PARAMETRIC STUDY ON THE CYCLE OF AN ELECTRIC HYBRID ADAPTIVE CYCLE ENGINE

*P. Jäger**[1], *M. Stößel*[1], *M. Krummenauer*[2], *D. Kožulović*[1]

1: University of the Bundeswehr Munich, Department of Aerospace Engineering,
Institute of Jet Propulsion, Munich, Germany,
2: Bundeswehr Technical Center for Aircraft and Aeronautical Equipment (WTD61),
Manching, Germany

ABSTRACT

A novel engine concept for a small adaptive cycle engine, using hybrid electric components, the "electric Hybrid Adaptive Cycle Engine" (eHACE) was developed. This concept consists of an electrically driven fan, a single spool core engine with a directly driven generator and variable nozzles for the core engine and the bypass stream. The electric energy for the fan is mainly supplied by the generator but can be enhanced by a battery storage. With this setup, the engine can be adapted for different flight conditions, ether to optimize for maximum thrust or for minimum fuel consumption. The eHACE is modelled using NPSS and a parametric study is conducted to determine the optimal engine settings for various flight mission points, resulting in initial sizing parameters for components specifically designed for the concept. In comparison to a small turbojet engine the eHACE can deliver increased thrust or reduced fuel consumption, depending on the engine setting.

KEYWORDS

hybrid electric, adaptive cycle, NPSS

NOMENCLATURE

ACE	adaptive cycle engine
BPR	bypass ratio
CVT	continuously variable transmission
DoH	degree of hybridization
eHACE	electric Hybrid Adaptive Cycle Engine
HPC	high pressure compressor
IJP	Institute of Jet Propulsion
NPSS	Numerical Propulsion System Simulation
SFC	specific fuel consumption
TIT	turbine inlet temperature
UAS	Unmanned Aerial System

Symbols

A	Area, $[m^2]$
F	thrust, $[N]$
M	Mach number, $[-]$
n	spool speed, $[rpm]$
P	power, $[W]$
p	pressure, $[Pa]$
w	mass flow, $[kg/s]$
Δ	difference, $[-]$
η	efficiency, $[-]$
Π	total pressure ratio, $[-]$

Indices

$corr$	corrected
CN	Core Nozzle
$Comb$	combustor
el	electric
Fan	fan
Gen	generator
Mot	motor
$mech$	mechanical
max	maximum
PEM	power electronics module
rel	relative

INTRODUCTION

A main focus for research and development in the aviation industry is to increase the efficiency of propulsion systems. This can lead to a reduction in fuel consumption and carbon footprint and helps aviation to become a more sustainable, "greener" industry. On the other hand, a more efficient propulsion system can increase the operating range of an aircraft with a given amount of fuel, enabling completely new flight mission capabilities. In this paper, the second objective is the main focus.

In conventional jet engine design, the engine components are optimized for a single design point during a flight mission, often requiring compromises in the performance and efficiency for conflicting flight mission requirements. Depending on how the impact of each flight mission point is weighted, the propulsion system can work far from its point of optimal performance and efficiency in the wide range of operating conditions during a flight mission. For subsonic level flight at constant speed, the aircraft drag correlates roughly to the square of the flight speed c_0, requiring high thrust for high flight speeds, and lower thrust for lower flight speed. To achieve a high propulsive efficiency eta_P, it is favourable to use the maximum possible air mass flow w_{max} to generate the required thrust F. w_{max} is limited by the engine inlet cross section, which in turn is limited by the design of the aircraft. In conventional jet engine architectures, the engines thrust F and air mass flow w are directly linked (Walsh & Fletcher (2004)), resulting in poor propulsive efficiency at engine speeds below the design speed. The concept of a "variable cycle" or "adaptive cycle engine"(ACE) targets this problem by decoupling the air mass flow from the thrust setting. This can be achieved by varying the bypass ratio and the fan pressure ratio of the engine. Various concepts for adaptive cycle engines (ACEs) have been studied in the past by General Electric (Johnson, J. E. (1996)) and Pratt & Whitney (Westmoreland, J. S. & Stern (1979)). These studies lead to engines like the "YF120" that powered prototypes of the YF-22 and YF23 fighter aircraft (Aronstein et al. (1998)) or very recently the "XA100" and "XA101" demonstrators. Like these two engines, most of the ACE concepts are designed for manned aircraft. They rely on mechanically complex components, like variable compressor vanes, some even experimenting with variable geometry turbines (Johnson, J. E. (1996)). This fact prevents the use of those engine architectures for smaller Unmanned Aerial System (UAS).

UAS with a total mass below $500-600kg$ are mostly driven by propellers and piston engines, or for faster flight speeds, small turbojets. These turbojets are light and relatively powerful, but are relatively inefficient, especially at part load. Conventional two spool turbofans are not known to the authors in this small engine class, mainly because the small engine size and the extreme engine speeds do not allow the implementation of a second shaft. Kadosh & Cukurel (2017) introduced an ACE concept, suitable for UAS in the range described above. A single spool turbojet is converted to an adaptive cycle turbofan by coupling a continuously variable transmission (CVT) to the main spool to drive a fan. With this CVT and a variable area bypass nozzle, the fans operating point can be varied and with it the bypass ratio and fan pressure ratio of the engine. The benefits of this concept were demonstrated by Palman et al. (2018), by comparing it to a geared turbofan configuration with a fixed gear ratio. Over two different flight missions of a small subsonic UAS, this ACE concept demonstrated a significant increase in loiter time (20%) or fuel savings up to 12% depending on the mission. A major drawback on this concept can be the CVT, as no existing model is known to the authors, which would be small and light enough for an aero engine while handling the power required. Hence, only numerical studies on this concept are known.

