Design a liquid hydrogen powered aircraft with surrogate models

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Introduction

- Goal: design a liquid hydrogen powered aircraft (a/c) from a numerical simulator[1].
- Three problems:
  1. Design an a/c in a deterministic context.
  2. Quantify the uncertainties impacting the a/c design.
  3. Design an a/c in an uncertain context.
- Constraint: the number of calls to the numerical simulator is limited.
  $\Rightarrow$ a surrogate model is required.
- Tools: the Python libraries
  - MARILib, for multidisciplinary airplane research,
  - scikit-learn, for machine learning,
  - OpenTURNS, for uncertainty quantification,
  - GEMSEO, to set the design problem and orchestrate the workflow,
  - NumPy and SciPy for general scientific computing capabilities,
- Deliverable: a report (10 to 20 pages) with introduction, sections, conclusion, images, . . . but not code. Do not forget context, explanations and style checking!

[1] The study case is kindly provided by Thierry Druot, Pre-Project Research Engineer at Airbus, seconded to ENAC. Thanks, Thierry!

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Context

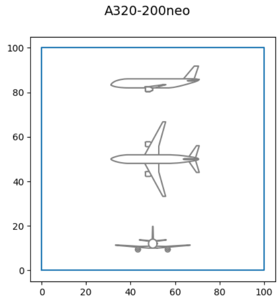
Hydrogen (H2) is a candidate to replace kerosene for future airplanes because it does not emit carbon dioxide when burning.

Study

We seek to evaluate the impact of the use of liquid hydrogen (LH2) in place of kerosene on the design and performances of a turbofan airplane.

Use case

We will focus on the design of an A320-type aircraft (a/c) with the same requirements as the classical kerosene A320 but powered with liquid hydrogen.



The 3 main problems with liquid hydrogen

Because of the airborne LH2 storage:

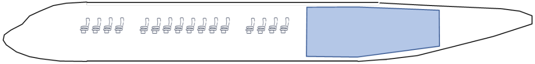
1. The very low **temperature** of LH2 (around 20 K, -253°C) requires very specific fuel system to take it from the tank and feed the engine at ambient temperature.
2. The **volume** of the tank is about 4 time bigger than with kerosene for an equivalent amount of internal energy.
3. The **weight** of tank is important due the necessary high level of insulation.

Point 1 is out of the scope of this study.
Points 2 and 3 are linked to the level of maturity of storing technology.

Technological level of LH2 tanking system

- Gravimetric index: $\mathrm{LH2_{mass}}/(\mathrm{LH2_{mass}} + \mathrm{Tank_{mass}})$
- Volumetric index: $\mathrm{LH2_{volume}}/(\mathrm{LH2_{volume}} + \mathrm{Tank_{volume}})$

	2021	2030
GI	0.1	0.3
VI	0.606	0.845



Put the tank in the rear fuselage.

$\Rightarrow$ Share the available length inside the fuselage between passengers and LH2 tank.
$\Rightarrow$ Lengthen the fuselage of the kerosene a/c up to a certain limit.
We will express a fuselage in terms of the ratio length/diameter and will take its maximum value from the A340-600 which is considered has an extreme.

The performances of the A320

- Nominal seat capacity = 150 pax (passengers)
- Nominal range = 3000 NM (1 Nautical Mile = 1852 m)
- Cruise speed = Mach 0.78
- Maximum Take Off Weight (MTOW) = 77000 kg
- Maximum Landing Weight (MLW) = 65000 kg
- Engine maximum thrust = 120 kN (103 Newtons)
- Engine Bypass Ratio (BPR) = 9 (ratio of cold flow over hot flow for a turbofan)
- Wing area = 122 m^2
- Wing aspect ratio = 9 ($wing\_span^2$ / wing_area)
- Fuselage aspect ratio = 11.0 (fuselage_length / fuselage_height, maximum is 13.4)
- Maximum Take Off Field Length (TOFL) sea level, temperature ISA+15, MTOW = 2200 m
- Maximum Approach speed sea level, temperature ISA, MLW = 137 kt ($\approx$ 253 km/h)
- Minimum Vertical speed Top Of Climb (TOC), 97% MTOW, cruise speed, ISA, Max Climb Rating (MCL) = 300 ft/min ($\approx$ 1.5 m/s)
- Minimum Vertical speed Top Of Climb (TOC), 97% MTOW, cruise speed, ISA, Max Cruise Rating (MCR) = 0 ft/min
- One engine inoperative minimum climb path, 97% MTOW, ISA, Maxi Continuous Rating (MCN) = 1.1%

A LH2 powered a/c for 2030

Passenger capacity wins over range

Range of 3000 NM could not be achieved with 150 passengers on board. Number of passengers, range or both must be reduced. After having discussed with marketing team, engineers have chosen to keep the passenger capacity and reduce the range to 1800 NM.

2030 horizon

Around 10 years to develop and certify $\Rightarrow$ 2030 technological level, assuming that there will be no significant impact on the engine characteristics and performances.

Find the "best" LH2 powered A320-like a/c

- Minimize its Maximum Take Off Weight (MTOW).
- Satisfy the same operational constraints as the kerosene A320 (except for the range).

The design problem - Objective

Minimize the MTOW (Maximum Take Off Weight).

