A device to reduce the temperature in front of the nozzles seems not reasonable because of high air mass flow rate and low cooling effectiveness. Finally, if nozzle count is reduced, the nozzle entry total pressure has to be increased.

For a final compact QSS (CQSS) design this appropriate pressure level has to be identified. Similar tests were performed by Rodgers [9]. He measured the acceleration time until 40% of the GG speed is reached, depending on nozzle count and nozzle entry pressure (see Fig. 6). These tests were declared as cold-crank test, which means no additional acceleration torque, like electric starter or turbine operation, was used. With a nozzle pressure of about 160 psig (~11 bar(a)) and five active nozzles, the start-up time is about 2.45 s. This performance can be also achieved by three nozzles and an increased pressure of 275 psig (~19 bar(a)). Further pressure increase reduces the nozzle count to two or one. But this means very high nozzle entry pressures which are difficult to deal with in an helicopter environment. Finally, increasing nozzle pressure for better start-up performance is only reasonable up to a certain pressure level.



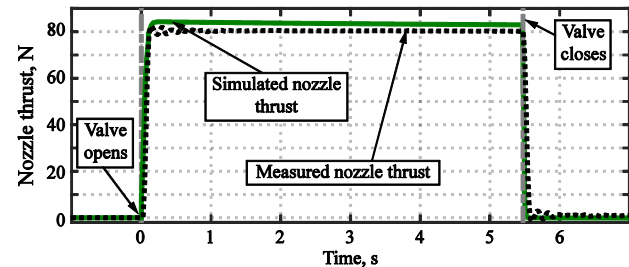
**Figure 6.** Start-up time to 40% design gas generator speed depending on nozzle count and nozzle entry pressure [9].

It was decided to realize the CQSS with three active nozzles. One reason was to have them almost evenly distributed in circumferential direction to reduce excessive radial loads on the shaft bearings. Based on analytical start-up performance calculations, each nozzle must provide a thrust of approximately 83.5 N. For verification reasons, simulations and experiments were conducted to find the appropriate pressure level. The simulations were done with the simulation tool ESPSS. Further information about this tool can be found in Isselhorst [12], Pérez-Vara et al. [13] and Moral et al. [14]. A compressed air cylinder bundle, a pressure regulator and a coaxial valve are main components of the experimental set-up (see Fig. 9). Further information about this set-up is given in Kerler et al. [15]. Evaluation of the simulation results revealed a nozzle entry total pressure of about 18 bar(a) (see Fig.7).



**Figure 7.** Total pressure in measuring pipe short before nozzle entry – experimental and simulation results [15].

The total pressure measured inside the measuring pipe was 17.9 bar(a). A measured thrust of about 80 N is achieved with this pressure. The simulated thrust is 83.5 N (Fig. 8). The differences between both values rely on measurement accuracy as well as manufacturing tolerances. The load cell which measures the thrust has an uncertainty of measurement of about 1% of its whole measurement range. This means, the maximum error can be up to +/-5 N. In addition, further flow effects inside the measuring tube may influence the result, too. The slower increase in pressure of the measured curve depends mainly on the response time of the pressure transducers. The results are very satisfying and define objectives for the CQSS design.



**Figure 8.** Nozzle thrust – Experimental and simulation results [15] [16].

### 3. AIRWORTHY QUICK-START SYSTEM DESIGN

The design of the airworthy CQSS design is realized in two different ways:

