Hybrid Turbo Compound Fan Engine an Eco-Efficient Propulsion System for Aviation

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Abstract
The path to electric propulsion systems depends on the development of powerful, compact and very light energy storage system with a high storage density. In order to create an environment-friendly intermediate solution in the medium term, especially for aircraft engines of medium power classes, it makes sense to use an innovative, electrically parallel hybrid unit based on rotary engines and electric boosters for start and climb phases as a propulsion system. An aero-engine application, based on the HSD concept (HSD = hybrid super-drive – hybrid Wankel rotary engine) for different hybrid-parallel propulsion systems is presented. In this article, the introduced technology is based on a currently produced family of multi-component Wankel rotary engines. The proposed HSD concept uses a chamber volume of 650ccm per rotor. The projected power range (0.8 to 1.36 MW) is covered by an innovative hybrid electric parallel turbo compound concept together with 2x4 rotary engine units. A novel, air-bearing turbo engine with integrated electric drive is used as a turbocharger for charging the rotary engine. For the aero-engine technology, the counter-rotating fan (CRF) concept shown as an example for an aircraft technology carrier (light jet) leads to a further increase in the efficiency of a complete system.

Keywords: rotary engine, hybrid combustion engine, aero-engine, air bearing, counter rotating fan, electric flight

1. Electric and hybrid-electric flight
The efficiency potential of current engine systems has been explored to extensive studies [33]. To meet these guidelines, many manufacturers from the aerospace industry, including the new developments for innovative engines (for example of coupled turbo- and piston engines [16]) want to introduce overall concepts for electrical flight [18]. Bauhaus Luftfahrt, as a research institute – cooperating inter alia with Airbus, Liebherr Aerospace and MTU, has developed in this context with the CE-liners a concept aircraft. With such an aeroplane, the electric fly with a commercial jet should be possible in 2035 [4]. All-electric aviation needs right overall concepts for new technologies. Thus, a huge developing expenditure will still be necessary for the battery technology, the fuel cell technology, the refueling, loading and in particular for the airport infrastructure [18]. Hybrid energy systems with a combustion engine, generator and electric motor can make a contribution to reducing
pollution in a transition phase (motivating for CO2 reduction) using technologies from the automotive industry. The problem seems to be particularly the supply of the required energy performance for a corresponding flight, and the realization of the power to weight ratio and safety of the required drive.

2. Technologies for the hybrid aero engine

The proposed propulsion technology is a hybrid drive consisting of a high-performance turbo compound Rotary engine (HSD) together with an efficient and compact electric motor. For the propulsion, the adaptation of modern counter-rotating fan is being considered. The advantages of using a turbo rotary engine as a hybrid engine, in combination with a suitable electric motor, could be demonstrated with an example of a regional commuter plane with propeller engine in [1].

2.1 Technologies for the core engine

The basic concept for the selected internal combustion engine is essentially based on the architecture of the KKM5 0 0 family from the company Wankel Supertec GmbH of Cottbus (www.wankelsupertec.de, [5]). In recent years, they have successfully developed the rotary piston engine system for diesel fuel. The electric, air-bearing turbomachine, which is used for charging the engine, based on technology from the company Euro-K GmbH of Cottbus (MTiG, www.euro-k.de [6], figure 1) and on the fundamental work of the authors [7].

![Figure 1. 4 Rotor Wankel Rotary engine bench (Industrialized technology, [5])](image)

The Wankel engine technology with an air-bearing e-turbo engine (see figure 12) provides a high power density and low vibration. Additionally, the modular design is an advantage for the development of the new drive concepts for general aviation in the future. The TBO times required for the aeronautical potential of this system have already been proven in the past through the use of the individual components in various applications. The technological basic development of the engine concept in particular for diesel and kerosene application has been described in various publications ([14], [15], [19]).

The combustion process has been extensively investigated and developed in the past, which is reflected in today's standard applications of the rotary motor system [10]. The power to weight ratio, which is very important for aviation applications, can be archived by Wankel engines up to 3 kW/kg. This can be located in the area between the commercial gas turbine aero engines without afterburner (up to 6 kW/kg actual in service) and the in-service aircraft piston engines (1kW/kg). By supercharging the core engine with the so-called MTiG-system (microturbine with integrated generator) with air bearings, oil-free cabin air can be guaranteed.