Former studies at the Institute of Jet Propulsion (IJP) introduced a comparable concept for a small ACE with hybrid electric components instead of a CVT, the electric Hybrid Adaptive Cycle Engine (eHACE) (Jäger et al. (2022)). This concept is further described in the next section. A system demonstrator was built using "off-the-shelf" components, mainly derived from the RC hobby sector. With this setup, the basic feasibility of the concept could be demonstrated, and potential difficulties identified. It also highlighted the shortcomings of the non-optimal components, significantly limiting the performance of the demonstrator. To study the concept further, it is necessary to understand the behaviour of the engine in various flight conditions and the influence of its variable components. After that, design constraints for custom components can be defined, to build an improved demonstrator engine. For this task, the eHACE is modelled using the Numerical Propulsion System Simulation (NPSS) and a parametric study on the influence of different component specifications is conducted.

EHACE-CONCEPT

The eHACE concept was developed as an ACE with low mechanical complexity, suitable for small UAS applications. A schematic drawing is presented in figure 1.

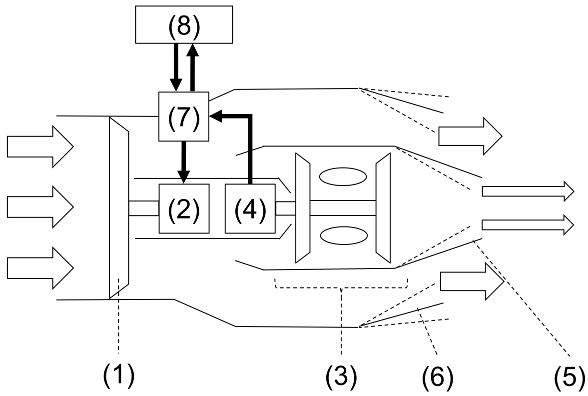


Figure 1: Schematic of the eHACE concept consisting of fan (1), electric motor (2), single spool core engine (3) with electric generator (4), variable core nozzle (5), variable bypass nozzle (6), power electronics module (7), battery power storage (8)

The eHACE concept consists of a single-spool core engine (3) and a fan (1). The coupling between these two components is achieved via two electric machines: a generator (4), which is directly driven by the core engine, and an electric motor (2), driving the fan. This approach avoids the mechanical complexity of a CVT, as described by Kadosh & Cukurel (2017). To control this electric coupling, a power electronics module (7) is required. This module matches the voltage level of the generator to that of the motor, controls the fan speed and the flow of electrical energy to and from a battery power storage (8). With the variable coupling between the fan and the core engine and the variable area bypass nozzle (6), the operating point of the fan can be set in the entire range of its performance map, independent from the operating point of the core engine. The resulting variable power demand of the fan requires the ability, to adapt the operating point of the turbine independently from its spool speed. This can be achieved either by adjusting the turbine inlet temperature (TIT) which is limited by the turbine design, or by adapting the turbine pressure ratio with the variable core engine nozzle (5). This concept is also applied in the F-35B fighter aircraft to power the lift fan for VTOL capabilities (see Bevilaqua, P. M. (1997)). By increasing core engine nozzle area A_{CN}, the turbine pressure ratio increases, resulting in a higher power output. Simultaneously, increasing A_{CN} reduces the nozzle exit velocity and therefore the thrust of the core engine. To apply this concept in the eHACE, the operating point of the turbine must be kept in an area of high efficiency. Otherwise, the decrease in turbine efficiency and with it the engines thermal efficiency can outweigh the possible increase in propulsive efficiency of the system, which could be gained by transferring power to the bypass flow. Accordingly, the turbine performance map is of significant importance for the eHACE concept.

The eHACE is a special modification of a series hybrid configuration. Compared to other hybrid electric propulsion systems, as surveyed by Wall & Meyer (2017) or Rendón et al. (2021), the airflow behind the electric fan interacts with the conventional core engine. Accordingly, in the eHACE the electric and conventional components are not coupled mechanically, but electrically and via fluid interaction. The power setting of the electrically driven fan influences the power output of the conventional core engine by varying the pressure and temperature at the compressor inlet. Furthermore, the operating point of the core engine influences the power consumption of the fan. At constant fan speed and bypass nozzle setting, increasing the core engine speed will increase the core engine mass flow and therefore, de-throttle the fan and reduce its power consumption.

For hybrid propulsion concepts, the degree of hybridization (DoH) is usually defined as the ratio of installed electrical power P_{el} to the total power of the propulsion system P_{total} or the electrically produced thrust F_{el} to the total thrust of the propulsion system F_{total} (see equation 1). The definition by power comes from the concept of one propulsor, that is driven by the conventional and electric components of a hybrid system. The definition by thrust is based on the idea of multiple propulsors, some driven conventionally, and some driven electrically.

$$DoH = P_{el}/P_{total} \qquad \text{or} \qquad DoH = F_{el}/F_{total} \tag{1}$$

Both definitions cannot be directly applied to the eHACE, which is intended to work as a low bypass turbofan with a variable bypass ratio (BPR). Accordingly, the total thrust of the system is generated by both, the electrically driven fan and the core engine. A definition of the DoH by the power used to drive the fan would neglect the thrust share of the core engine exhaust. The power output of this exhaust is dependent on the flight speed of the aircraft. Accordingly, no single power value can be defined to be included in the power-DoH. For a definition of the DoH by thrust, the share of electrically generated thrust is required. This value cannot be easily determined because of the fluid interactions between the components explained above. Instead, the DoH of the eHACE could be defined by the percentage of the electric power for the fan which is drawn from the battery, as described by equation 2:

$$DoH_{eHACE} = P_{Fan,Battery}/P_{Fan,total} \tag{2}$$

The fan can be powered only by the generator, or only from the battery, or in part from both sources. This results in a DoH between 0% and 100% by the definition in equation 2. To keep the size and weight of the battery low, the fan power should be only drawn from the generator for the main duration of a flight mission. Battery power should only be utilized for short time peak thrust settings. The effects of the battery power share on the engine and its thrust are discussed further in the RESULTS section.