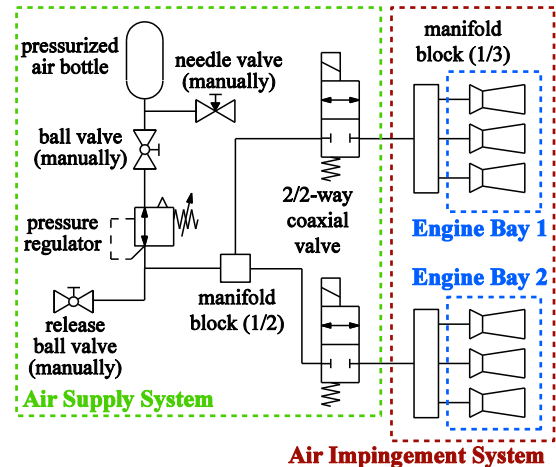
- The first one is to define a system with parameters of the airworthy one but realized with respect to ground test-bed application. This means, the used parts of the hydraulic sector are mainly not optimized for aerospace application. Therewith, a cost effective realization at the test bed is possible. Overall, this system is not optimized regarding weight and used space as well as regarding length of pipes and hoses. Furthermore, additional adapters are incorporated in the flow paths to offer measurement possibilities for temperature and pressure of the flow. These adapters are usually not required for helicopter application.
- The second design is based on the parameters of the first design and accounts especially for helicopter application with respect to lightweight design, compactness, safety, reliability and robustness. However, this system

is modeled just virtually and gives a prospect of how such an airworthy CQSS can look like.

### 3.1 Basic considerations for experimental CQSS design for testbed application

The CQSS for testbed application is designed in a way which comes close to the CQSS for helicopter application. But instead of expensive aerospace certified components, the testbed setup is realized with widely used parts of the hydraulic sector. In general, the CQSS has a mass flow of 0.5 kg/s and an operation time of approximately 2.2 s, resulting in an air mass demand of 1.1 kg at a pressure level of about 18 bar(a). The equivalent air volume is 50 l at 18 bar(a) pressure. However, for any kind of reasonable air-frame integration, this volume is far too big. Feasible cost effective high pressure sources are pressurized bottles for diving applications. These are available with pressure levels up to 300 bar(a). Since the institute is owner of a 200 bar(a) air pressure pump, a pressure bottle of maximum 230 bar(a) working pressure is a reasonable choice. These bottles have standardized connecting screw diameters of 25 mm offering sufficient flow path diameter. Based on the requirement of having the capability for two consecutive QS, the bottle volume was determined to at least 15 l. A minimum pressure level of about 80 bar(a) inside the bottle ensures at all operation times the required overall mass flow of 0.5 kg/s. An adapter for pressure and temperature measurement as well as refilling the bottle is connected to the bottle. Further downstream is a ball valve which is closed for refilling process and opened when the CQSS is armed for operation. The bottle pressure has to be reduced to the nozzle working pressure of 18 bar(a). This is realized with a pressure regulator which can handle 300 bar(a) input pressure and provides an output pressure range up to 100 bar(a). The required output pressure of the pressure regulator is higher than 18 bar(a) because further downstream is a pressure releasing valve and other devices causing total pressure loss. This pressure regulator output pressure is found by a parameter study with ESPSS. Between ball valve of the bottle adapter and pressure regulator is a measuring adapter offering static pressure measurement and recovery temperature measurement. This device is also available after the pressure regulator. Then, between pressure source and AIS is a coaxial valve to release the pressurized air to the nozzles. Such a valve is the best choice regarding weight and high flow rates as well as safety and compactness. Another aspect is the fast response time. Opening and closing times are about 0.1 s. Besides these main components, some other components are required like flow distribution manifolds, adapters and valves as well as sensors for system health monitoring. The diameter of the flow paths cross section areas are defined to realize slow flow velocities inside the manifolds, adapters, pipes and hoses. A slower velocity causes less total pressure losses. Thus, a trade-off between pressure loss, cross section area and weight has to be found. In this case, flow velocities with a maximum of Mach 0.3 are acceptable. Significant further compressibility effects can be avoided.

Fig. 9 shows the scheme of the system's final design for integration in a twin engine powered helicopter.

