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PERFORMANCE INVESTIGATIONS OF CYCLE-INTEGRATED PARALLEL HYBRID TURBOSHAFTS

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ABSTRACT

Motivated by long term target settings for research and innovation in Europe and in North America initial investigations of parallel hybrid electric power plant systems have already shown a significant fuel reduction potential for the transport aircraft. Within the classical parallel hybrid topology, an electric motor assists the gas turbine by suppling mechanical power to the power shaft. In this paper, the implications of a more sophisticated parallel hybrid variant, namely the Cycle-Integrated Parallel Hybrid (CIPH) is investigated with regard to an advanced turboshaft engine application for helicopters. For this purpose several compressor stages of a baseline turboshaft (TS) power plant, and, are thereby decoupled from the turbine section offering an independent drive and control of the compressor stages. The baseline power plant of the investigated concept is derived for a 12-ton-helicopter accommodating 19 passengers on a 450nm mission. It consists of an axial-centrifugal compressor powered by the high pressure turbine, and, a free low pressure (power) turbine delivering a maximum power of 3300 kW at constant rotational speed. For the presented study the axial compressor section is electrified with the help of linear electric motors mounted at the blade tips. Due to the implications of the electric motor counter rotating stages are considered most appropriate for the design and performance investigations. The electric motor energy is supplied by a power management and distribution system with built-in redundancies, and, energy storage via batteries are taken into account. A hybrid electric topology can be easily characterized by the degree of power hybridization, H_P, being defined as the ratio of installed electric power to the total power installed. With this configuration a CIPH TS with a H_P of 19.7% is identified to be a suitable solution. With the implementation of electric power within the cycle, an additional degree of freedom controlling the power plant can be established. During part load conditions a power specific fuel consumption improvement of over 45% and an increase in overall efficiency of more than 90% compared to the conventional TS was found. The investigation of the usable part load range has shown that the maximum installed electric power imposes an additional limiting factor. At the vehicular level, a retrofitted version of the reference helicopter equipped with the CIPH turboshaft features a range reduction of more than 50%, but simultaneously offering an energy reduction potential of over 28% and a CO_2 reduction potential of over 42%.

NOMENCLATURE

APSS	Advanced Propulsion System Synthesis
CIPH	Cycle-Integrated Parallel Hybrid
DC	Direct Current
E-BREAK	Engine Breakthrough Components and Subsystems
EIS	Entry Into Service
EPS	Energy and Power System
H_P	Degree of Power Hybridization
HPT	High Pressure Turbine
ISA	International Standard Atmosphere
LEM	Linear Electric Motor

LPT	Low Pressure Turbine
MTOW	Maximum Take-Off Weight
OPR	Overall Pressure Ratio
PMAD	Power Management and Distribution
PMSM	Permanent Magnet Synchronous Motor
PR	Pressure Ratio
PSFC	Power Specific Fuel Consumption
SL	Sea Level
SRIA	Strategic Research and Innovation Agenda
SSPC	Solid State Power Controller
TS	Turboshaft

1. INTRODUCTION

The aviation community is confronted with ambitious CO_2 and noise reduction targets for future aircraft mainly forced by the European Flightpath 2050 and their comparable Strategic Research and Innovation Agenda (SRIA) as well as the equivalent American environmental targets with NASA Environmentally Responsible Aviation N+ series. Aircraft concepts designed for an entry into service (EIS) year of 2035 should reach a CO_2 reduction potential of 60% compared to the datum year 2000 [1]. Based on the targets of the SRIA the airframe and the propulsion system should contribute to an equal percentage of 30% to the overall energy and power reduction for the year 2035. A possible approach fulfilling those emission targets was already identified with universally electric [2], [3] as well as hybrid electric [4]–[7] transport fixed wing aircraft concepts. The hybrid-electric aircraft studies have identified block fuel saving potentials of up to 20% for short to medium range applications [6].

Beside the application of hybrid concepts for fixed-wing aircraft also rotorcraft are of high interest enhancing the power train performance. The design requirements and boundary conditions of those power trains are differing significantly from fixed-wing aircraft mainly driven by the hover requirement. According to the EASA CS-29 the power train of a helicopter has to be designed for a category A certification in a way that during an engine failure in take-off or landing conditions a safe continued approach or a safe climb out to a stable single-engine cruise condition is ensured [8]. This design case normally implies that the engines are running in deep part load especially during cruise, which has in turn a negative impact on the fuel consumption.

For energy and power systems (EPS) of hybrid electric vehicles there are currently three different main topology types available as sketched in FIGURE 1 namely serial, parallel and serial-parallel hybrid. Within a serial hybrid topology the main power transfer is performed electrically, which means there is no direct mechanical coupling between the propulsor and the gas turbine. The total electric power (equal to required propulsion power) is converted to mechanical energy with the help of an electric motor. The advantage of this topology is that the gas turbine can run in its efficiency optimum in each operation point. The disadvantage of this topology is that it requires an additional generator, which is sized for the same power as the gas turbine and the electric motor has to be sized for the entire required power demand. Therefore, the increased gas turbine efficiency or other design/operational effects at vehicular level need to compensate for the additional efficiency losses due to the generators and the required increased EPS mass.

