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Simple hybrid propulsion model for hybrid aircraft design space exploration

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Abstract This article introduces a semi-empirical model for an electric fan and a minimalistic model for a turbofan. The electric fan model provides an easy selection of optimal characteristics based on power loading. The turbofan model has provision for power extraction, and exhibit a physical behaviour. These two models allowed exploring the performance of a hybrid-electric aircraft featuring two turbofans under the wing and one electric fan at the rear of the fuselage. Associated with a proper energy management, such a hybrid aircraft may prove to be competitive if the power to weight ratio of the electric machines reaches 8 kW/kg and the energy density of the batteries reaches 540 Wh/kg.

Introduction

A hybrid electric propulsion system adds many optimization parameters to the aircraft, such as the amount of electric-driven thrust relative to the total thrust, the capacity of the batteries, and how and when is the electric propulsor used.

To allow for rapid exploration of the design space and accurate selection of the most promising solution, we need to have simple semi-empirical models of the components making the propulsion chain components.

This article presents two of these models, the electric fan and the simplistic turbofan, as well as a first exploration performed on a three-engine hybrid aircraft configuration.

Notations

BPR	Bypass ratio
D	Fan diameter (m)
F _n	Net thrust (N)
M	Flight Mach number
P	Pressure
P _w	Power (W)
T	Temperature
V	Flight speed (m/s)
x	Shaft speed ratio
γ	Heat capacity ratio (1.4)
η	Efficiency
π	Pressure ratio
τ	Temperature ratio

subscripts

0	infinite upstream
des	design
i	total
f	fan, including inlet and exhaust
n	net
pol	polytropic
r	ram (total to static, station 0)

Electric Fan model

One of the main components of a future hybrid-electric aircraft will be an electric fan.

The efficiency of the electric propulsor can be defined as:

$$\eta = \frac{F_n V_0}{P_w}$$

Where F_n is the net thrust, V₀ the flight speed and P_w the power input.

This definition of the efficiency is different from the propulsive one, as it takes into account the thermal losses in the propulsor.

For comparison, if the propulsor is fan of efficiency η_{pol} and pressure ratio π_f, then the usual propulsive efficiency is

$$\eta_{pr} = \frac{2 \left(\sqrt{(\tau_r - 1)(\tau_r \tau_f - \tau_f^{1-\eta_{pol}})} - \tau_r + 1 \right)}{\tau_r (\tau_f - 1) - (\tau_f^{1-\eta_{pol}} - 1)}$$

Whereas the electric fan efficiency is

$$\eta = \frac{2 \left(\sqrt{(\tau_r - 1)(\tau_r \tau_f - \tau_f^{1-\eta_{pol}})} - \tau_r + 1 \right)}{\tau_r (\tau_f - 1)}$$

One can notice the positive $\tau_f^{1-\eta_{pol}} - 1$ term representing the compression losses.

Considering $\tau_f = \pi_f^{\frac{\gamma-1}{\gamma \eta_{pol}}}$, the main design parameters influencing the efficiency, beside the flight conditions τ_r, are as expected the fan pressure ratio π_f and the fan efficiency η_{pol}. These two parameters cannot be imposed arbitrarily. There are limits, imposed by the state of the art, on the possible pressure ratio and associated efficiency. To capture these, a study of several existing fans of various sizes was performed. It allowed drawing the following correlation:

$$\eta = -0.1014 \operatorname{sign}(C - 0.20724) \log \left(\frac{C}{20000} \right) \left| \frac{C - 0.20724}{C - 0.1185} \right|^4$$

Where C is a correlating parameter:

$$C = \frac{P_w}{D^2 M^3 P_{t0} \sqrt{T_{t0}}}$$

The various coefficients have been obtained via least square optimisation.