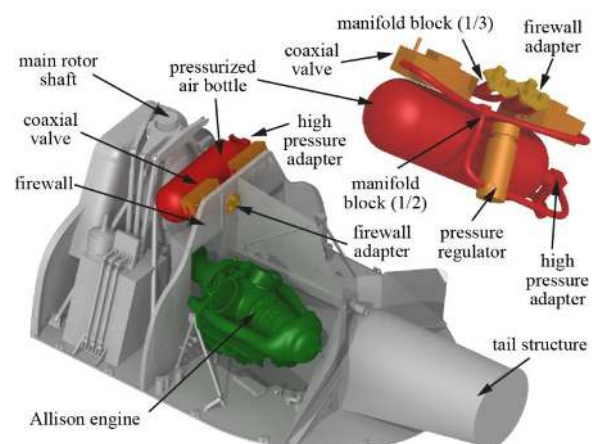


**Figure 9.** Scheme of an airworthy QSS for testbed application and helicopter integration.

In general, the ASS comprises one bottle and one pressure regulator. After the pressure regulator, the manifold block (1/2) splits the one flow path into two feeding lines for both engines. This junction is not needed and thus not realized for the CQSS at the testbed. Further downstream is the coaxial valve and another manifold block (1/3) where the single feeding line for the engine is divided into three supply lines for each nozzle of the AIS. The control of the CQSS is integrated in the engine controller.

### 3.2 Basic considerations for an airworthy CQSS design for helicopter application

Since lightweight is crucial, regular bottles made of steel are too heavy. Thus, a high pressurized air tank made of composite material is a good choice. Here, already aerospace certified pressure bottles made of carbon and glass fiber with aluminum liner and 300 bar(a) working pressure are available. Since the maximum pressure is greater than the 200 bar(a) used in the testbed solution, the bottle volume may be reduced for further weight saving. A possible integration of the system in a BO 105 helicopter is illustrated in Fig. 10.

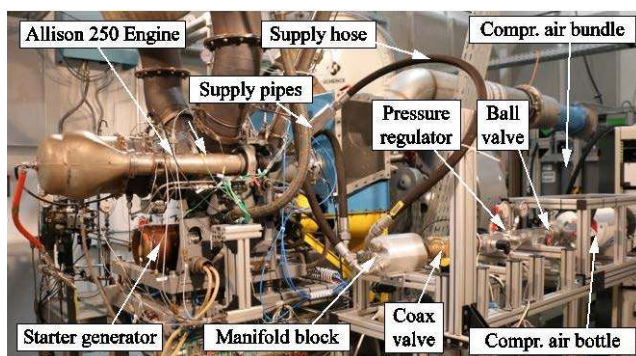


**Figure 10.** CAD model of a possible QSS arrangement within the BO 105 fuselage.

This airworthy CQSS has a weight of 46.4 kg using common components [16]. If special optimized components are used, the weight can be reduced to approximately 36 kg. All main components are located in the helicopter main transmission compartment due to safety reasons. None important component should be integrated into the fire risky engine bays. The CQSS fits almost into the transmission compartment. For this design, some small modifications of the engine cowlings have to be done. An advantage of this CQSS location is its closeness to the helicopter's center of gravity since helicopters are sensitive to center of gravity changes. Further details of the design can be found in Kerler et al. [16]. Between bottle and pressure regulator is an adapter and a ball valve. The adapter is used for bottle condition monitoring as well as for bottle pressurization. The ball valve is required for safe bottle replacement. For weight saving, only one bottle is used to supply both AIS of the engines with pressurized air. This means, a manifold block with two output lines (1/2) is used between the pressure regulator and the coaxial valves. This manifold block is missing in the testbed CQSS.

#### 4. EXPERIMENTAL RESULTS

The testbed QSS was set up as described in section 3.1. An overview of the installation gives the image in Fig. 11. The ASS and the (1/3) manifold block are mounted on a moveable rack. The supply hoses of the AIS can be quickly disconnected from the supply pipes. This arrangement allows an easy removal of the CQSS from the engine itself. The compressed air bottle is mounted in an own rack which is located at the top of the ASS rack. Thus, the bottle rack can be detached easily for transportation to the refilling station of the institute. In the background of the image in Fig. 11 the compressed air bundle is visible. For first GG acceleration tests (described in section 4.1) the CQSS's compressed air source was the compressed air bundle. The output port of the bundle was directly connected to the pressure regulator. Since the 600 l volume of the bundle is 40 times greater than the bottle volume, the pressure regulator entry conditions of the air are nearly constant during the short test runs.