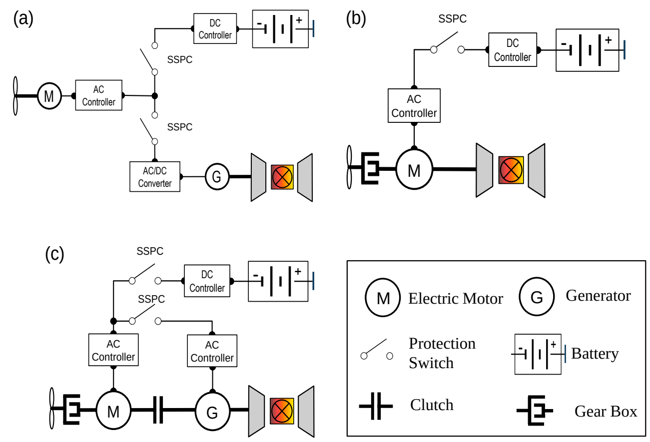

FIGURE 1: Common topologies in hybrid electric vehicles with a battery supplied electrical chain. a.) Serial hybrid b.) Parallel hybrid c.) Serial-Parallel hybrid.

The second topology type is the parallel hybrid where the main power transfer node is mechanical [9]. The advantage of this arrangement is that the electric power train does not to be sized for the entire propulsion power. Typically the electric power train and the kerosene power train are linked via a gearbox to the power shaft. The disadvantage is that the gas turbine is still mechanically linked to the propulsor and does not show during operation the flexibility and variability like the serial hybrid topology offers.

The third type is the serial-parallel hybrid topology, which is a combination of the serial and the parallel hybrid topology. It also combines the advantages of both topologies and the ability to switch the mode during operation and does also allow for recharging a battery. Nevertheless, this flexibility requires the most involved components and therefore also the most complex control system. Due to this complexity it seems to be not the preferred topology type for airborne applications and is currently more of interest for the ground based transportation sector, also with regard to braking energy recovering [9].

The hybrid electric aircraft studies mentioned before have mainly studied the classical parallel hybrid power plants in detail. This paper will highlight a special variant of the parallel hybrid power plant, where the hybridization of dedicated power consuming components has been investigated. Hereby, electric motors supplied by batteries are powering a number of compressor stages or even the entire compressor. This concept is based on the patent described in [10]. Due to this configuration the definition of the classical parallel hybrid has to be extended to a cycle-integrated parallel hybrid (CIPH) power plant, where the electric power is not directly supplying the power shaft.

The focus of this paper will give a deeper insight in the performance characteristic of a CIPH turboshaft (TS) power plant for a helicopter application. The impact of different off-design hybrid ratios will be shown in the compressor performance map as well as the corresponding power specific fuel consumption (PSFC) reduction potential. Furthermore a first assessment on airframe level will be performed. For that reason a retrofitted (constant maximum take-off weight, MTOW) variant of a 12 ton reference helicopter is used as platform to analyze the hybrid EPS and identifying the potential range capability and the possible fuel and CO_2 reduction potential.

2. HYBRID ENGINE CYCLE EFFICIENCY POTENTIAL

The principle idea of the CIPH power plant concept is the electrification of single compressor stages or an entire compressor section at a time. The expected advantage of this approach is to increase the core efficiency by adding a more exergetic efficient energy source, namely electric energy, to the Joule-Brayton cycle as indicated in FIGURE 2. The benefit of this concept is that the conversion process of the electric energy with the help of electric motors is not limited by the Carnot efficiency.

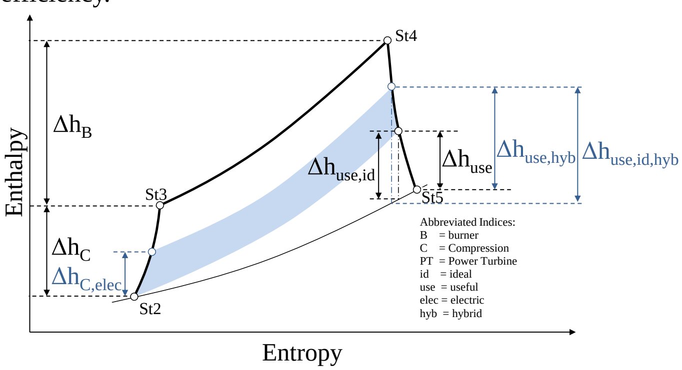

FIGURE 2: Schematic illustration of the possible impact adding electric energy to the engine cycle

The core efficiency as commonly used in gas turbine performance computation is defined as

$$\eta_{CO} = \frac{P_{use}}{P_{\sup}} = \frac{\dot{m}_{PT} \cdot \Delta h_{use,id}}{\dot{m}_{fuel} \cdot FHV} \approx \frac{\dot{m}_{PT} \cdot \Delta h_{use,id}}{\dot{m}_B \cdot \Delta h_B}$$