The state of development on the Wankel-HSD system (figure 1) can be described as follows:

- The basic technology of the Wankel engine for multi-fuel combustion (gasoline, diesel, kerosene) was developed largely and validated [5], [12].
The basic technology which has found its niche markets outside the aviation industry is used for special applications and is constantly being developed.

2.2 Electrical drives for the representation of the hybrid component

Siemens already has developed lightweight and powerful aircraft engines for aeronautical applications. With the electric drive SP260D, an output of 260kW, the power to weight ratio of 5.2kW/kg with a maximum continuous speed at 2500rpm and a maximum torque of 1000Nm, η = 95%, a test aircraft could already start and be operated electrically [13], [19], [2]. Such an air drive can be used and adapted as a hybrid extension with an internal combustion engine. At the same time, in inflight operations, using a generator is required.

The research group "Bauhaus Luftfahrt" assumes in a draft of the CE-Liner, that with a storage capacity of 2000Wh/kg in light batteries, which have to be developed, also for larger aircraft the electric flight is possible [4], [21]. KIT/FG Energiewirtschaft in Karlsruhe, however, has already developed battery materials with a capacity of 450Wh/kg [19], [20]. With such a system, the battery volume and for a 15-minute take-off boost, the capacity can be reduced to the extent that an installation in a commuter aircraft without increasing the weight to volume ratio of the aircraft is possible. With this available battery system and power electronics a power to weight ratio of 2.9kW/kg for the hybrid HSD-System instead of 3.6kW/kg [26] for small turboprop systems (e.g. PW535B) can be realized. For power electronics, a compact system from the automotive industry can be used with products from the manufacturer Continental [22].

2.3 Hybrid systems in aeronautical propulsion

In [1], the parallel hybrid system has been discussed using the example of a Beechcraft 1900. This aircraft uses originally a serial drive system. In this paper, the focus will be in the field of parallel hybrid systems in the range to 1500kW. These drive systems could be implemented as a mild- or medium-hybrid or a full hybrid concept. Figure 2 shows the position of the engine benches in the fuselage. In this paper, the HSD concept is visualized using the example of a sheathed counter propfan (CRF). This approach is chosen because for business jets the possible speed range during flight is reasonable in a flight Mach number range up to 0.75. Furthermore, a technology demonstrator with the selected hybrid drive technology could be implemented easier in this class of aircraft range than in the commercial aircraft sector. In the selected aircraft concept, a good integration of the HSD drive in the fuselage resulted at an angle of $\alpha_{HSD_{1-2}} = 90^\circ$ (see figure 2). Because the HSD is shorter than comparable shaft engines, therefore the torque transmission of the main engine to the CRF appears to be easier. Thus, the torque transmission to the angular gear (see Figure 3) at engine speed $n_{Motor}$ can be carried with a direct shaft (L-configuration). When using a shaft engine, a planetary gear and, because of the longer machine length, a Z-arrangement of the powertrain is required. In such an angular gear, the required speed $n_{CFR_{a,b}}$ can be transmitted.

![Figure 2. HSD-drive concept for the Business Jet MariE-1 with an engine angle of $\alpha_{HSD_{1-2}} = 90^\circ$](image)

![Figure 3. Transmissions-concept of the HSD-CRF-Power plant with $\frac{n_{CFR_a}}{n_{Motor}} = -\frac{n_{CFR_b}}{n_{Motor}} = 1:4$ to $1:2$ (L-Configuration)](image)
The term "HYBRID" has a double meaning in the HSD engine. On the one hand, a hybrid combustion process with stratified charge takes place in the air-compressing Wankel engine. By a high-pressure direct injection, the fuel is supplied into the combustion chamber and ignited there [10]. Otherwise, in a hybrid concept, the Wankel engine is very well suited for a combination with electrical drive systems. The system can also be classified in the parallel hybrid category.