**Figure 11.** CQSS test setup with compressed air bundle and compressed air bottle at the Allison 250 testbed.

The experiments were conducted in four main test campaigns. The first two campaigns used the compressed air

bundle as pressure source. The other two used the bottle. Each campaign is split into a cold quick-start (CQS) and a hot quick-start (HQS). The CQS is without any fuel injection and thus no combustion takes place. This setup is used to determine general CQSS behavior and to investigate important CQSS parameters, for instance air temperatures in the supply pipes and at the pressure regulator as well as static pressures at these stations. The HQS is important to determine the overall QS performance and proper gas turbine operation during QS.

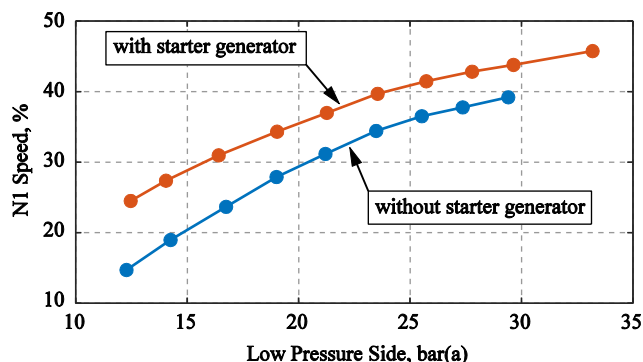
For temperature measurements thermocouples of type K and with a diameter of 1 mm are used as compromise for fast response and good durability. Signal conditioning was achieved with appropriate 7B modules of manufacturer Analog Devices. Final measurement accuracy is about  $\pm 2$  K. The recovery factor for calculation of static and total temperature is set to 0.85. Pressure is measured with pressure sensors type A-10 of manufacturer WIKA. The sensors were chosen in a way, that the maximum design pressure of the sensor is two times the expected pressure at the measurement position. The sensors have an accuracy of  $\pm 1.5\%$  of their range and a response time less than 4 ms. Total pressure measurements were realized with a pitot tube. The data acquisition system from manufacturer United Electronic Industries has a sample rate of 2500 samples per second for each measurement channel.

##### 4.1 Compressed air bundle – cold quick-start

For future rotorcraft application it was decided to reduce the nozzle count from five to three to save weight. This means, that the nozzle mass flow has to be increased to ensure the required overall 500 g/s air mass flow through the nozzles. Thus, the nozzle entry total pressure must be raised until each nozzle provides a mass flow of 167 g/s. How the engine behaves during a quick GG acceleration with just three nozzles and different nozzle entry pressures is investigated in the following.

The static pressure short after the pressure regulator was chosen as variable, since it can be easily adjusted with the pressure regulator. Downstream the pressure regulator is defined as low pressure side. These static absolute pressure values are on the x-axis of Fig. 12. On the y-axis is the resulting final GG speed after an acceleration time of 4 s. After this short time period the coax valve was closed. Longer valve operation was not required since the final QS should take less than 3 s. There was no combustion and the tests were conducted with and without the starter motor to identify the influence of the starter motor on the acceleration performance during acceleration as well. The test series was started with a similar pressure level like the proof-of-concept design. But due to pressure losses over pressure regulator and coax valve and losses caused by pipes and manifolds, the final nozzle entry total pressure drops to 5.2 bar(a). However, to finish the acceleration test series, the pressure level after the pressure regulator was further increased until the required nozzle entry total pressure of about 18 bar(a) was reached with setting the low pressure side to 33 bar(a). In Fig. 12 it can be seen as

well that the starter motor's influence gets less distinctive for greater GG speeds and therewith nozzle entry pressures. However, the additional rotational speed gain is between 5% and 10% and thus significant. This means, during QS the starter motor should operate to ensure greater GG accelerations. Both curves in Fig. 12 are leveling for greater nozzle entry pressures. An extrapolation of the red curve with starter motor support indicates a reasonable static pressure level after the pressure regulator of 33 to 35 bar(a). Pressure levels beyond these values would lead to insignificant additional GG speed gaining.

