Aerodynamic Design of Propellers for Distributed and Hybrid-Electric Propulsion

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MOTIVATION

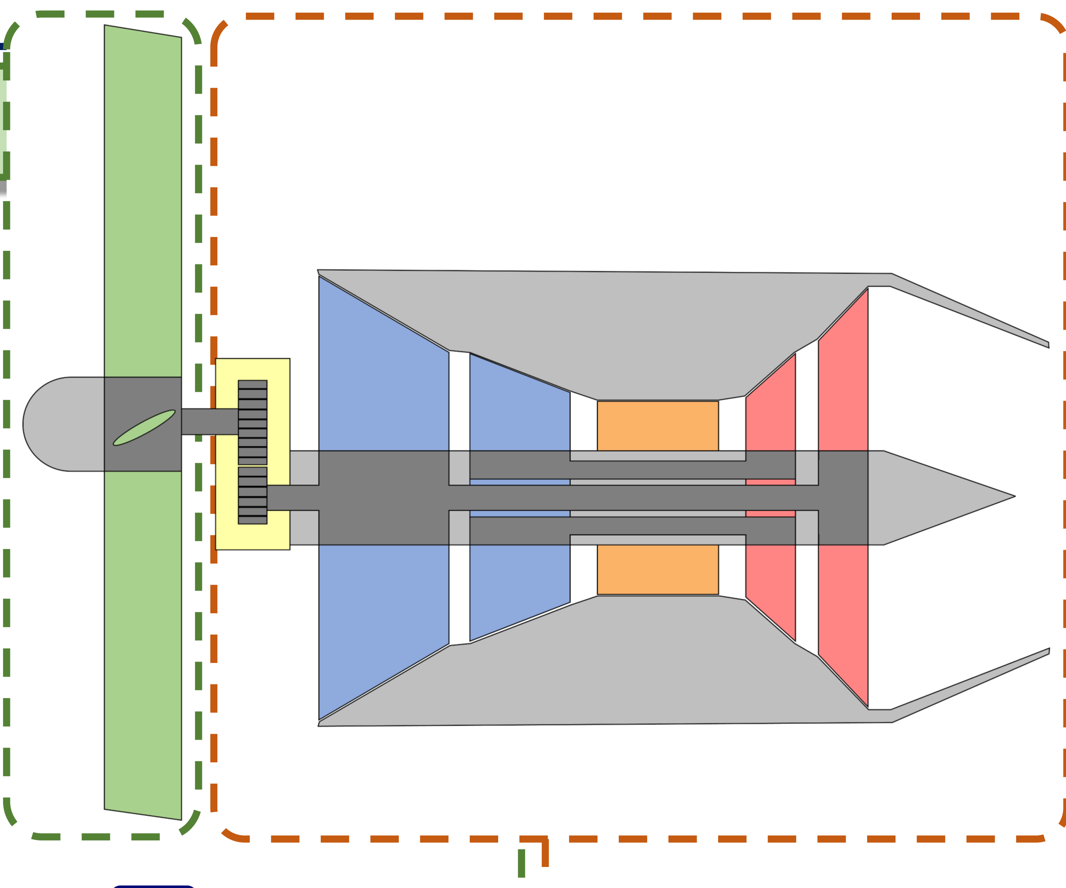
Sustainable aviation requires propulsion systems that combine high aerodynamic efficiency with advanced thermal engine performance. The **Propfan engine**, integrating a high-efficiency propeller with an optimized thermal core, promises lower fuel consumption and reduced emissions. This efficient architectures also pave the way for **hybrid-electric powerplants**.

The objective of this research is to address these challenges modelling complex propellers and optimizing thermal engines by:

- Developing **incremental surrogate models** for propeller design
- Implementing a **modular MDO framework** for thermal engine optimization that allows powerplant hybridization

The outcome will contribute to the development of **efficient, low-emission propulsion technologies** for sustainable aviation.