That is the ratio of the useful power, P_{use}, to the power supplied to the power plant as effective fuel enthalpy flow, P_{sup}. In case of a conventional power plant this expression is equal to the mass flow at the power turbine, $\dot{m}_{PT}$, times the ideal available enthalpy, $\Delta h_{use,id}$, divided by the fuel mass flow, $\dot{m}_{fuel}$, times the fuel heating value, *FHV*. The latter of these may be approximated by the burner enthalpy rise $\dot{m}_B$ times Δh_B, in the first instance. Looking at a hybrid electric power plant, where a part of the compressor power, $P_{C,elec}$, is supplied by electric means, the definition of η_{CO} expands to

$$\eta_{CO,hyb} = \frac{P_{use,hyb}}{P_{\sup,hyb}} = \frac{\dot{m}_{PT} \cdot \Delta h_{use,id,hyb}}{\dot{m}_{fuel} \cdot FHV + P_{ins,elec}}$$
$$\approx \frac{\dot{m}_{PT} \cdot \Delta h_{use,id} + P_{C,elec}}{\dot{m}_B \cdot \Delta h_B + {P_{C,elec}}/{\eta_{elec}}}$$
$$\text{with } P_{C,elec} = \dot{m}_C \cdot \Delta h_{C,elec}$$

In the hybrid cycle case the ideally available delta enthalpy at the power turbine, $\Delta h_{use,id,hyb}$, is significantly increased compared to the conventional cycle, because due to the reduced turbine power demand in the compressor section. For the prediction of the hybrid core efficiency the required electric power needs to be corrected by the overall electric system efficiency, η_{elec}. It can be already seen that as long as the electric efficiency is higher than the chemical conversion efficiency of the engine an increase of the overall power plant efficiency can be expected.

An important descriptor for the electrification intensity of such a hybrid power plant design is the Degree of Power Hybridization, which is defined according to [9] as

$$H_P = \frac{P_{use,elec}}{P_{use,tot}} = \frac{P_{use,elec}}{P_{use,elec} + P_{use,\,fuel}}$$

where $P_{use,elec}$ is the maximum installed electrical power at the battery (equal to $P_{C,elec}$ corrected by η_{elec}) and $P_{use,fuel}$ the maximum supplied power demand from the fuel. A H_P of 0 means in this case that no electric power is supplied to the power plant, which is equal to a conventional kerosene powered power plant, while a value of 1 means that the entire power comes from the battery and the propulsor is fully electric-driven. For hybrid electric power plants featuring electrically powered compressors values for H_P lower approximately 0.5 will be expected.

3. SYNTHESIS OF HYBRID ELECTRIC POWER PLANT

In the following section the reference TS power plant is described and the associated conversion process to the hybrid TS variant. For that purpose a possible electric system architecture is proposed including an eligible electric motor type.

3.1. BASELINE POWER PLANT ARCHITECTURE

As baseline a TS power plant for a helicopter application is used. The configuration and power requirements of this TS are similar of those used as a study platform within the E-BREAK (Engine Breakthrough Components and Subsystems) project. The power plant features an axial-centrifugal compressor powered by a cooled high pressure turbine (HPT) and which is delivering in its reference operational point in take-off and international standard atmosphere (ISA) conditions at sea level (SL) a power output of 3300 kW at the low pressure turbine (LPT). One characteristic of helicopter TS is that the LPT is running at constant speed during all flight phases.

3.2. ELECTRIC POWER ARCHITECTURE

Adding electric energy to the Joule-Brayton cycle requires electric motors to convert the electric energy to mechanical energy. By integrating electric motors within gas turbine power plant further electric components are required like batteries, which supply the electric motors with electric power, and an associated Power Management And Distribution (PMAD) system, which ensures that the power is transferred in a redundant environment to the motors as exemplary shown in FIGURE 3.

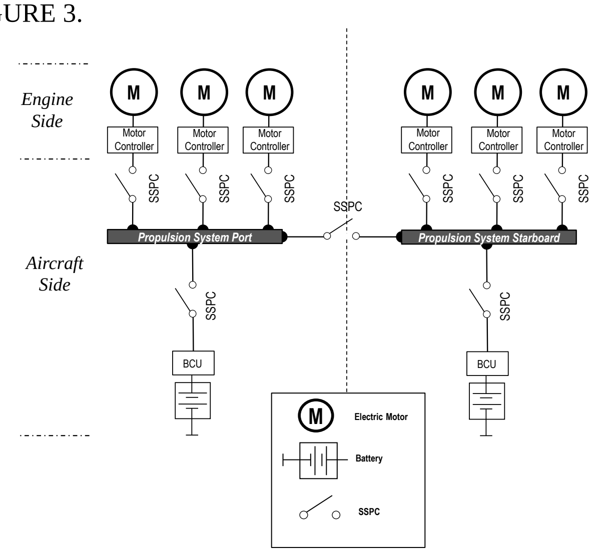

FIGURE 3: Principle sketch of the used electric power architecture

The system architecture is designed for a constant system voltage of 3000 V direct current (DC) mainly forced by the battery. The power is hereby transferred from the battery via a bus system to each electric motor installed within the power plant. The motors as well as the batteries are protected by Solid State Power Controllers (SSPC), which isolate a faulty component in a failure case and ensure that the remaining components are kept still operable. Each power plant has its dedicated transmission system with the possibility to connect each system via a SSPC if for example a battery fails. From a bill-of-material view the electric motors and associated motor controllers are accounted to the engine side and the remaining electrical system to the aircraft side comparable to the conventional fuel system.