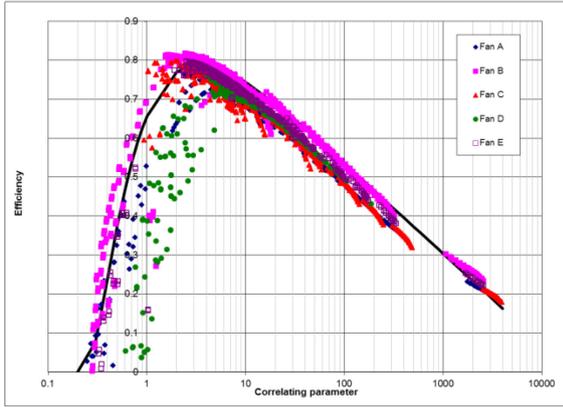


Figure 1: Fan efficiency vs. correlating parameter

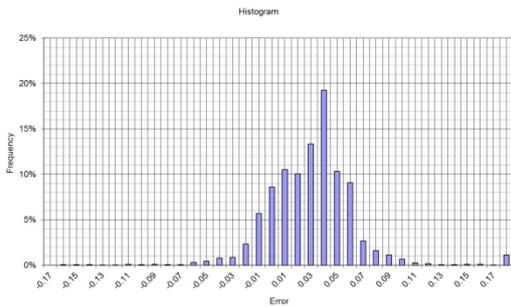


Figure 2: Error distribution

It is important to note that the fan pressure ratio, which plays an important role in the propulsive efficiency, is replaced here by the power loading Pw/D^2 , which is much easier to handle in the propulsion system sizing.

The statistic shows that, according to the current state of the art in inlet, fan and nozzle design, there is an optimum power loading.

The same curve can be used for off-design performance computation.

Minimalistic gas turbine

The other component of the hybrid electric propulsion system is a turbofan, which can provide thrust and high power at the same time. The requirement for the gas turbine model is to have the least number of parameters while still having a physical behaviour. In particular, the SFC curve shall have a minimum.

To achieve the goal of minimum number of parameters, the chosen architecture is a dual-flow, single spool turbofan. The engine features a fan, a single compressor, a combustion chamber and a turbine. Power can be extracted from or injected in the engine shaft.

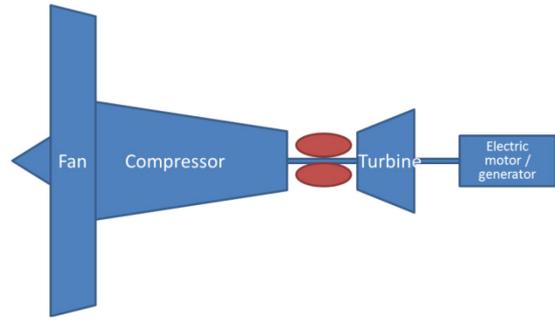


Figure 3: Gas turbine architecture

Components efficiencies are fixed at state-of-the-art levels.

The only remaining parameters are then:

- The design fan pressure ratio
- The design overall pressure ratio
- The by-pass ratio
- The primary and secondary exhaust areas, which are deduced from the required thrust for a given flight conditions

The gas considered is perfect, with $\gamma=1.4$.

Off-design operation is obtained by solving the system of 3 equations where the computed section area of turbine vane, primary exhaust and secondary exhaust shall be equal to their on-design value. The three unknowns are the ratio of total flow to design total flow, the ratio of by-pass ratio to design by-pass ratio and the ratio of shaft speed to the design shaft speed.

Component efficiencies are assumed fixed.

The pressure ratios of the fan and the compressor follow a law linear with shaft speed:

$$\pi = 1 + (\pi_{des} - 1) \frac{x - a}{1 - a}$$

where x is the shaft speed ratio.

The value of the coefficient a has been determined empirically, and is given in the following table.

Component	a
Fan	0.85
Compressor	0.45

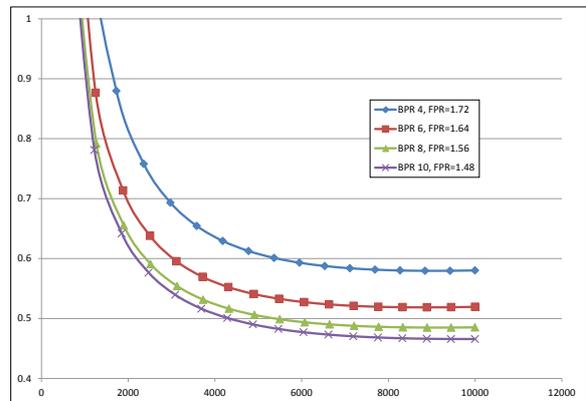


Figure 4: Specific Fuel Consumption curves

As for the electric fan, the design parameters of the turbofan shall be chosen taking into account the state

of the art or its foreseeable evolution.