Until now, only a serial hybrid electric aircraft from Diamond Aircraft [31] has been realized. The advantages and disadvantages of the serial principle for aeronautical applications have been discussed in [1] and [24]. In a parallel hybrid aerospace propulsion system, electric motor and internal combustion engine can be operated simultaneously. With this addition of drive power, the individual drive machines can be designed to be smaller and more effective. This leads to a reduction in the space and weight installation. However, this reduction will be repaid partly through energy storage (battery) and partly via power electronics. This depends on the chosen level of hybridization $H_{Hybrid}$ of the drive system [34]:

$$H_{Hybrid} = P_{Elektro}/(P_{eff/HSD} + P_{Elektro})$$

This study shows that a mild hybrid system with $H_{Hybrid} < 0.23$ can certainly be a viable variant for the aviation in the future. Full-Hybrid Systems use the combustion engine only for range extending and are possibly an option for extending the range of an electrical flight system. Figure 4 shows the basic structure of the explored powertrain. A Wankel Turbo-Compound is connected with a Counter-Rotating Fan Propulsor by a shaft and gearbox-system. The electric boost system is mounted on the outgoing shaft from the Wankel system. Therefore, the combustion engine and booster can act in parallel with the drive train, which adds the torques of the individual drives. This allows a weaker design of the engines, saving costs, weight and space. Currently, hybridization levels of 25% to 40% appear to be appropriate.

Using this degree of hybridization, the energy storage capacity is designed according to the "take-off mode". E-machine(s) and internal combustion engine(s) (ICE) are both working at maximum power (boosting, see Figure 5, red parts are working). In cruising mode, the ICE works and the electric motor can support it. Additionally, the E-Machine can increase the load of the ICE to higher torque and charges the energy storage. This is very helpful when engine damage occurs and also improves the entire energy management (particularly in the landing approach).

![Figure 4. Basic structure of the powertrain in ICE-Modus](image)

![Figure 5. Boost function during takeoff. E-machine and ICE (red) made max. performance.](image)

![Figure 6. MariE-1 as a technology platform for 2 HSD CRF engines](image)

| Parameter       | Symbol | Value     |
|-----------------|--------|-----------|
| Length          | $L$    | 18.49m    |
| Max. takeoff weight | $M_{TOW}$ | 5.300kg |
| Vengpaht        | $S$    | 10.130m   |
| Ving area       | $A$    | 26.247m$^2$|
| Passenger       |       | 14        |
| Crew            |       | 2         |
| Height          | $h$    | 0.90m     |
| Cell-diameter   | $d$    | 2.10m     |
| Performance     |        |           |
| Engine          | $P$    | 2x 1.350kW |
| Range           | $R$    | 3.300km   |
| Max. cruise speed | $Ma$ | Mach 0.75 |
| Service Ceiling |        | 11.000m   |

Table 1. Design parameter for the business jet MariE-1
In the descent phase, mainly the electric machine works, the internal combustion engine only works as a support for the propulsion system. The electric motor can act as a generator to fill the battery at steep descent so that the drive can now regain potential energy for the use by taxiing on the ground. Figure 6 shows a technology platform for the use of 2 HSD CRF engines. On landing, the electric motor and the ICE both operate. This is necessary to make an effective thrust reversal and makes it possible to provide enough power for a go-around. During the subsequent, "taxi operation point" only the electric engine works (figure 7). To develop a combined hybrid drive, a power split system is realized, which represents a combination of serials and parallel concepts. At present, weight disadvantages at a power weight of 1.5kW/kg for conventional Hybrid Engines compared to 3.5kW/kg MTOW for small Turbine Engines [26] do not recommend a hybrid operation in an aircraft system. So, there still is no economical hybrid system in an aircraft. For these reasons, a single-shaft parallel hybrid rotary engine weight with a MTOW of 3kW/kg was chosen for the selected system (see also Figure 7) and optimized with near future technical capabilities for the flight systems. It should be determined if the economic use of such a system reduces emissions and increases the power to weight ratio of hybrid development.