For the estimation of the efficiencies of each single component the parameters shown in Table 1 are used, which already represents a forecast to a long term perspective mainly based on [3]. All components are cooled by a decentralized liquid cooling system and it was assumed that the thermal management system is able to keep the components in all operating points at a constant operating temperature. The additional power demand required for the cooling pumps is considered during the performance analysis.

Table 1: Assumptions of electric component parameters for a long term perspective

Component	*Specific Power/Energy*	*Mean Efficiency [%]*
Battery [11]	1500.0 Wh/kg*	97.0
Controller [3]	21.0 kW/kg	99.0
Converter [3]	18.0 kW/kg	99.0
Cable (Alu.) @ 3 kV [12]	5.2 – 6.5 kg/m**	~100.0
Protection Switch [3]	44.0 kW/kg	99.0
Liquid Cooling System [3]	1.2 kW/kg	30.0

* Target of battery system (incl. cables, housing, etc.)
** valid for a power range between 1MW and 2MW

A central component of a CIPH power plant is the electric motor delivering the required compressor work. Beside the efficiency of the electric motor also the maximum rotational speed is an important parameter depending on the installation constraints. Table 2 gives an overview of typical electric motor types with the efficiencies and maximum tip speeds (relative velocity between rotor and stator of the electric motor).

Table 2: Overview of possible electric motor types and their parameters

Type	*Efficiency [%]*	*Tip Speed [m/s]*
Permanent Magnet Synchronous Motor [13]	95.0	250
Linear Electric Motor [14]	92.0	400
Asynchronous Motor [15]	94.0	200
Asynchronous Motor (solid rotor) [15]	85.0	Up to 500

Asynchronous motors, which convert the electric energy with the help of the Faraday's law to mechanical energy, show a good tip speed behavior, but at relative low efficiencies. Therefore actually two electric motors show the best potential for CIPH applications. First the Permanent Magnet Synchronous Motor (PMSM) offering a high efficiency but at a relative low tip speed, mainly structurally limited by the permanent magnets mounted on the rotor [13]. The second motor is the Linear Electric Motor (LEM), which shows a good trade-off between efficiency and tip speed potential. FIGURE 4 shows a possible integration concept of a LEM linked to fan

[16] or compressor blades based on [14]. Concerning this installation approach of the electric motor it can be already seen why the tip speed of the electric motor is a limiting factor of a compressor, because the electric motor speed also dictates the tip speed of the compressor blades (depending on an inner or outer installation position) and in turn also the possible work potential. This type of installation, also with regard to the integration of the electric motor in the power plant, seems to be the most favorable one. For the estimation of the efficiency, mass and geometric dimensions of the LEM a simplified scaling model based on [14] is used.

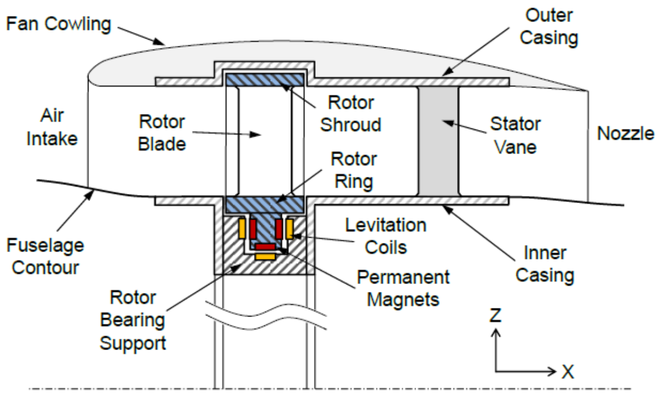

FIGURE 4: Example of a linkage of an electric motor with a fan blade. Taken from [16]

3.3. HYBRID POWER PLANT CONCEPT

The LEM was chosen as the preferable solution including the proposed installation approach suggested by [14] with LEM installation at the blade tips. With this kind of installation the tip speed of the compressor blades are limited by 400m/s according to Table 2 and is lower compared to the reference TS engine. In turn this installation approach means that the mentioned work potential per stage is reduced, which can inferred that for a given pressure ratio (PR) a larger number of stages will be required. To counteract this effect the type of the electric motor integration offers the possibility of counter rotating compressor (CRC) stages, where each grid of one stage is controlled and powered by a dedicated LEM. The introduction of an electric system makes the CRC more attractive although it has been already investigated for more than 60 years [17]. Due to its associated relative complex mechanical system, the CRC concept was dropped again in the past, because this mechanical system resulted often in an increased overall system mass [18]. The radial compressor and depending on the resulting H_P part of the remaining axial compressor will be still powered by the HPT. For a simplification in the sizing of the CIPH TS the PR of the radial compressor is set constant in the design point for the overall design space. The requirements for the power shaft are not changed compared to the reference configuration, which means that the LPT will run at a constant speed within the entire envelope.