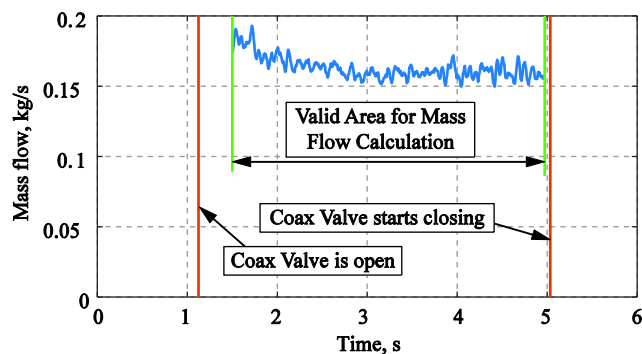


**Figure 12.** Allison 250 gas generator acceleration tests with compressed air bundle and with/without starter motor support

Similar tests were made by Hönle [11] with the TQSS. Here, the effective shaft torque was compared to the nozzle entry pressure. In addition some aspects are discussed about flow interaction of the air jet with the radial compressor. One of these is the definition of the real transfer efficiency  $\eta_{noz}$ . Hönle [11] sets it to 0.85 based on his findings.

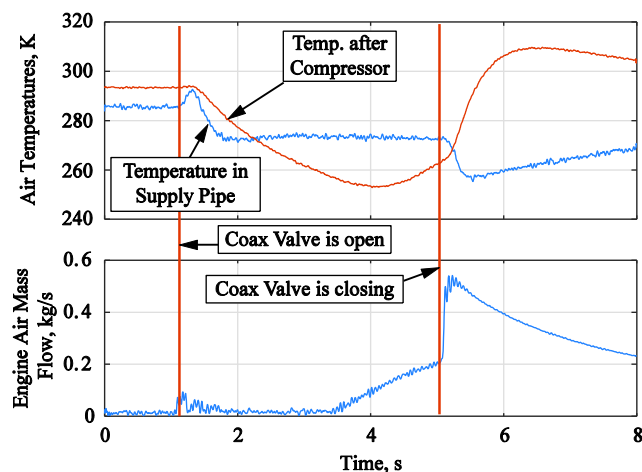
Besides the requirement of maximum GG speed gaining, the overall air mass flow provided by the three nozzles should be close to the 0.5 kg/s of the TQSS which is using shop air. This impinged air mass flow is also close to the air mass flow the engine is sucking in during idle mode. For nozzle mass flow calculation a supply pipe with measurement equipment is located upstream to one of the nozzles. Measured data are static and total pressure as well as the recovery temperature of the air flow. The mass flow can be then calculated with known geometry and Mach number. For this investigation, the CQS with compressed air bundle and a static pressure of 33 bar(a) at the low pressure side is used. This test is represented by the right most point of the red curve in Fig. 12. Due to aerodynamic effects and the measurement setup, valid mass flow results are available for a time period from 0.5 s after the open command for the coax valve until the close command. The calculation results are shown in Fig. 13. The slight descent of the mass flow curve is mainly caused by decrease of total pressure at the nozzle entry over this short time period. Since the pressure level in front of the pressure regulator is decreasing, the flow through the pressure regulator is also decreasing causing this decrease in total pressure inside the nozzle supply pipe. Calculations of the mean air mass flow during this time period of 3.5 s show a value of 0.163 kg/s. Since the first 0.5 s are not considered, the real averaged air mass flow may be slightly

higher. However, summing up all nozzles, an air mass flow of 0.489 kg/s is entering the Allison 250 engine, which is quite close to the required 0.5 kg/s. For further QS tests, the pressure right after the pressure regulator can be slightly increased.