3. Use of the HSD8650-40 in a business jet
To investigate the applicability of the hybrid engine application in a real-world system, a business jet for up to 14 passengers and a 2-man crew was designed (MariE-1, Figure 6). The established specifications and boundary conditions were based on the in-service aircraft. The use of a fan concept was realized, which allows reaching cruising speed at Ma = 0.75. The higher cruising speed compared with propeller aircraft makes it possible to provide a higher speed during takeoff and landing safely, so that the aircraft can be queued in the normal approach management on large airports [14].
Advanced engine developments are adjusted to high bypass ratios. This allows for more economical flight operations by improving external efficiency. Currently, engines are under development, with a bypass ratio of up to 1:24.5, such as at an ANEA configuration [23]. The main part of the generation of propulsion is taken from the fan with the bypass stream.

With the MTU CRISP concept of a counter-rotating fan (CRF) an effective drive concept was developed. With this concept, operating costs can be reduced and it may be achieved a significant reduction of aircraft noise [32]. Therefore, outer efficiency increases further and can reach up to 93% [27]. Now, if such a concept is not driven by a gas turbine, but with the above-HSD, the benefits of an effective turbo-compound concept are combined with a modern propulsion system. For these reasons, the technology platform will be equipped with hybrid drives of the type CRF-HSD-8650E-40.

3.1 A selected aircraft as a technology carrier
For an analysis of the applicability of the CRF-HSD engine system, an aircraft of the class "Light Jets" was modelled (Figure 6). It was ensured that advanced performance parameters were observed [17]. In addition, it should be possible to integrate the intended HSD engine with all the necessary auxiliary units in the fuselage twice (for redundancy).

3.2 Aircraft Engine System Architecture
Based on the experiences with the basic engine family (rotary piston engines of chamber volume class 500ccm) own preliminary investigations (as shown in [1]) were carried out for aircraft engines for the year 2030 with the project name HSD (Hybrid Super-Drive) (650ccm chamber volume class) were carried out. Deviating from the basic engine concept, this system has been extended with an enlarged rotor, a parallel-connected electric motor, an e-turbocharger (based on the MTiG) and a sufficient e-energy storage.

3.3 A Wankel rotary engine as a fan drive.
Based on the experiences with the basic engine family (rotary piston engines of chamber volume class 500ccm) own preliminary investigations (as shown in [1]) were carried out for aircraft engines for the year 2030 with the project name HSD (Hybrid Super-Drive) (650ccm chamber volume class) were carried out. Deviating from the basic engine concept, this system has been extended with an enlarged rotor, a parallel-connected electric motor, an e-turbocharger (based on the MTiG) and a sufficient e-energy storage.

Compared with the reciprocating engine, the Wankel engine with the same performance has a lower system weight. They may also be optimized for good specific fuel consumption, which is possible by an advanced stratified charge method [11]. This new aircraft engine concept covers the range up to 1500kW. For this purpose, it uses the advantages of the Wankel rotary engine technology combined with a highly charged supercharger (MTiG technology = microturbine with an integrated generator and air-bearings = E-turbocharger [24]).

In the presented technology platform, two Twin-Pack Systems of HSD8650E-40 with 1365 kW should drive two CRF-fans, so that the required performance parameters can be achieved. In this configuration, an electrical power proportion of 40% on the Wankel-HSD-power was found to be sufficient for the load requirement. For further investigation, a machine with a corresponding booster is examined. For this purpose, each has a twin pack formed of two motor benches, equipped with a four-rotor Wankel engine (see Figure 1, Figure 9). The connection is made via a gear assembly and the CRF-speed is set via the angular gear (see figure 3 for transmission concept). With a chamber volume of 650 cc per rotor and charging with a pressure ratio of $\pi_{\text{turbo}} = 3$ (reached 4.5 in height operation) can be achieved at a ground level output of up to 975kW for the part of the internal combustion engine.

To increase the engine power in the start and climbing phase a 390kW e-motor is coupled with the drive train.
3.3.1 The fan concept
Modern engines currently use the “Geared Turbofan” (GTF), in which speeds of the fan and low-pressure turbine are changed via a reduction gear. Both components operate at a reduction ratio of 3:1 in their optimum ranges [26]. To realize a larger fan diameter, the bypass ratio can be increased up to 1:12. Thus, the same propulsion can be realized with lower consumption in modern engines. Using a counter-rotating fan (CRF) this ratio can be further increased. After the development of CRISP by MTU [28], [27] further investigations at DLR were performed. A realization of such an engine on an aircraft was held by the Kuznetsov NK-93 [29]. This forms a by-pass ratio at 1:16.6. Further developments are currently being carried out at DLR [42], [27], [28]. The selected CRF here has a size of 50 inches and provides thrust performance of more than 17kN in Climb mode.

