On the design of a hybrid hydrogen-powered aircraft – A technical feasibility study

Victor H. Cantú, Alia Akrout, Jérémy Cure, Kévin Cocq

Altran TEC, Capgemini Engineering, 4 Avenue Didier Daurat, 31700, Blagnac, France

{victor-hugo.cantu-medrano,alia.akrout,jeremy.cure,kevin.cocq}@capgemini.com

Keywords : *aviation, hydrogen, hybrid engine, multiobjectitve optimisation, metaheuristic*

1 Introduction

The aviation sector is responsible for 2-3% of all anthropogenic carbon emissions and 12% of transport-related emissions. In order to address this problem, the European Comission devised the "Flight Path 2050" reduction targets: 75% CO_2 reduction per passenger kilometer relative to the capabilities of typical new aircraft in 2000, as well as 90% NO_x and 65% perceived noise reduction [1, 2]. Considering the increasing amount of air travel, these goals are unlikely to be reached by evolutionary improvements of existing aviation technology and, in fact, the overall carbon emissions are predicted to increase further in the years to come [2, 3].

As an alternative to hydrocarbon fuels (directly correlated with CO_2 emissions), one solution is the use of hydrogen as fuel. Compared to kerosene, hydrogen has three times higher gravimetric energy density (33.3 kWh/kg); nevertheless, its volumetric energy density is four times lower than hydrocarbons, which gives some difficulties regarding the integration of the tanks into the aircraft.

Besides, once hydrogen is used as a fuel, it can be used either into a gas turbine or to generate electricity using a fuel cell (e.g., PEMFC). In this work, a mathematical optimisation approach is used to evaluate the feasibility of a hybrid hydrogen-powered aircraft retrofit. The propulsion systems include hydrogen-fuelled gas turbine propulsion, hydrogen fuel cell electric propulsion (which can be coupled with lithium-ion batteries), as well as the current technology used, i.e., kerosene-fuelled gas turbine propulsion.

2 Methodology

The mathematical model considers five different types of constraints, namely, the total mass at take-off and landing, the thrust, power and energy requirements. The aircraft design must ensure the feasibility of the flight for a given mission (assumed as a long cruise phase). As an example, the first constraint, regarding the maximum total mass at take-off, is partially developed below:

$$m_0 + m_P + m_{fS} \leq MTOM \tag{1}$$

where m_0 is the aircraft mass without neither the propulsion system nor the fuel storage system, m_P is the mass of the propulsion system and m_{fS} is the mass of the fuel storage system, which comprises the fuel and the storage tank. The propulsion system considers the type and number of engines as follows:

$$m_P = mE_{th_{ker}} nE_{th_{ker}} + mE_{th_{H2}} nE_{th_{H2}} + mE_{el} nE_{el} \tag{2}$$

where $mE_{th_{ker}}$ and $mE_{th_{H2}}$ are the unit mass of thermic engines, and $nE_{th_{ker}}$ and $nE_{th_{H2}}$ are their respective quantities. The terms mE_{el} and nE_{el} are the corresponding unit mass and quantity of electric engines. Therefore, the variables $nE_{th_{ker}}$, $nE_{th_{H2}}$ and nE_{el} can take only nonnegative integer values.

The complete model considers some design specification of the propulstion system, more specifically, the decision variables consist in the number and type of engines used, the amount of specific fuel, and the number of PEMFC and batteries (if required). Also, the model accounts for the storage system mass, which is estimated as a function of the amount and type of fuel. The resulting problem is formulated as a four-objective problem, consisting in the minimization of 1) the mass of kerosene, 2) the mass of hydrogen storage system, 3) the number of PEMFC and batteries, and 4) the amount of CO_2-eq emissions.

The solution of the problem is addressed through an evolutionary algorithm based on the decomposition paradigm (MOEA/D) using the augmented achievement scalarizing function (AASF), with a population of 300 individuals and a maximum number of generations of 10 000. The obtained approximation of the Pareto front is shown in Figure 1. It is observed that solutions that promotes the use of hydrogen correspond to those that entail the lowest carbon emissions.

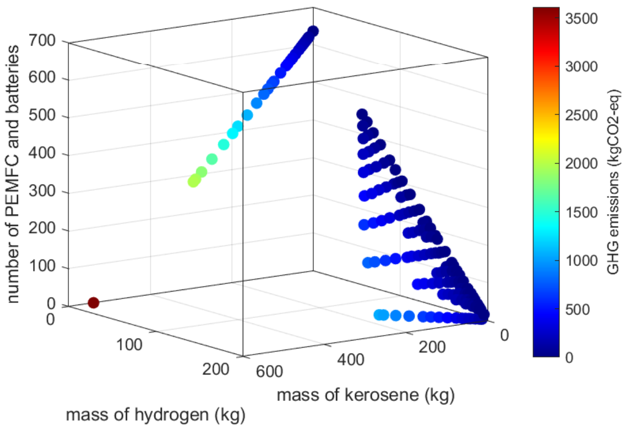

FIG. 1: Obtained approximation of the Pareto front for a given flight mission.

3 Conclusions and perspectives

This study aimed at identifying potential alternatives to classical aircraft design. The problem was tackled using a mathematical optimisation approach, considering aircraft design specifications and aerodynamics as model constraints, with the end of identifying the most promising aircraft configurations. We envisage to further develop the model to consider the different flight phases and to estimate the carbon emissions integrating a life cycle assessment approach.

References

[1] McKinsey and Company. *Hydrogen-powered aviation: A fact-based study of hydrogen technology, economics, and climate impact by 2050.* Tech. rep. Clean Sky 2 and FCH 2, 2020.

[2] T Kadyk, R Schenkendorf, S Hawner, B Yildiz and U Römer. Design of Fuel Cell Systems for Aviation: Representative Mission Profiles and Sensitivity Analyses. *Frontiers in Energy Research*, 7:35, 2019.

[3] A G Rao, F Yin, and J P van Buijtenen. A hybrid engine concept for multi-fuel blended wing body. *Aircraft Engineering and Aerospace Technology: An International Journal*, 6(86): 483–493, 2014.