**Figure 13.** Calculated mass flow (based on measured data) of one nozzle during CQSS operation

One crucial issue during QS to keep in mind is the air temperature of the expanded injected air. Since it is cooling down during expansion, it can cause thermal stress in the radial compressor. Then, it can be too cold for reliable fuel ignition inside the combustion chamber. The ESPSS simulations prior the experimental tests revealed air temperatures close to 200 K after the nozzle. In Fig. 14 the air temperature inside the supply pipe as well as the air temperature short after the compressor section is shown. Furthermore, the engine air mass flow at the engine inlet and the coax valve position is shown. When the coax valve is opened, the air between the valve and the nozzles is being compressed, indicated by the small temperature increase at time 1.1 s. After that, the expanded air from the air bundle is approximately 10 K colder than its storage temperature. After the valve was closed, the air inside the supply pipes gets colder due to further expansion to ambient pressure. Since the impinged air is further expanding, the temperature drops in the section after the compressor, which shows the red curve. The temperature drops until 251 K.



**Figure 14.** Static air temperatures of supply pipe and section after the compressor as well as engine air mass flow at the compressor inlet during QS.



At time 3.5 s the compressor has reached a certain rotational speed, where the compressor starts to act as it should be. This can be seen in the increasing curve of the engine air mass flow. Due to the compression, the compressed air's temperature is increasing and is mixing with the cold impinging air mass flow. Thus, the air temperature after the compressor is also slightly increasing. When the coax valve is closed, the mass flow blockage due to the injected air is gone and the compressor air mass flow makes a sudden jump to greater values until it is run out. This also accounts for the temperature after the compressor. Further investigation of other air temperatures and pressures at different engine station revealed no critical values for future HQS.

#### 4.2 Compressed air bundle – hot quick-start

Based on the findings of the CQS tests with the compressed air bundle, HQS are performed. Main parameters of FADEC adaption for a QS are fuel injection timing, amount of fuel and deactivation timing of the coax valve. For first tests, the known parameters of the TQSS were taken and adapted to have kind of conservative adjustments. An interesting point is the QSS deactivation and in the following the resumption of the compressor's work, as seen before in Fig. 14. The conservative settings are fuel injection at 20% GG rotational speed and deactivation of the QSS at 52% GG rotational speed. The result is shown as blue curve in Fig. 15. On the x-axis is the elapsed time and on the y-axis is the absolute pressure at the end of the compressor section. The coax valve opens and the pressure at the end of the compressor is slightly increasing. At time 2.2 s fuel is injected into the combustion chamber and ignition takes place. This increases the overall pressure level at the compressor end. Since the QSS is deactivated at 52% GG speed, the GG has not reached the required 60% rotational speed at idle mode. The compressor should operate in a regular manner but surge occurred for nearly a second until real regular compressor operation is achieved at 4.5 s and the GG is operating at stable 60% speed. An explanation can be that the compressor has not reached an operation point where sufficient pressure increase is possible to cope with the back pressure from the combustion chamber. Nevertheless, this surge behavior is not tolerable for a safe QS.

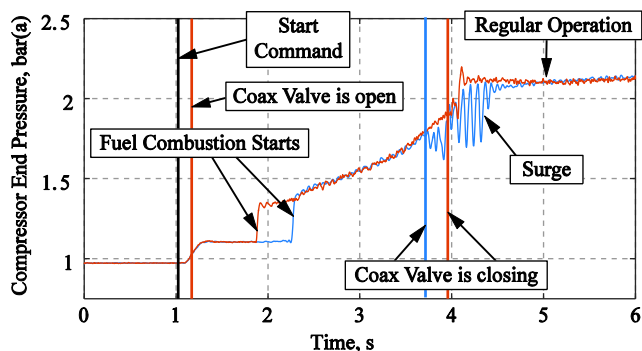


Figure 15. Pressure at the end of the compressor for two HQS with cylinder bundle and different FADEC settings.

Within a second test the deactivation limit was pushed to 58% GG rotational speed. Here the compressor works fine as the red curve in Fig. 15 shows around time 4 s. The transition from nozzle operation mode to regular compressor operation may be further smoothing by QSS deactivation at 60% GG rotational speed. This will be investigated in the future. To shorten the start-up time the beginning of fuel injection starts earlier at 14% GG speed. However, on compressor end pressure this does not have any significant influence. The fuel schedule was not changed. Further HQS tests with some changes in FADEC parameters were performed for finding a better QS performance. But in summary, the red curve in Fig. 15 represents one of the best HQS with the compressed air bundle. The result is a start-up time of 3 s from off-state until 60% GG rotational speed is reached.