NPSS-MODEL

The eHACE concept is modelled using the standard component elements provided by NPSS. A schematic drawing of the NPSS model of the eHACE is presented in figure 2 and the component specifications used in this model are described below.

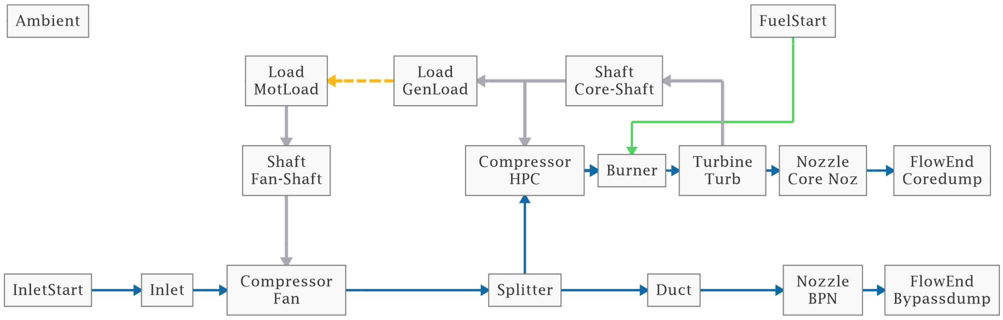


Figure 2: schematic of the NPSS model of the eHACE

Engine inlet, Fan and Bypass System

The engine inlet is modelled with a constant pressure recovery factor of $p_2/p_1 = 0.97$. The actual pressure recovery of an inlet depends on a variety of factors such as inlet design, the flight conditions and engine mass flow. Therefore, the used fixed value cannot accurately depict reality but is sufficient for a first estimation.

One of the goals of this study is to determine design constraints for a fan, specifically designed for the eHACE concept. Accordingly, no predefined performance map is used. The efficiency is assumed constant at $\eta_{Fan} = 0.85$. The pressure ratio Π_{Fan} is varied in the parametric study and the corrected mass flow results from combinations of fan power and Π_{Fan}.

In the splitter after the fan, the total pressure losses for the core stream and the bypass stream are estimated with a fixed value of $dp/p = 0.1\%$. For the bypass duct, a pressure loss of $dp/p = 0.1\%$ is assumed. The bypass nozzle is modelled as a convergent nozzle with a variable throat area. This area is automatically adjusted by NPSS to achieve either a chocked nozzle flow or a static nozzle exit pressure equal to the ambient pressure, depending on the available pressure ratio and the atmospheric conditions.

In theory, the bypass nozzle could be closed completely, which would make the eHACE a turbojet. Based on the experiments in previous studies (see (Jäger et al. 2022)), it is assumed that some air should always flow through the bypass to ensure cooling for the core engine and for example, the power electronics module. Therefore, a minimum BPR of 0.1 is assumed.

Core Engine and Reference Turbojet

The core engine model consists of the high pressure compressor (HPC), the combustor, the turbine and the variable core nozzle. To limit the variables in this parametric study, the design factors and the sizing of the core engine are held constant. The design parameters for core engine model are based on an existing micro jet engine, which is intended to be used in future experiments at the IJP, hence the specific choice of the values described below. This core engine model is also used as a reference turbojet engine, together with an inlet of the same characteristics as the one described above. This reference turbojet is used to evaluate the impact of the fan driven by the electric coupling, and therefore, the effectiveness of the eHACE concept.

For the HPC, a proprietary performance map is used and slightly scaled to the following values at the maximum mechanical engine speed for ISA conditions: $w_{corr,HPC} = 0.62 kg/s$, $\Pi_{HPC} = 3.9$ and $\eta_{HPC} = 0.77$. The combustor is modelled with a fixed efficiency of $\eta_{Comb} = 0.90$ and a relative pressure loss of $dp/p = 5\%$ since no data is available on the behaviour at part load. This low combustor efficiency is attributed to the simple combustor design used in most micro jet engines. The lower heating value of the fuel is assumed at $42000 kJ/kg$. One of the main limitations in gas turbine engines is the maximum TIT. For small scale applications, an uncooled turbine design must be assumed, limiting the TIT to $1100K$ for conventional material choices. The core engine nozzle is modelled as a convergent nozzle. Its throat area A_{CN} is varied to determine the setting which is best suited to the mission point demand. The turbine map is of special importance for the eHACE concept to work, as described in EHACE-CONCEPT. The turbine from the NASA "Small Engine Technology Program" (see Franklin et al. (1968)) features the required large area of high efficiency. A performance map of this turbine was extended to describe the reduction in efficiency for high pressure ratios and scaled to match the compressor operating point described above, including 1% mechanical losses of the shaft. This results in the following values: $w_{corr,T} = 0.3334 kg/s$, $\Pi_T = 1.964$ and $\eta_T = 0.90$. The scaled turbine map with the described operating point and the effects of power off-take by the generator and increased A_{CN} are presented in figure 3. At constant speed and A_{CN}, increased power off-take is achieved by increasing the fuel flow and with it the TIT. This leads to a decrease in corrected turbine speed and a slight reduction in mass flow due to thermal throttling. Instead of increasing fuel flow and TIT, A_{CN} can be increased, resulting in a higher air mass flow and turbine pressure ratio, to achieve the increase in turbine power output.