It is proposed to take into account the following limits when choosing the turbofan design parameters:

- Corrected flow at compressor exit shall be higher than 2 kg/s. This is a feasibility limit for full axial compressor
- The fan pressure ratio and by-pass ratio can be chosen for optimal power loading, as for the electric fan, and balanced pressure ratio between the two flows, i.e: $\pi_f = \pi_c \pi_t$. This corresponds to an optimal engine.

Alternatively, the following correlation can apply:

$$\pi_f = 1.88 - 0.04 BPR$$

Application to an hybrid aircraft configuration

The hybrid aircraft configuration studied here is derived from a typical single aisle short range aircraft. The main difference is in the propulsion system layout: instead of having two gas turbines under the wing, the hybrid aircraft has a third engine, an electric fan, located at the rear of the fuselage. Power is provided to the electric fan from a battery pack and from generators linked to the two turbofans under the wing.

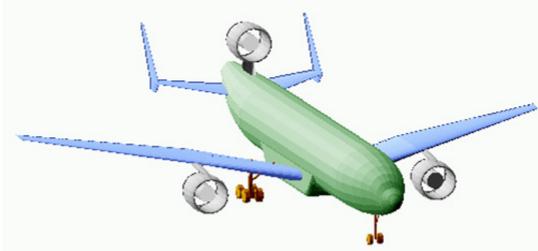


Figure 5: Notional view of the hybrid aircraft

Thermodynamically speaking, the electric fan operation increases the by-pass ratio of the propulsion system as a whole. In cases where the diameter of the underwing engines is limited, this gives the opportunity to increase the propulsion system efficiency beyond what could be feasible using today's thermal-only technology.

The hybrid system, consisting of generators, batteries, cables, power management electronics, and electric fan, adds a considerable weight to the aircraft. On top of that, aircraft engines operations are very smooth and stable: there is no such thing as highly variable load which is favourable to the hybrid car, for instance.

Hence, the use of the hybrid system shall be maximized to get the full benefit of its presence on board.

The picture below shows how the power is used on board. Blue arrows are energy streams. Dotted lines are for small streams, plain lines are for large

streams.

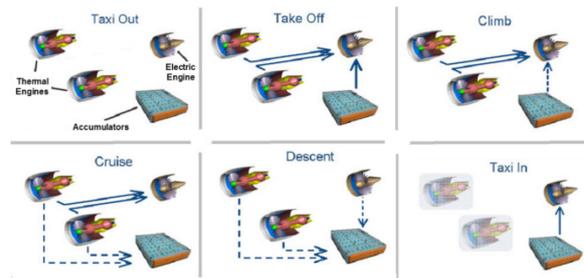


Figure 6: Hybrid aircraft energy management

- At take-off, energy is taken from both thermal engines and from the batteries to provide maximum power to the electric fan.
- During climb, less power is taken for the batteries, in an attempt to minimize the required battery size and weight.
- During cruise, the batteries are being recharged.
- In descent, some energy may be recovered from the electric fan in windmill mode.
- In taxi in, the thermal engines are shut down and the aircraft moves on the electric fan only, thus reducing the airport pollution.

The batteries are recharged or exchanged during turn-around time, so that the mission start is always performed with fully charged batteries.

A sizing of this aircraft, using the above described engine models, has been performed and compared to a conventional aircraft on the same payload/range requirements.

The hybrid aircraft proved to be competitive (i.e. same Maximum take-off weight) if the energy density of the batteries is higher than 540 Wh/kg, and the power density of the motor and generators is higher than 8 kW/kg.

Conclusions

The electric fan and the minimalistic turbofan models have been described and successfully used in an aircraft sizing optimization, for both a conventional and a hybrid electric aircraft. The required performance of the electric components for the hybrid aircraft to be competitive does not seem out of reach. More work will be performed to improve the aircraft configuration, and in particular look for synergies.

References

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