3.3.2 The operation of the hybrid engine
The hybrid engine is operating with a permanently connected electric motor at the output of the Wankel engine. The drive banks are coupled via the gear set in the HSD unit and used to drive the engine shaft (CRF). The electric motor is disposed on the shaft of the drive, to supply a power assist (see Figure 4, 6, 8). In the start and climb phase, the system together provides sufficient energy to reach the altitude and, ultimately, the cruising speed. With the energy stored in the battery, both engines of the technology carrier can be used up to 15 mins at full load. The electric motor can selectively supply power when the internal combustion engine due to the reduced air pressure at higher flight levels provides less energy. Another control option is the electric turbocharger whose compressor pressure ratio can be increased and adapted to the respective requirements.

![Mission Profile for a 2.5-hour cruise (1700km)](image)

**Figure 10.** Mission Profile for a 2.5-hour cruise (1700km)
Of the HSD engine during the complete flight

In cruise mode, the E-machine operates as a generator and supplies the excess power of the combustion engine for charging the energy storage (battery). After reaching the maximum charge of the accumulator, the power of the engine can be reduced and the load can be controlled with optimal consumption. Here, also the charge pressure through the MTiG is adjusted to the required value. Thereby an eco-efficient operation is guaranteed. Based on a case study with an expected range of 1700 km, the driving of the system can be demonstrated. The simulations have shown that, depending on flight conditions, fuel consumption can be up to 50% lower than the consumption of a turbofan engine in such an aircraft.
4. Performance, efficiency and fuel consumption (rates CRF-HSD-engine / GTF Geared Turbo Fan-engine)

For a first comparison, a scenario with an approximately two-hour cruising flight was selected. Thermodynamic methods were used to investigate how the energy consumption of a GTF-system and a hybrid HSD system evolved during a flight task. To produce the required shaft power for the technology platform, hybrid HSD 8650 Wankel engines with a degree of hybridization of 28.6% is used (figure 9). These engines are connected through a transfer driveshaft to the transmission unit of the CRF. The available drive power is given by the degree of hybridization $H_{\text{hybrid}}$ by [35]:

$$P_A = \frac{P_{\text{eff/HSD}} \cdot \eta_{\text{gearbox}} \cdot \eta_{\text{CRF}}}{(1 - H_{\text{hybrid}})}$$  \hspace{1cm} (2)

To evaluate the drive system, the comparison of the efficiencies of the different subsystems is useful. For the reciprocating engine of the HSD-engine, the efficiency can be written as follows [35]:

$$\eta_{\text{eff/ICE}} = \eta_{\text{burn out}} \cdot \eta_{\text{therm}} \cdot \eta_{\text{HP}} \cdot \eta_{\text{CC}} \cdot \eta_{\text{mech}}$$  \hspace{1cm} (3)

(HP = high-pressure loop, CC = charge cycle loop, mech = mechanically.)

For the entire hybrid HSD system, the efficiency of the electrical parts must be considered. The following equation results for the complete drive unit:

$$\eta_{\text{eff}} = \frac{W_e}{E_{zu}}$$  \hspace{1cm} (4)

For this purpose, the supplied energy from battery and fuel for the internal combustion engine must, by introducing a dimensionless energy ratio $\varepsilon = \frac{E_{\text{Fuel}}}{E_{\text{Bat}}}$, be summarized as follows:

$$\eta_{\text{eff}} = \frac{\eta_{\text{ICE}} \cdot E_{\text{Fuel}} \cdot \eta_{\text{Masch}} \cdot E_{\text{Bat}}}{E_{\text{Bat}} + E_{\text{Fuel}}}$$  \hspace{1cm} (5)

Derived from this, the equation for the total efficiency can be set up:

$$\eta_{\text{eff}} = \frac{\eta_{\text{ICE}} \cdot E_{\text{Fuel}} \cdot \eta_{\text{Masch}}}{1 + \varepsilon}$$  \hspace{1cm} (6)

Figure 11 shows the efficiency of hybrid combination engines as a function of dimensionless energy distribution between battery capacity and fuel-energy content.