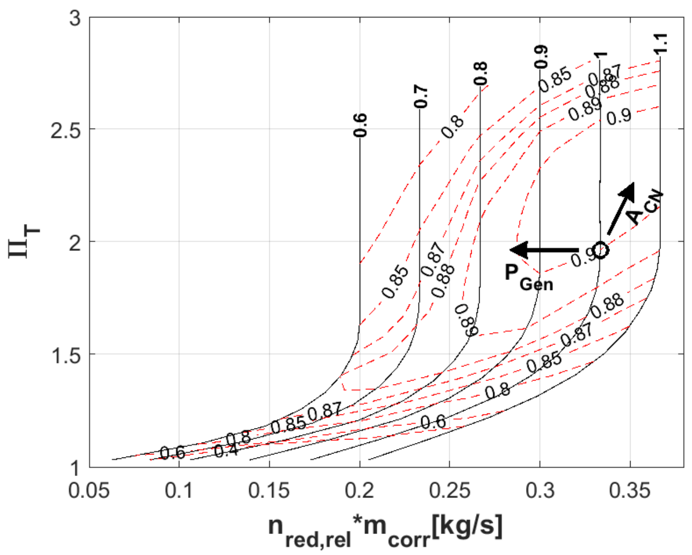


Figure 3: turbine performance map

Electric Motor and Generator

The electric motor and generator are modelled as mechanical loads on the core engine shaft and the fan shaft, respectively. For both machines a constant efficiency of $eta_{Mot} = eta_{Gen} = 0.95$ is assumed. The maximum mechanical input power for the generator is defined at $P_{Gen,max} = 14kW$ at the maximum mechanical core engine speed. This limit is assumed based on the availability of small high power generators, capable of the high shaft speeds of a micro jet engine. Representing the behaviour of an electric generator, the available output power is linear dependent on the shaft speed. P_{Gen} is varied within the parametric study but is limited by the core engine speed and the maximum TIT of the core engine.

As described earlier, the fan motor can be driven with the electric power supplied by the generator, the battery, or in part from both sources. With an estimated efficiency of the power electronics module of $\eta_{PEM} = 0.97$, the maximum available power for the fan without battery usage is defined according to equation 3. The product of three component efficiencies results in a transmission efficiency between the core engine shaft and the fan of $\approx 87.5\%$. This is relatively low value compared to a fixed gearbox with transmission efficiencies up to 99% and can be a limiting factor for the concept.

$$P_{Fan,max,sustained} = P_{Gen,max} \cdot \eta_{Gen} \cdot \eta_{PEM} \cdot \eta_{Mot} = 14kW \cdot 0.8754 = 12.256kW \quad (3)$$

FLIGHT MISSION POINTS

The eHACE is intended for the application in small subsonic UAS. As described earlier, the concept is most useful for flight missions with significant mission time spent at part load conditions. A good example would be a surveillance mission starting with a long distance "cruise", as much "loiter" time as possible over a destination area. For military UAS, another mission point can be important, which is high speed flight in low altitude, further labelled "dash".

The current study is conducted independently from an actual aircraft design to investigate the design influences and the component interaction of the eHACE. This decision brings limitations for the definition of the flight mission points. Without a specific aircraft configuration, its weight, the drag and lift forces and their relation and consequently the required thrust for the flight mission points are not defined.

Instead, the "cruise" point is set as a design point, and the engine optimized for lowest specific fuel consumption (SFC) at this flight condition. The thrust requirement for the "loiter" points are then correlated to the achieved thrust at the "cruise" point. According to Raymer (2018), a jet powered aircraft loiters optimally at the maximum lift to drag ratio C_L/C_D, while cruising optimally at 86.6% of the maximum lift to drag ratio. For a first approximation, a constant weight of the aircraft, and consequently constant lift is assumed. With this assumption, the drag and the necessary thrust at the optimal loiter speed can be defined at 86.6% of the drag and thrust at cruise. In absence of an actual aircraft configuration, the optimal flight speed and Mach number for "loiter" cannot be determined. Instead, a range between $M_0 = 0.4$ and $M_0 = 0.6$ is investigated to study the influence of the flight Mach number at a constant loiter altitude.

The "dash" point represents the highest in flight thrust requirement for the system. The achievable Mach number depends on the drag of the aircraft and the achievable thrust of the propulsion system. With both values unknown, a Mach number of $M_{0,dash} = 0.7$ is assumed as a starting point to study the capabilities of the eHACE and the influence of its variable components for in-flight operation under high dynamic pressure.

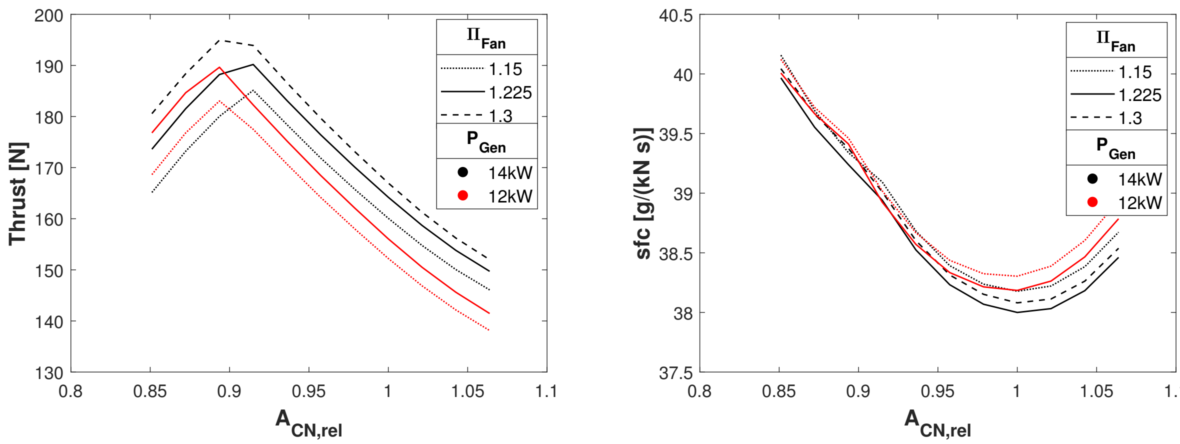
Based on these considerations, the following mission points were defined for the parametric study:

- ”cruise” at Mach 0.9 at an altitude of 9000m
- ”loiter” at Mach 0.4 to 0.6 at an altitude of 3000m
- ”dash” at Mach 0.7 at an altitude of 500m
- ”static” for maximum static thrust at sea level

RESULTS

Cruise

The ”cruise” point demands high thrust for a significant time. Accordingly, the battery should not be used for this mission point and the fan power is directly coupled to the generator power as described by equation 3. It is assumed, that the core engine runs at maximum engine speed to allow the maximum power off-take by the generator. To determine the optimal engine settings for lowest SFC, a parametric study is conducted, varying Π_{Fan}, P_{Gen} and A_{CN}. The fan mass flow results from the set combinations of P_{Gen} and Π_{Fan}. The nozzle area for the bypass nozzle is automatically adjusted to achieve choked flow in the bypass nozzle. Selected results for thrust and SFC are presented in figure 4, also showing the influence of the P_{Gen} and Π_{Fan}. A_{CN} is normalized to the value for lowest SFC. For $P_{Gen} = 12kW$ no graphs are presented at $\Pi_{Fan} = 1.3$, because the power is not sufficient for this pressure ratio.



(a) (b)

Figure 4: Thrust and SFC over A_{CN}

It is shown that the maximum thrust and the minimal SFC can be achieved with $P_{Gen} = P_{Gen,max} = 14kW$. The thrust increases with Π_{Fan}, whereas an optimal value for the lowest SFC is found at $\Pi_{Fan} = 1.225$. A_{CN} has a higher influence on thrust and SFC than Π_{Fan} or

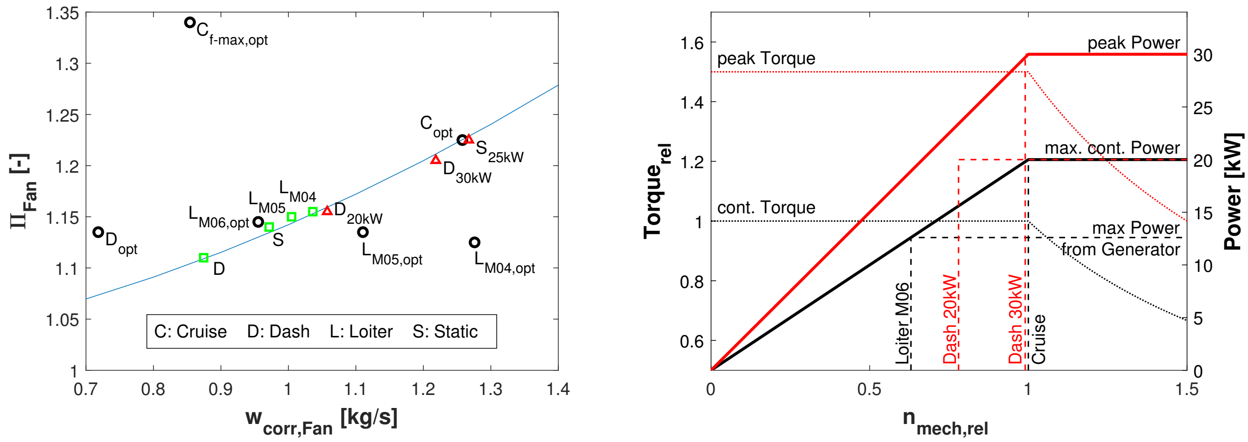
P_{Gen}. If A_{CN} is set too small, the core engine speed is reduced to not exceed the maximum TIT. This results in reduced thrust as can be seen in figure 4a for $A_{CN,rel} < 0.9$. It is worth noting, that for a constant Π_{Fan} the BPR increases with the generator power. The lowest achievable SFC is $38.0g/(kN \cdot s)$ with $\Pi_{Fan} = 1.225$ and a BPR of 0.65, resulting in a thrust of $F = 164.2N$. This thrust will be used as a reference for the required thrust at "loiter" as described in the previous section. The thrust share of the bypass flow is relatively low at $\approx 5\%$. Still, the fan serves an important purpose for the cruise condition by raising the pressure level in the core engine and therefore, increasing its thermal efficiency. The lowest SFC is achieved with P_{Gen} at its maximum. This indicates that the turbine is capable to transfer more power from the core flow to the fan without a significant decrease in turbine efficiency but is limited by the capabilities of the generator.

If, at a constant $P_{Gen} = 14kW$ and $\Pi_{Fan} = 1.225$, A_{CN} is reduced until the maximum TIT is reached, the thrust can be increased to $F = 190.2N$ at an SFC of $38.9g/(kN \cdot s)$. With the reduced A_{CN}, the BPR increases to 0.70. By reducing the bypass nozzle area from this point until the minimum BPR is reached, Π_{Fan} increases to $\Pi_{Fan} \approx 1.34$ and a maximum thrust of $F = 198N$ could be reached. This operating point might not be achievable if the limitations of a fan performance map are considered, as shown below.