4. OVERALL PERFORMANCE SIMULATION

The following section gives an overview of the assessment parameters used for the CIPH power plant comparison as well as the simulation approach of the engine performance and in turn the approach simulating the power plant at vehicular level.

4.1. ASSESSMENT METRICS

For the assessment of the CIPH TS three parameters are used. Beside the overall efficiency described in Section 2 the power specific fuel consumption (PSFC) is required for the estimation of the potential fuel and possible CO_2 reduction during flight. The PSFC is defined as

$$PSFC = \frac{\dot{m}_{Fuel}}{P_{ins}}$$

While the PSFC is only considering the fuel consumption a second parameter covers also the electric energy demand for the assessment at aircraft level. Both energy sources are combined in the overall energy demand for a specified mission and is defined as

$$E_{ins} = m_{Fuel} \cdot FHV + m_{Bat} \cdot \rho_{Bat}$$

m_{Fuel} is the required total fuel for the defined mission, FHV the fuel heating value, m_{Bat} the installed battery mass and ρ_{Bat} the battery specific energy.

4.2. ADAPTION OF CONVENTIONAL CYCLE PERFORMANCE SIMULATION

The model was set up for the TS power plant within an in-house engine simulation environment called Advanced Propulsion System Synthesis (APSS). To simulate the CIPH power plant, the simulation routine needed to be adapted from the reference TS architecture. First, the low pressure, CRC needed to be powered by an electric motor instead of the HPT as illustrated in FIGURE 5. Second, the metrics and efficiency prediction for a slowly rotating CRC needed to be implemented.

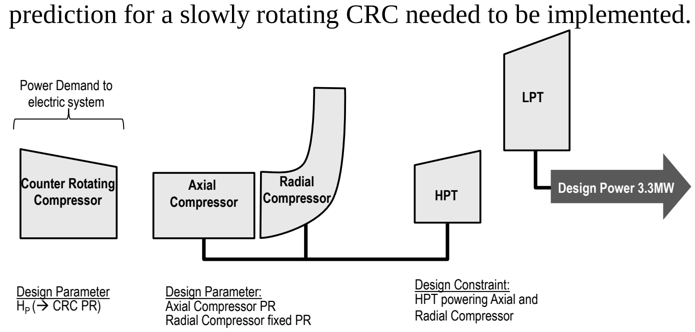

FIGURE 5: Schematic configuration of the simulated hybrid electric turboshaft power plant

To achieve the first, the power demand is determined by the compressor component based on the given PR, the polytropic efficiency of the compressor and the compressor mass flow. The power demand is then translated into electrical power demand after the efficiency chain formed by the electric motor, PMAD as well as the battery. Thus, the required electric power $P_{use,elec}$ is determined, as well as the derived metrics H_P and PSFC.

To estimate the loading of the CRC, it was assumed that the first stage always rotates with the maximum permissible tip speed, $u_{tip,1}$, of 400 m/s in order to achieve the lowest possible stage loading. The second grid of a stage was assumed to rotate in opposite direction of the first grid with a tip speed of

$$u_{tip,2} = -q_N \cdot u_{tip,1}$$

where q_N is the tip speed or rotational speed ratio [18]

$$q_N = \frac{n_2}{n_1} = \frac{u_{tip,2}}{u_{tip,1}}$$

In case of the definition that grid 1 is rotating at the maximum possible tip speed of the electric motor in this configuration, q_N is limited in this case to a maximum value of 1. A value of 0 for q_N would represent a classical rotor-stator compressor configuration. The loading ψ was assumed to be equal in each grid so that the average flow coefficient

$$\overline{\varphi} = \frac{\varphi_1 + {q_N}^2 \cdot \varphi_2}{1 + {q_N}^2} = \frac{\varphi_1 + {q_N}^2 \cdot (q_N \cdot \varphi_1)}{1 + {q_N}^2} = \varphi_1 \cdot \frac{1 + {q_N}^3}{1 + {q_N}^2}$$

$$\textit{with}$$

$$\varphi_1 = \frac{C_{Axial}}{U_{Mean}}; \varphi_2 = q_N \cdot \varphi_1 \quad \text{and}$$

$$dh_1 = \frac{dh}{1 + q_N^2}; dh_2 = \frac{dh \cdot q_N^2}{1 + q_N^2}$$

$$\rightarrow \overline{\psi} = \frac{dh}{\frac{U_{mean}^2}{2}} = \frac{dh_1 \cdot (1 + {q_N}^2)}{\frac{U_{mean}^2}{2}} = \psi_1 \cdot (1 + {q_N}^2)$$

are obtained. As can be seen, the loading in a grid is reduced by a factor of $1/(1+q_N^2)$ per stage when compared to a single rotating compressor. The design performance of the CRC was estimated by means of the deltas in averaged stage coefficients ψ and φ in contrast to the performance of the reference compressor according to [19], [20]. End wall losses, tip losses and secondary losses were assumed to be not affected by the counter rotating mode of operation. The off-design performance of the components was simulated using standard component maps of GasTurb [21] assuming the aerodynamics in a CRC are similar to the aerodynamics in a single rotating compressor for which the component maps were derived.