#### 4.3 Compressed air bottle – cold quick-start

The compressed air bundle tests paved the way for final tests with a bottle as pressure source. Thus, the compressed air bundle was replaced by the compressed air bottle of 15 l volume and maximum 200 bar(a) pressure level. First, CQSS were performed to identify critical engine parameters during this short phase. Since the air mass inside the bottle and the bottle pressure is decreasing during QS, the entry pressure of the pressure regulator is accordingly changing and causing less mass flow through the pressure regulator. This can be seen in Fig. 16 where the total pressure inside the supply pipe is dropping with decreasing bottle pressure. The QSS operation time was set to 3 s. For the HQS with the bottle this time should not exceed.

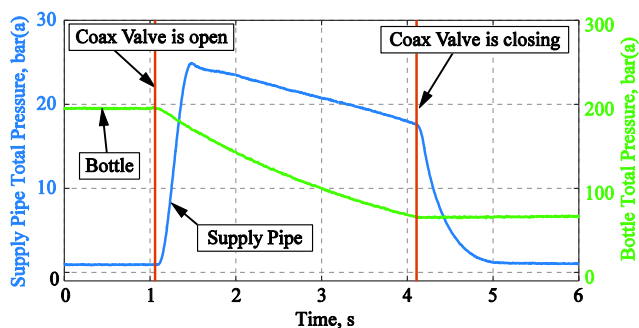


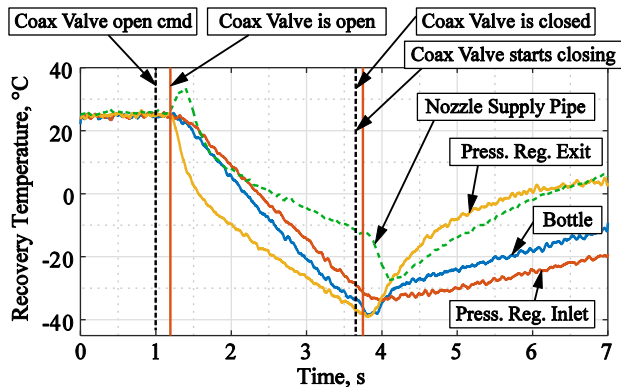
Figure 16. Total pressure in the supply pipe and in the bottle for a 3 s CQS.

The bottle pressure drops to 67 bar(a) within these 3 s. The lowest measured air temperature at the bottle exit was 228 K. Air temperatures at the compressor end were about 250 K. Further downstream, the air temperature was increasing, what is a good prerequisite for proper initial fuel ignition. The final GG rotational speed was 45% and is a good starting basis for the following HQS with the bottle as pressurized air source.

#### 4.4 Compressed air bottle – hot quick-start

Based on the findings of the HQS with the cylinder bundle and the CQS with the bottle, the FADEC was modified and tests were conducted. The recovery temperatures at certain measurement points of the CQSS are shown in Fig. 17. The

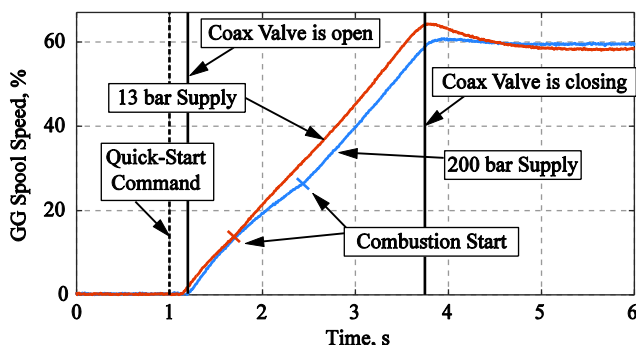
QS starts at 1 s and the command for coax valve opening is given. After 0.2 s the valve signals, that it is fully open. Due to compression of the stored air volume at ambient pressure inside the hoses, the temperature in the supply pipe is slightly increasing until it drops due to the following expanded cold air downstream the pressure regulator. The pressure regulator is at the beginning closed. Since it cannot deliver the air mass at adjusted pressure the stored air between pressure regulator and coax valve expands faster and the temperature drops faster as well. This can be seen during 1.2 s and 1.7 s. Like pressure vs. time curve of Fig. 16, the air temperature inside the bottle as well as the air temperature at the pressure regulator entry drops almost linearly until a minimum at  $-40\text{ }^{\circ}\text{C}$  (233.15 K) is reached.