Fan and Motor Operating Points

If the optimal fan operating points for all investigated mission points are plotted with Π_{Fan} over the corrected mass flow, the shape of a fan performance map can be defined. Figure 5a shows the fan operating points for each mission point. The optimal points (depicted as black circles) are widely spread in the map, making it impossible to be covered by a conventional fan design. The optimal point for maximum static thrust is not shown in figure 5a, it would be at $\Pi_{Fan} = 1.06$ and $w_{corr} = 2.2kg/s$. Since a major goal of the eHACE is a mechanically simple engine architecture, the use of variable guide vanes or such means is not considered in this study. Instead, compromises must be made by adjusting the engine settings to shift the fan operating points into a reasonable range. In the mission points for maximum thrust, this slightly reduces thrust and increases SFC for the points optimized for lowest SFC. In the fan operating map, a line of highest efficiency is assumed as a quadratic function, including the optimal point for cruise. The shape of this curve is a reasonable choice for a first estimation, but depends on the actual fan design. By adapting the bypass nozzle area, the operating points of the fan can be shifted close to this line (shifted points depicted as green squares in figure 5a). For these shifted operating points, the initial assumption of constant fan efficiency is applicable, whereas it is unsuitable for the operating points far off this high efficiency line. The operating point for maximum thrust at cruise is far off from any other operating point in the map and can not be achieved. Accordingly, the maximum thrust at cruise is limited to $F_{max,cruise} = 190.2N$ as mentioned above.

For the operation of an electrically powered fan, the motor characteristics must be considered since they are not dependent on the ambient conditions. If the fan operating point at cruise is set at $n_{corr,rel} = 100\%$ and $n_{mech} = 100\%$, the points for "loiter" at $M_0 = 0.6$ and "static" will be placed around the speed line of $n_{corr,rel} \approx 60\%$, resulting in a mechanical speed of $n_{mech} \approx 63\%$. An electric motor is usually limited by its maximum torque, which is constant up to the design speed and reduces in the overspeed area at $n_{mech,rel} > 1$ (see figure 5b). Accordingly, the motor power decreases linearly with the mechanical speed. In this study, the optimal engine settings for all evaluated mission points are achieved with the maximum available P_Gen.



(a) **(b)**

Figure 5: fan and motor operating points

Therefore, the fan motor must deliver the same continuous output power of $P_{Fan} \approx 12.3kW$ at the "cruise" point and at the lower mechanical speed of "loiter" at $M_0 = 0.6$. Accordingly, the design point for this power must be set at the lower mechanical speed of $n_{mech} \approx 63\%$ for the "loiter" point. As shown in figure 5b, this results in an oversized motor approximately by factor 1.6 with a maximum continuous fan motor power of $P_{Fan,cont.} \approx 20kW$ and part load operation at "cruise".

The peak torque and with it peak power can exceed the continuous values for a certain amount of time, until the thermal limit of the motor is reached. Assuming that the peak power can exceed the continuous power approximately by factor 1.5, a maximum peak motor power of $P_{Fan,peak} \approx 30kW$ can be achieved. This is useful for mission points with peak thrust requirements at low altitude like "static" or "dash". In figure 5a, feasible fan operating points for "dash" with the motor output power increased to $20kW$ or $30kW$ are shown as red triangles. The corrected fan speed at these points is $n_{corr,rel,20kW} \approx 75\%$ and $n_{corr,rel,30kW} \approx 95\%$. This results in mechanical motor speeds of $n_{mech,20kW} \approx 78\%$ and $n_{mech,30kW} \approx 99\%$. As can be seen in figure 5b, this is within the estimated operation range of the motor. For maximum thrust at the "static" condition, the maximum fan motor power has to be limited to $\approx 25kW$. As shown in figure 5a, the fan would be run at overspeed otherwise, due to the higher corrected mass flow compared to "dash".

Loiter

As described in FLIGHT MISSION POINTS, the required thrust for the "loiter" points is derived from the thrust for lowest SFC at "cruise". With a cruise thrust of $F_{cruise} = 164.2N$, the loiter thrust is defined at 86.6% of that at $F_{loiter} = 142.2N$. The NPSS model is set up to iterate towards this thrust by adjusting the core engine speed and the bypass nozzle area for given combinations of Π_{Fan}, P_{Gen} and A_{CN}. A reduction of the A_{CN} increases the core thrust, while increasing Π_{Fan} and BPR results in increased bypass thrust. The optimization goal is the engine setting for minimal fuel burn, which equals the setting for lowest SFC since the thrust is held constant.

For each Mach number investigated, an engine setting for an absolute minimum for SFC was determined at the maximum available P_{Gen}. This minimum SFC increases with the Mach number. With increasing Mach number, the influence of the ram drag, which is the product of the engine air mass flow and the flight velocity, increases. Accordingly, the bypass thrust share decreases due to the limited fan power. To counter this, the core engine speed is increased, and A_{CN} reduced, resulting in a higher thrust from the core engine.

As depicted in figure 5a in the previous section, the optimal fan operating point for loiter at a constant altitude changes with the Mach number. This is caused by the independence of the fan motor power from the ambient conditions, whereas the corrected fan mass flow depends on the intake pressure and therefore, the flight Mach number. At $M_0 = 0.4$, Π_{Fan} is low and the corrected fan mass flow high for the optimal setting, with increasing Π_{Fan} and decreasing mass flows for higher Mach numbers. To achieve a feasible fan operating map, the fan operating points for $M_0 = 0.4$ and $M_0 = 0.5$ were shifted to better align with the defined high efficiency line, as discussed above. This shifting increases the SFC by 0.16% on average. The trends stated above still apply for the shifted operating points, but with lower gradients as the shifted operating points are more clustered in the fan map. The lowest SFC is achieved with the maximum available P_{Gen}. This highlights, that the generator is the limiting component for further reductions in SFC.