The design problem - Design parameters

- Engine maximum thrust: 100 kN $\leq$ thrust $\leq$ 150 kN
- Engine Bypass Ratio (BPR): 5 $\leq$ BPR $\leq$ 12
- Wing area: 120 m^2 $\leq$ area $\leq$ 200 m^2
- Wing aspect ratio: 7 $\leq$ ar $\leq$ 12

The design problem - Operational Constraints

- Take Off Field Length: TOFL $\leq$ 2200 m
- Approach speed: VAPP $\leq$ 137 kt
- Vertical speed MCL rating: 300 ft/min $\leq$ VZ_MCL
- Vertical MCR rating: 0ft/min $\leq$ VZ_MCR
- One engine inoperative climb path: 1.1% $\leq$ OEI_PATH
- Time To Climb to cruise altitude: TTC $\leq$ 25 min
- Fuselage Aspect Ratio: FAR $\leq$ 13.4

The design problem - Uncertain technological parameters

1. Tank gravimetric index $\sim \mathcal{T}(0.25, 0.3, 0.305)$
2. Tank volumetric index $\sim \mathcal{T}(0.8, 0.845, 085)$
3. Aerodynamic efficiency factor $\sim \mathcal{T}(0.99, 1., 1.03)$
4. Propulsion efficiency factor $\sim \mathcal{T}(0.99, 1., 1.03)$
5. Structure efficiency factor $\sim \mathcal{T}(0.99, 1., 1.03)$

where $\mathcal{T}(l, m, u)$ is the triangular distribution with mode m and bounds l and u.
Note that these probability distributions are not symmetrical as it is always easier to make something less efficient than expected.
The efficiency factors 3, 4 and 5 represent the part of indetermination that relies in any creative activity. They are related to the main technical areas involved in a/c design.

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Numerical simulator

To solve the problem, a Python function is provided to compute the criterion and the operational constraints from the design and technological parameters:

`data = fct_turbofan_h2(techno, design, mode)`

This function packages a dedicated Python script which is an application of MARILib (Multidisciplinary Airplane Research Integrated Library) developed at ENAC to support Airplane Conceptual Design Teaching and some research activities[2].

Computational cost

The execution time of this function is low for academic reasons but must be considered as high for representativeness ones. The number of calls to the function is limited.

[2]Thierry Druot, Mathieu Belleville, Pascal Roches, François Gallard, Nicolas Peteilh, et al. A Multidisciplinary Airplane Research Integrated Library With Applications To Partial Turboelectric Propulsion. AIAA Aviation 2019 Forum, Jun 2019, Dallas, United States. hal-02160977

Global problem

The global problem aims to minimize the MTOW while ensuring operational constraints by varying four design parameters.
By the way, the a/c design takes place in an uncertain environment where the technological choices can be probabilized.
In the following, we will note

$$f : x, u \mapsto f(x, u)$$

the MARILib-based model of a liquid hydrogen powered model where x are the design parameters and u the uncertain ones.

Problem 1: design an a/c in a deterministic context

1. As the number of calls to f is limited, we will create a surrogate model $\hat{g}$ of

$$g : x \mapsto f(x, u_{\text{fixed}})$$

   where u_{fixed} could be the mean value for instance, or the pessimistic values of the uncertain technological parameters[3].
2. Then, we will use this surrogate model in an optimization process to minimize the objective whilst ensuring the constraints by varying the design parameters.

As f is actually not expensive for academic reasons, we will solve the problem compare the optima found with $\hat{g}$ and g.

[3] We could solve the problem with each option and compare the optimal designs.

Problem 2: quantifying the uncertainties in the a/c design

1. As the number of calls to f is limited, we will create a surrogate model $\hat{h}$ of

$$h : x \mapsto h(x_{\text{fixed}}, u)$$

   where x_{fixed} could be the optimum found in Problem 1, or the center of the design space[4].
2. Then, we will use this surrogate model to quantify the output uncertainties (mean, variance, boxplots, sensitivity indices, ...).

[4] We could solve the problem with each option and compare the results.

[Optional] Problem 3: design an a/c in an uncertain context

1. As the number of calls to f is limited, we will create a surrogate model $\hat{f}$ of

$$f : x, u \mapsto f(x, u)$$

2. Then, we will use this surrogate model in an robust optimization process to minimize the mean objective whilst ensuring the constraints with high probability by varying the design parameters.

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Prerequisites

- Clone the branch *modia* of the project LH2PAC:
  - SSH: `git clone -b modia git@gitlab.com:MatthiasDeLozzo/l2pac.git`.
  - HTTPS: `git clone -b modia https://gitlab.com/MatthiasDeLozzo/l2pac.git`.
- Add the absolute path of the project directory to your `PYTHONPATH`.
- Create an anaconda environment named *lh2pac* with
  - `conda create -n lh2pac`
  - `pip install gemseo[all]`
  - `pip install gemseo_mlearning`
  - `pip install sphinx`
  - `pip install furo`
  - `pip install sphinx_gallery`

First steps

- Activate you environment with conda activate lh2pac.
- Move to the project directory.
- Move to the directory named *project*.
- Compile the project with `make html`.
- Open the file *index.html* with your web browser.
- Let's continue on *your* LH2PAC website.