The burner exit temperature T4 and the Overall Pressure Ratio (OPR) are variables in a parametric study to identify a favorable cycle. Additionally, a chosen H_P is iteratively achieved by varying the PR of the CRC (Π_{CRC}). As defined in the selected concept, the radial compressor is conventionally powered by the HPT and delivers a constant PR. For a given OPR, an additional axial compressor could be required to meet the target OPR in combination with the axial CRC and the radial compressor PR.

Since part of the compression energy is provided by an electric motor, the specific power of the cycle is increased and, hence, the core mass flow is reduced. The reduced core mass flow is a result of the sizing iteration scheme to achieve the required shaft power. Moreover, cooling air flow is adapted in dependence of the cooling air temperature T3 and the burner exit temperature T4 to keep a constant turbine stator and rotor temperature.

For the estimation of the required stages of the CRC a simplified scaling model is used, which estimates the possible stage pressure ratio of the counter rotator, $\Pi_{St,CRC}$, as function of the reference stage pressure ratio, $\Pi_{St,Ref}$, as well as the tip speed ratio and the q_N

$$\Pi_{St,CRC} = 1 + (\Pi_{\mathrm{St,Ref}} - 1) \cdot \frac{u_{Tip,1}^2}{u_{Tip,\mathrm{Ref}}^2} \cdot (1 + q_N^2)$$

4.3. SIMULATION PROCESS OF THE HYBRID ELECTRIC ROTORCRAFT

For the aircraft level assessment of the conventional and the CIPH rotorcraft an in-house Matlab® based helicopter performance tool is used [22]. This tool is able to determine the required fuel as well electric energy demand for a specified mission. For that reason the thrust requirements of the helicopter for different flight states are determined with simplified aerodynamic methods using for the drag calculation a combination of the blade element method and momentum theory mainly based on [23]. The engine performance data is provided via look-up tables for different Mach numbers, altitudes, ISA deviations and thrust lever positions. For the hybrid electric variant the required battery capacity is estimated using a discharge model of an advanced Lithium-Ion battery [11].

Within this tool the reference helicopter is modelled for a design mission of 450nm and a maximum take-off weight (MTOW) of 12 tons and a maximum payload of 19 passengers. The CIPH variant for the aircraft level assessment is based on the reference helicopter, where the MTOW is fixed, which allows for simplifications in a potential certification process of the helicopter. For the simulation of the flight performance the two conventional kerosene powered TS power plants are replaced by the CIPH power plants plus the associated electric system. The fuel system of the reference helicopter is kept. With this configuration the maximum possible range is estimated for the CIPH helicopter determining the required fuel and battery mass for the specified mission at fixed MTOW.

The mission profile for the reference as well as for the CIPH helicopter includes a 30 second take-off phase in hover mode, a climb phase with a climb rate of 5m/s, a cruise phase at given cruise altitude of 3000ft and maximum speed of 150kts, a descent phase at also 3m/s descent rate and finally a landing phase with a 30 second hover phase (reserves are not considered in this scenario).

5. RESULTS

First the final sized CIPH TS is presented fulfilling the SRIA 2035 targets. Based on the CIPH concept the impact of different off-design hybridization ratios and part loads are shown for the overall efficiency and PSFC change. Second, the aircraft level results for the retrofit version of the reference helicopter are discussed.

5.1. FINAL HYBRID POWER PLANT

Based on an expansive possible design space for different design variants a potential CIPH TS power plant was selected within a qualitative down selection process. The most suitable candidate out from this process, which was also used for further performance investigations, is featuring single rotating CRC stages located at the inlet of the power plant. During the sizing process of the power plant the baseline cycle parameters like OPR and T4 are kept from the reference TS cycle, where a trade study have shown that those parameters are also fitting the performance of the CIPH TS best.

A suitable design H_P of the CIPH TS fulfilling the SRIA 2035 targets was determined in the operational point with 19.7%. In this configuration the electric system has to deliver a power of about 1500 kW, which was also chosen as the design point of the electrical system. Compared to the reference TS an increase in the overall efficiency could be achieved by relative 18.7% and a decrease in PSFC by 32.2%.

The q_N had to be set to its maximum value of 1 to keep the number of required stages in a feasible range. For the target PR it offers therefore an electrically powered three stage CRC and a two stage axial compressor with a radial compressor powered by the HPT. The setup of the HPT and the LPT was kept. The final design of the CIPH TS is sketched in FIGURE 6.