Static and Dash

The "static" condition is included to evaluate the maximum static thrust of the system at sea level standard. Without the ram drag of an in-flight condition, it is favourable to maximize the engine air mass flow and the BPR. This behaviour occurs because the splitter- and duct pressure losses are proportional to the absolute pressure level. Accordingly, the lowest losses and therefore, the highest thrust can be achieved with a low fan pressure ratio and high mass flow. The resulting fan operating point with $\Pi_{Fan} = 1.06$ and $w_{corr} = 2.2kg/s$ is far off from all other fan operating points as shown in figure 5a. With a fan, that is designed to work at this operating point, the eHACE would operate at a BPR of 2.4. The resulting size of the fan and the bypass duct are not appropriate for the other investigated mission points. Accordingly, the operating point is shifted towards the defined high efficiency line, resulting in a reduction in maximum thrust by $\Delta F_{max,static} \approx -6.3\%$.

The "dash" condition is included to investigate the behaviour of the eHACE at low level high speed flight. This mission point requires the maximum thrust of the system, but only for a short amount of time. With this time constraint, the ability of the electric motor for peak power can be used as described above. As a consequence of the high ram drag at low altitude high speed flight, the BPR and with it the engine mass flow should be kept as low as possible. The resulting fan operating point at $\Pi_{Fan} = 1.135$ and $w_{corr} = 0.72kg/s$ might be above the surge line of the fan. Therefore, the BPR is increased to shift the fan operating point to the high efficiency line in the map, which reduces the thrust by $\Delta F_{max,dash} \approx -2\%$.

For these short time operating points, the battery could supply the difference between the P_{Gen} and the fan motor power, or the complete power could be drawn from the battery. This choice does not affect the fan operating point, but the operating point of the turbine and the maximum achievable thrust. Without power off-take by the generator, A_{CN} can be reduced without reaching the TIT limit. Figure 6 shows this effect for the static condition and the fan motor power at $25kW$. The steps in the graphs are attributed to the discrete steps in for A_{CN} in the parametric study. The highest thrust can be reached, if 100% of the fan power is supplied by the battery. For this mission point, the difference in thrust between $P_{Gen} = 14kW$ (battery power share $\approx 40\%$) and no power off-take by the generator (battery power share $= 100\%$) is $\approx 5.3\%$. The behaviour at "dash" with the fan motor power at $20kW$ or $30kW$ is comparable. The huge difference in battery power share translates directly to the required power output and storage capacity of the battery and therefore, its size and mass. Accordingly, this choice depends on the aircraft and the flight mission if the added weight can be tolerated over the increased maximum thrust.

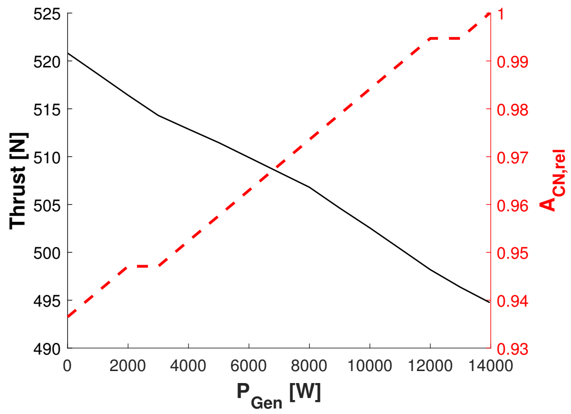


Figure 6: Thrust over P_{Gen} for "static" with $25kW$ fan motor power

Performance Comparison to a Turbojet Engine

To compare the performance of the eHACE system and to evaluate the impact of the fan with the electric coupling, a turbojet engine with a variable area nozzle is simulated at the same flight mission points as the eHACE. A turbojet is the only available engine architecture in a thrust and size range comparable to the eHACE. As described in NPSS-MODEL, the core engine of the eHACE is used as a reference turbojet without any scaling done to its components, and an inlet with the same characteristics as the eHACE-inlet is used.

The desired thrust at "cruise" ($164.2N$) can only be achieved by the turbojet if the maximum TIT is increased by $\approx 40K$, which will reduce engine life. Without this increased TIT, the reference turbojet reaches a maximum thrust of $160.2N$ for the ambient conditions at "cruise".

The results for the maximum achievable thrust at the flight conditions investigated are presented in table 1. For the static condition with additional battery power, two thrust values are presented. First, the fan power is supplied in part from the generator and the battery ("static, 25kW") and second, the fan power is drawn from the battery only ("static, 25kW-Bat") resulting in increased thrust, as described above. For the presented "dash" points with additional power, the fan power is supplied by both, the battery and the generator at its maximum power. The eHACE can generate a higher thrust at all investigated flight conditions, even without drawing power from the battery. The thrust of the turbojet stays the same for the various operating points of the eHACE presented for "static" and "dash", since no power can be added in the turbojet.

The compared results for SFC are presented in table 2. For the eHACE, the presented results or those with the fan operating points shifted towards a line of high efficiency (see section "Fan and Motor Operating Points"). At "loiter" the reference turbojet is near its temperature limit

Mission Point	Thrust Turbojet	Thrust eHACE	Difference %
cruise	160.2	189.3	+18%
loiter, M0.4	236.3	275.2	+16.4%
loiter, M0.5	238.8	271.8	+13.8%
loiter, M0.6	244.4	275.4	+12.7%
static	339.2	398.4	+19.1%
static, 25kW	339.2	494.8	+45.8%
static, 25kW-Bat	339.2	520.8	+53.5%
dash	307.8	326.3	+7.5%
dash, 20kW	307.8	354.4	+16.8%
dash, 30kW	307.8	390.0	+28.5%

Table 1: maximum thrust $F[N]$ for the turbojet and the eHACE

and above the TIT limit for "cruise". To compare the SFC at "static" and "dash", the eHACE is throttled back to the maximum achievable thrust of the reference turbojet. To compare operating points with power drawn from the battery, the SFC is not a sufficient parameter. Instead, the "specific energy consumption" could be used, and optimum values of battery power share determined for each flight mission point, which is beyond the scope of this paper. Accordingly, only the operating points without battery usage are included in table 2. The eHACE achieves a lower SFC at all mission points investigated, but only by a small margin at "loiter" and "dash", decreasing with the flight Mach number.