**Figure 17.** Recovery temperatures of the CQSS powered by the bottle at certain measurement positions.

The temperature short after the compressor section drops to  $-21\text{ }^{\circ}\text{C}$  (252.15 K) until the compressor is working properly and a temperature increase is realized due to compression. The measured temperature between both turbines of the engine drops to almost 273 K until combustion takes place and temperature is rising. Thus, conditions inside the combustion chamber during the QS are at all time sufficient for reliable ignition of the injected air.

The final GG acceleration result is shown in Fig. 18. Here, the blue curve is the QS with the 200 bar compressed air bottle supply and the red curve is a QS with 13 bar shop air supply of the proof of concept design. This TQSS has a start-up time advance of 0.3 sec. Nevertheless, with bottle supply, start-up times of 2.8 sec can be reliably achieved.



**Figure 18.** GG spool speeds of QS with 13 bar and with 200 bar air supply.

This was proven several times at the testbed. This start-up time can be improved, if combustion is starting much earlier. But a certain GG speed is required for sufficient fuel pressure to achieve reasonable spray generation of the fuel nozzle inside the combustion chamber. However, the cold air temperature in the combustion chamber has a non-negligible influence on proper combustion.

## 5. CONCLUSION AND OUTLOOK

This paper shortly describes the development process of an airworthy and compact compressed air supply for an engine QSS for rotorcraft application. Based on a given proof-of-concept design with low pressure shop air, an analysis of adjustable system parameters was performed and a new air supply with high pressure source was designed. Tests of this system were conducted in first case with a cylinder bundle to ensure constant inlet conditions of the system, followed by final tests with a bottle as compressed air source. The experimental test campaign was successful and the engine can be quick-started within 2.8 s using the compact compressed air supply. Further work has to be done on control parameters of the system and improvements regarding combustion. In addition, the overall system has to lose weight for real rotorcraft application. This can be achieved for instance with a pressure bottle based on carbon and shorter pipes and hoses. Another investigation has to be done on systems failures. This means, how does the engine behave if the system is somehow unrequested activated during regular engine operation.

## NOMENCLATURE

### Abbreviations

AIS	Air Impingement System
ASS	Air Supply System
CQS	Cold Quick-Start
ESPSS	European Space Propulsion System Simulation
FADEC	Full Authority Digital Engine Control
GG	Gas Generator
HQS	Hot Quick-Start
ISEO	Intended Single Engine Operation
QS	Quick-Start
QSS	Quick-Start System
CQSS	Compact Quick-Start System (3 Nozzles)
TQSS	Testbed Quick-Start System (5 Nozzles)
MCP	Maximum Continuous Power
SFC	Specific Fuel Consumption

### Symbols

$\dot{m}$	Mass flow, [kg/s]
$p$	Pressure, [bar, Pa]
$r$	Radius/distance, [m]

$v$	Velocity, [m/s]
$t$	Time, [s]
$A^*$	Nozzle throat cross section area, [m <sup>2</sup> ]
$F$	Force, [N]
$I$	Jet momentum, [N/s]
$R$	Gas constant, [J/(kg K)]
$T$	Temperature, [K]
$\alpha$	Deflection angle, [deg]
$\beta$	Deflection angle, [-]
$\eta$	Efficiency, [-]
$\kappa$	Isentropic coefficient, [-]

## Indices

<i>air</i>	Air parameter
<i>exit</i>	Nozzle exit
<i>i</i>	Sum count
<i>id</i>	Ideal
<i>n</i>	Nozzle count
<i>noz</i>	Nozzle related
<i>QSS</i>	Quick-Start System
<i>t</i>	Total Value

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