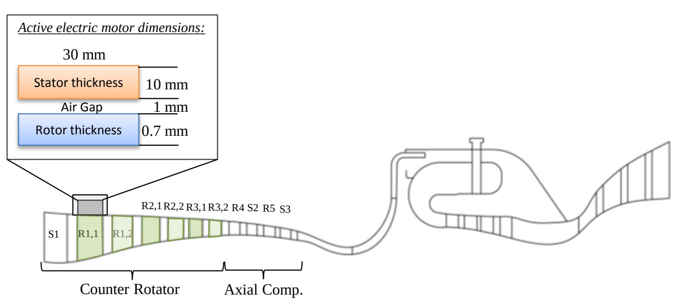

FIGURE 6: Simplified flow path sketch of the hybrid electric turboshaft with counter rotating axial compressor and linear electric motor installation.

5.2. HYBRID POWER PLANT CHARACTERISTICS

The CIPH power plant has been also investigated in part load conditions to identify the hybridization impacts of this concept. With the implementation of the electric system also a new degree of freedom can be used to control the power plant. For a conventional power plant the part load characteristic offers normally only one operating line. FIGURE 7 shows the impact on the PSFC and the overall efficiency of the CIPH TS relative to the reference TS for different power demands and off-design H_Ps for take-off SL conditions. In the first instance of the evaluation of the impact of a CIPH TS on the PSFC and overall efficiency q_N of the CRC was fixed to 1 for all part load points to allow an investigation of the impact of the hybrid system only.

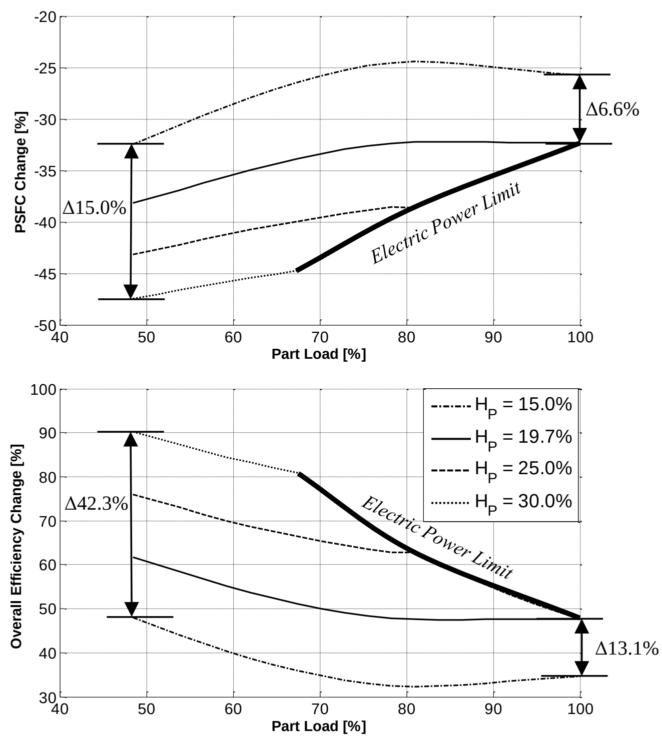

FIGURE 7: Impact of different off-design degrees of hybridization in part load at ISA, SL on the overall efficiency and power specific fuel consumption.

For the part load study the electric power demand of the CRC is varied in a range that the effective off-design H_P reaches values between 15% and 30%. A H_P of 15% was identified in this design case as the lower limit for the CIPH power plant, because the axial-centrifugal compressor cannot deliver the required PR anymore for the required power demand. It can be already seen that for even relative low H_Ps of around 15% a decrease in the PSFC during full load of over 25% can be reached compared to the reference TS. Even for power demands half of the full load a PSFC reduction of over 30% can be achieved. Increasing the H_P the PSFC can be further reduced by over 45% compared to the reference. But what can be also recognized is that for H_Ps higher than the design H_P, the possible part load area, where the higher H_P can be used, is shrinking due to the limitation of the maximum power demand of the electric system. To extend this hybrid part load area the design point of the electric system has to be changed, which in turn has the disadvantage that the system mass would increase. The overall efficiency change of the entire CIPH TS shows similar characteristics like the PSFC. Also here the overall efficiency can be increased in the full load point by up to 35% for low H_Ps compared to the reference TS. But the highest effect using the hybridization effect can be achieved in part load characteristics, where efficiency increases of up to 90%, also limited by the installed electric system design power.

The impact of the electrified compressor can be also seen in the associated compressor map (cf. FIGURE 8). The shown map includes the operating lines of the CRC for different H_Ps. It can be recognized that for H_Ps higher than the design H_P the operating lines running here in a second limit on the right side of the map, which is normally limited by the mechanical properties of the rotor. For an optimal design of the CIPH TS the design of the electric system has to be harmonized with the mechanical properties of the rotor. For example, if the entire PSFC part load range of the CIPH TS should be available during the mission, it must be ensured that the speed limit of the compressor offers a satisfying safety margin when increasing the electric system design power (shift of the electric power limit to the right). This in turn would imply a higher power plant system mass, but would offer on aircraft level a higher potential to optimize the flight profile, which could increase the overall vehicular efficiency and reduce the overall system mass.