Mission Point	SFC Turbojet	SFC eHACE	Difference %
cruise @ 164.2N	42.6	38.0	-10.8%
loiter, M0.4 @ 142.2N	39.9	38.3	-4.0%
loiter, M0.5 @ 142.2N	41.4	40.4	-2.4%
loiter, M0.6 @ 142.2N	42.8	42.3	-1.2%
static @ 339.2N	34.9	29.4	-15.8%
dash @ 307.8N	44.9	43.1	-4.1%

Table 2: SFC in $g/(kNs)$ of the turbojet and the eHACE

SUMMARY

In this study, the behaviour of the eHACE concept and the influence of its variable components was investigated for several flight mission points. With this study, the operating range of a fan was determined, which can work well with the given parameters of the core engine and the limited generator power. The ideal operating points for such a fan cannot be covered by a fan without variable geometry and had to be shifted into a reasonable range. Furthermore, an initial sizing of the electric motor to power the fan was conducted. To deliver the required power at the different mission points with the wide range of ambient conditions, the electric motor must be oversized approximately by factor 1.6 compared to the maximum power delivered by the generator.

For the eHACE concept to work as intended, the turbine performance map is of high importance. The turbine needs a relatively wide operating range with high efficiency to accommodate the variable power off-take by the generator, without significantly reducing turbine efficiency. With the chosen turbine map, the core engine could handle more power off-take by the generator than the $14kW$, which were set as a limit in this study. For future studies, the power limit of the generator should be increased or the core engine size decreased to determine the optimal power level of the electric components and their relation to the turbine parameters.

It could be shown, that the eHACE concept can significantly increase the thrust and reduce the specific fuel consumption when compared to a turbojet engine similar to the eHACE core engine. The comparison to a turbojet is used, because this is the only engine architecture available in the thrust range up to $500N$. The eHACE will be heavier and larger than a turbojet engine due to the integrated electric machines and the added fan and bypass. This applies even if the turbojet is scaled up to generate the same maximum thrust at all flight conditions. With the lower SFC of the eHACE, a "break-even" point can exist, at which the larger size and mass of the engine is compensated by the lower fuel consumption. This point depends on the flight mission of the aircraft, mainly on how much time is spend at various flight conditions and the required thrust at these conditions. It has to be investigated, for which kind of flight mission the eHACE concept is most useful, and if the increased mass and complexity is justified.

The investigated flight mission points can represent a high percentage of the flight mission time of a UAS. Still, to completely evaluate the assets and drawbacks of different engine architectures, a complete mission analysis is necessary. This includes at least a basic design for a UAS with defined mass and aerodynamic behaviour and will be subject to future studies at the IJP.

REFERENCES

Aronstein, D. C., Hirschberg, M. J. & Piccirillo, A. C. (1998), *Advanced Tactical Fighter to F-22 Raptor: Origins of the 21st Century Air Dominance Fighter*, American Institute of Aeronautics and Astronautics, Reston ,VA.

Bevilaqua, P. M. (1997), 'The Shaft Driven Lift FAn Propulsion System for the Joint Strike Fighter', *Proceedings of the American Helicopter Society 53rd Annual Forum* .

Franklin, W., Heilbron, J. & Moskowitz, S. (1968), 'USAAVLABS Technical Report 68-50B, Small Gas Turbine Engine Component Technology- Turbine, Volume II: Phase II Summary Report'.

Jäger, P., Stößel, M., Krummenauer, M. & Niehuis, R. (2022), 'Studies on an Electric Hybrid Adaptive Cycle Engine', *Proceedings of the XXV. International Symposium on Air Breathing Engines (ISABE)* (2022-219).

Johnson, J. E. (1996), 'Variable Cycle Engine Concepts', *AGARD Conference Procedings 572* .

Kadosh, K. & Cukurel, B. (2017), 'Micro-Turbojet to Turbofan Conversion Via Continuously Variable Transmission: Thermodynamic Performance Study', *Journal of Engineering for Gas Turbines and Power vol.139 (2)* (022603).

Palman, M., Leizeronok, B. & Cukurel, B. (2018), 'Mission Analysis and Operational Optimization of Adaptive Cycle Micro-Turbofan Engine in Surveillance and Firefighting Scenarios', *Proceedings of the ASME Turbo Expo: Turbomachinery Technical Conference and Exposition* (GT2018-75323).

Raymer, D. P. (2018), *Aircraft design: A conceptual approach*, AIAA education series, sixth edition edn, American Institute of Aeronautics and Astronautics Inc, Reston, VA.

Rendón, M. A., Sánchez R., C. D., Gallo M., J. & Anzai, A. H. (2021), 'Aircraft Hybrid-Electric Propulsion: Development Trends, Challenges and Opportunities', *Journal of Control, Automation and Electrical Systems, vol.32* (5), 1244–1268.

Wall, T. J. & Meyer, R. (2017), 'A Survey of Hybrid Electric Propulsion for Aircraft', *53rd AIAA/SAE/ASEE Joint Propulsion Conference* (AIAA 2017-4700).

Walsh, P. P. & Fletcher, P. (2004), *Gas Turbine Performance: Second Edition*, Blackwell Science.

Westmoreland, J. S. & Stern, A. M. (1979), 'Variable Cycle Engine Technology Program: Planning and Definition Study, Final Report', (NASA-CR-159539, PWA-5581-12).