An evaluation of this analysis shows that with a high degree of electrification, the hybrid system has a higher efficiency than a single internal combustion engine can deliver. The mechanical efficiency of the internal combustion engine, therefore, was assumed to be 41%. When using modern battery systems, new electric motors and other electrical components, energy efficiency up to 75% can be achieved from the electrical system.

Particularly at high levels of hybridization, the propulsion of a 10-ton aircraft with consumption in the take-off phase of 0.01kWh/kg-aircraft-weight until reaching cruising altitude shows a strong increase in its efficiency. Similarly, a cruise fuel consumption of about 0.1kWh/kg-aircraft weight.
shows an improvement. A high battery weight can be compensated by the efficiency of the drive. The efficiency of the overall machine is heavily dependent on the part of the power consumption of the hybrid shares in the respective flight phase. Weight-optimized, the efficiency is higher with a higher content of electrical Engine. Weight-optimized, the efficiency is higher at a higher ratio of the electric drive.

With the airspeed to the jet exit speed ratio $\zeta = C_{\text{airplane}}/W_{\text{nozzle}}$ follows with the quality criterion for the implementation of the jet power into propulsive power (external efficiency $\eta_{\text{propulsion}} = \left(\frac{2\zeta}{1+\zeta}\right)$), the total efficiency (with an adjusted nozzle) [30], [36]:

$$\eta_{\text{total}} = \frac{\text{thrust performance}}{E_{\text{fuel}}} = \eta_{\text{internal}} \cdot \eta_{\text{propulsion}}$$ \hspace{1cm} (7)

$$\eta_{\text{total}} \approx \eta_{\text{eff/ Hybrid System}} \cdot \eta_{\text{gearbox}} \cdot \eta_{\text{CRF}} \cdot \left(\frac{2\zeta}{1+\zeta}\right)$$ \hspace{1cm} (8)

Figure 12. MTiG, electrical coupled MTiG in the complete turbo-compound-system as a central turbocharger (E-Engine 2: n_{MTiG}=70000 to 80000rpm), E-engine 1: HSD-Booster

With increasing altitude, the exhaust exergy losses are reduced because the described shaft engine concept is a highly efficient and turbo-compound engine with high efficiency $\eta_{\text{eff/HSD}}$. Because of the electrical supported E-central turbo, the system is also very flexible (MTiG, see Figure 12). As in the case of the described application, the MTiG gets a branched and charged partial airflow by the CRF with a pressure ratio of $\pi_{\text{CRF}} = 1.3$, the electric power output is increased in the MTiG against the basic version (see [1]) in the following ratio:

$$\frac{P_{\text{MTiG, CRF}}}{P_{\text{MTiG, base}}} \approx \left(\frac{\pi_{\text{CRF}}}{\pi_{\text{base}}}\right)^{\frac{k-1}{k}} \left(\frac{\eta_{\text{CRF}}}{\eta_{\text{base}}}\right)$$ \hspace{1cm} (9)

The boost pressure can, as already described in the HSD concept, be adjusted in such a way that the effective efficiency (limiting pressures of the Wankel core engine: compression pressure 70bar, combustion maximum pressure 102 bar) in combination with the altitude-related decrease in temperature compared to the base value could be increased:

$$\eta_{\text{eff/HSD, altitude}} > \eta_{\text{eff/HSD, ground level}}$$ \hspace{1cm} (10)

Further, in the described power class, the range of effective efficiency of the HSD drive compared with a gas turbine engine is better in the following estimated ratio:

$$\xi_{\text{eff}} = \frac{\eta_{\text{eff/HSD}}}{\eta_{\text{eff/gas turbine}}} \approx (1.0) 1.15 \text{ to } 1.2$$ \hspace{1cm} (11)

On the propulsion efficiency side, if the CRF concept is compared to a geared fan (see Figure 13) with a modern bypass ratio of 10 to 14, then $\eta_{\text{propulsion}}$ results in an advantage in the selected design point (Ma = 0.75) from:

$$\xi_{\text{propulsion}} = \frac{\eta_{\text{propulsion, CRF}}}{\eta_{\text{propulsion, geared fan}}} \approx 1.06 \text{ to } 1.09$$ \hspace{1cm} (12)
\[ \xi_{\text{eff}} = \frac{\eta_{\text{gearbox/HSD}}}{\eta_{\text{gearbox/gasturbine}}} \cdot \frac{\eta_{\text{CRF/HSD}}}{\eta_{\text{FAN/gasturbine}}} \cdot \delta_{\text{external}} \]  

where \( \delta_{\text{external}} \) represents a factor that evaluates the external efficiencies between a geared turbofan and an HSD engine. This factor shows a small advantage for the HSD-concept [25].