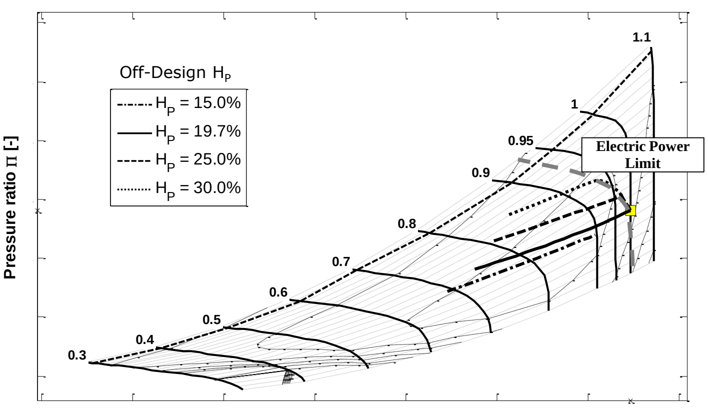

FIGURE 8: Impact of different off-design hybrid ratios on the electric counter rotating compressor performance.

5.3. IMPACT ON VEHICULAR LEVEL

The assessment on vehicular level was performed in a first instance with the help of a retrofit version of the reference helicopter. This means that for the energy demand determination the MTOW was fixed and the required fuel and battery capacity were determined for a resulting hybrid mission range at the design H_P of 19.7%. In a first approach the fixed H_P at the design point was chosen for all flight segments, because this hybridization strategy seems according to the compressor map shown in FIGURE 8 as the most efficient one. With this kind of hybridization strategy the CIPH helicopter is able to fly about 220nm, which is a decrease in range capability of more than 50% compared to the reference helicopter. But nevertheless, for the hybrid mission range the CIPH helicopter could save over 28% of overall energy and allows also for a CO_2 reduction potential of over 42% compared to the reference helicopter, which was also simulated at the same hybrid mission range of 220nm. This reduction potential is based on the reference helicopter originally designed for the 450nm design mission. If this reference helicopter would be downsized to the hybrid electric mission range the potential of possible energy reduction could be reduced, which was not further investigated within this paper. But due to the relative high CO_2 and energy reduction potential it can be expected that even for a downsized baseline helicopter for 220nm the CIPH helicopter will still show a better environmental footprint. This in turn would imply that the optimum market segment for a CIPH helicopter is for short range applications.

6. CONCLUSION AND OUTLOOK

In this paper a conceptual study for a Cycle-Integrated Parallel Hybrid (CIPH) electric turboshaft for a helicopter application has been discussed featuring an electric driven compressor. As design target for the CIPH power plant the environmental goals of the Strategic Research and Innovation Agenda (SRIA) are used. At first an overview of key electric components and their possible development perspectives to an entry-into-service year of 2035 were given and a possible battery powered electric system architecture was proposed. Furthermore, different motor types have been studied, where for that kind of application a linear electric motor was identified to be the most eligible motor type and was chosen for the further investigations. After the determination of potential electric components for a CIPH application the turboshaft power plant has been sized for a 3300 kW take-off power at sea level and standard atmosphere conditions. For the identification of a suitable design the degree of power hybridization, H_P, has been used. The H_P is defined as the ratio of the installed electric versus the total propulsor shaft power. For the turboshaft concept within this study a H_P of around 19.7% has been identified as most suitable concept to be in compliance with SRIA 2035 goals. With this configuration the power specific fuel consumption (PSFC) could be reduced in the operational point by over 30% compared to the reference turboshaft and the overall energy demand by 12.5%. The electric system is designed for a maximum power of 1500 kW required for the electrified compressor.

The CIPH turboshaft has been also studied in part load conditions using the H_P as additional degree of freedom to increase the part load capability with regard to PSFC and overall efficiency. It was identified that especially for low off-design power demands the CIPH turboshaft shows the highest fuel reduction potential of over 45% for a H_P of 30%, which is equal to an overall efficiency improvement of over 90%. It could be also shown that the chosen design power of the electrical system imposes a new limit in the part load characteristic. H_Ps higher than the design H_P can be only used for small range before the maximum electric power demand is reached. If the entire part load characteristic should be available the electric system has to be designed for a higher power demand, but which would have a negative impact on the overall system mass.

The CIPH turboshaft has been also investigated on vehicular level. A helicopter with constant maximum take-off weight has been equipped with the CIPH turboshaft supplied by batteries and the resulting range and energy demand for the new mission range at the design H_P was determined. For that kind of application a fuel and, in the first instance, CO_2 reduction potential of over 42% could be achieved, but at a reduced range capability of around 50% compared to the reference helicopter.

The next steps will be covering an optimized matching of the electric power and the compressor speed to identify further mass reduction potentials. Furthermore, also an optimization of the power plant control will be performed using a variable H_P over all flight segments. Also the impact of an efficiency change of the electric system during the mission should be covered, which was set constant in the first calculation, but could also have a significant impact on the overall performance as shown by [24]. For an appropriate comparison of the CIPH with the reference helicopter, the reference helicopter should be sized for the hybrid mission range, which was not considered in this paper.

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