By parallel hybrid system technology, while weighting the different phases of flight (see Figure 14), a further increase of the efficiency can be settled. This can be shown in terms of the fuel consumption ratio over the entire flight. The value must be within the following range:

\[ 0.78 = \frac{1}{1.27} > \frac{B_{\text{HSD,CRF}}}{B_{\text{geared fan}}} > \frac{1}{1.44} = 0.7 \]  

(14)

This would mean that an HSD CRF only consumes about 60% of the fuel consumption of a comparable geared turbo fan. This value certainly represents a theoretical limitation. Three effects can explain it:

1. Although the average internal efficiency is slightly worse in cruise mode by the phase-wise use of the electrical component, the effect of the more fuel-efficient mode of the HSD-combustion engine predominates by a balanced load adaption.
2. In the climb phase, the energy of the charged battery significantly increases the efficiency of the system in the flight phase of the electrically assisted flight.
3. The third effect is defined by the approach phase. Here, the Wankel engine can be adjusted in a very low load point relative to a conventional engine, since the electric motor takes over the descent control and recuperation. This flight phase can be realized theoretically without consumption when the HSD-combustion engine component is switched off and only the electric motor works. For safety reasons, however, such a shutdown is omitted.

Comparing a GTF with a CRF-HSD reveals, in particular, the propulsion advantage of a Counter Rotating Fan and the advantage of an optimized Hybrid Wankel rotary engine compared to a small turbine engine. In particular, the improved efficiency of the internal combustion engine component is significant. This is made possible by the fact that the combustion engine part can be used in the partial load range of the entire system in the effective mode. Fully-loaded phases are supported by the more effective E-System. With this configuration, higher efficiency of the aircraft propulsion can be achieved.

In a simulation of a geared turbo engine with CRF, the hybrid HSD-System at least has already an efficient advantage of nearly 16%. Because modern propulsion systems show no great efficiency losses in part-load behaviour, an adjustment of this efficiency was omitted in the simulation.

**Figure 13.** Propulsive efficiency as a function of the flight Mach number. Estimation: \( \text{Ma} = 0.75 \) (according to [36])

**Figure 14.** Flight phases with a turbofan engine [30]
A high overall appreciation in efficiency is obtained with short overall flight times because of the stronger effect of the evaluation of the relationship between an electric motor and combustion engine. For long flight times (3300 km maximum range), the efficiency of the hybrid system must be reduced due to the prolonged use of the pure combustion engine. Thus, the following result is obtained for the fuel consumption ratio for the described exemplary engine:

\[
0.6 > \left( \frac{B_{\text{HSD-CRF}}}{B_{\text{geared fan}}} \right)_{\text{minimum}} > 0.44
\]  \hspace{1cm} (15)

On average, therefore, the best possible reduction in consumption of the CRF-HSD engine compared to a fictitious geared engine in the lower thrust class (as is used in a comparable jet) of 30% is quite possible.

\[
\left( \frac{B_{\text{HSD-CRF}}}{B_{\text{geared fan}}} \right)_{\text{min. average value}} \approx 0.3
\]  \hspace{1cm} (16)

5. Conclusion

By simulating the propulsion of a business jet from the size class light jets, this study demonstrated that a parallel hybrid drive like the described HSD-engine can be used for eco-efficient flying. By coupling innovative components and technologies, a system has been created allowing a reduction in fuel consumption up to 30% compared to present engines, depending on the flight mission.

Such a system can support to initiate the target system in 2030 completely changing to a fully electric flying system as a technology bridge to meet the European Commission's emissions reduction targets in aviation.

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