CFM RISE, open rotor engine concept [Source: CFM]



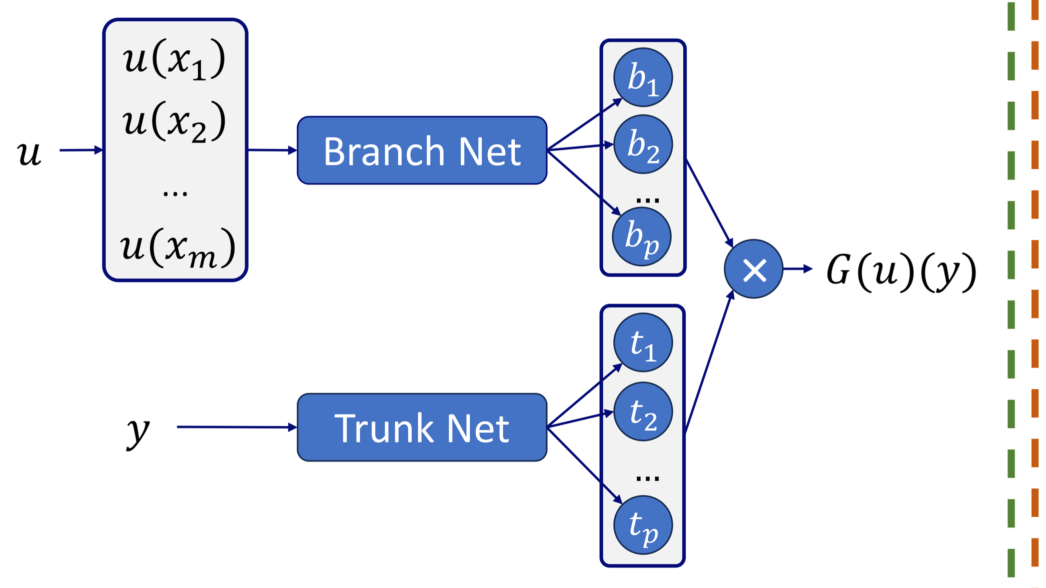
PROPELLER AERODYNAMICS

State of the Art

Traditional **Blade Element Momentum Theory (BEMT)** is widely used due to its low computational cost. However:

- It fails to account for **inter-blade interference** in multiblade or distributed setups
- Static aerodynamic databases from tools like XFOIL are limited under high load or post-stall conditions

Recent advances in surrogate modelling, especially **DeepONets** [1, 2], offer a way to directly predict pressure distributions (C_p) from geometry and flight conditions, surpassing traditional CL/CD models.



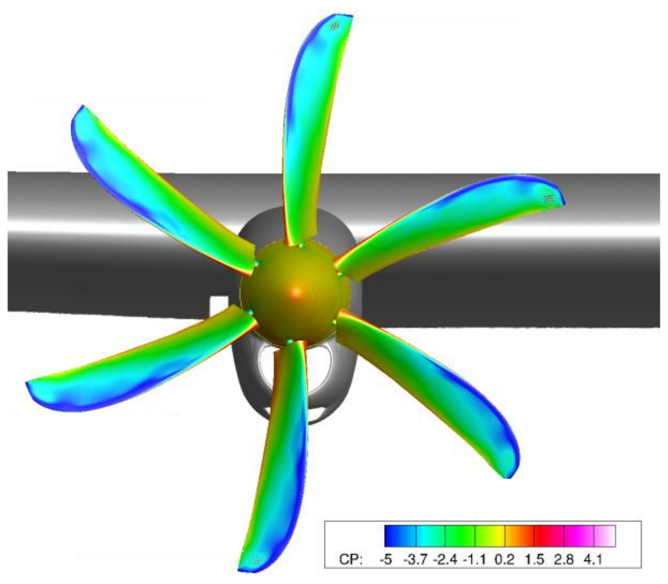
Deep Operator Network (DeepONet) diagram

Moreover, high-fidelity computational fluid dynamics (CFD) is being used to improve accuracy in multiblade scenarios, although it remains computationally expensive for large-scale optimization.

Methodology

DeepONet Surrogate to enhance BEMT Solver

- Neural network to predict C_p distribution from airfoil geometry and flight conditions
- Integrating BEMT solver with the DeepONet, the solver includes corrections for compressibility



C_p distribution over a 6-bladed propeller [5]

Multiblade Effects & Inter-Blade Interaction Modelling

- Study of how increasing blade count affects aerodynamics and pressure distribution around propeller blades using cascade simulation
- Exploring theoretical corrections to improve the multiblade aerodynamic predictions

Increasing level of fidelity of the propeller model with CFD simulations

THERMAL ENGINE DESIGN

State of the Art

Designing hybrid-electric propulsion systems involves tight coupling between thermal and electric subsystems. Key challenges include:

- Accurate modelling of **energy storage and management** (liquid hydrogen, fuel cells, …)
- **Integration** of **electric** elements with **thermal** core
- Allow switching between **different modes of operation** (only fuel, hybrid-electric…)

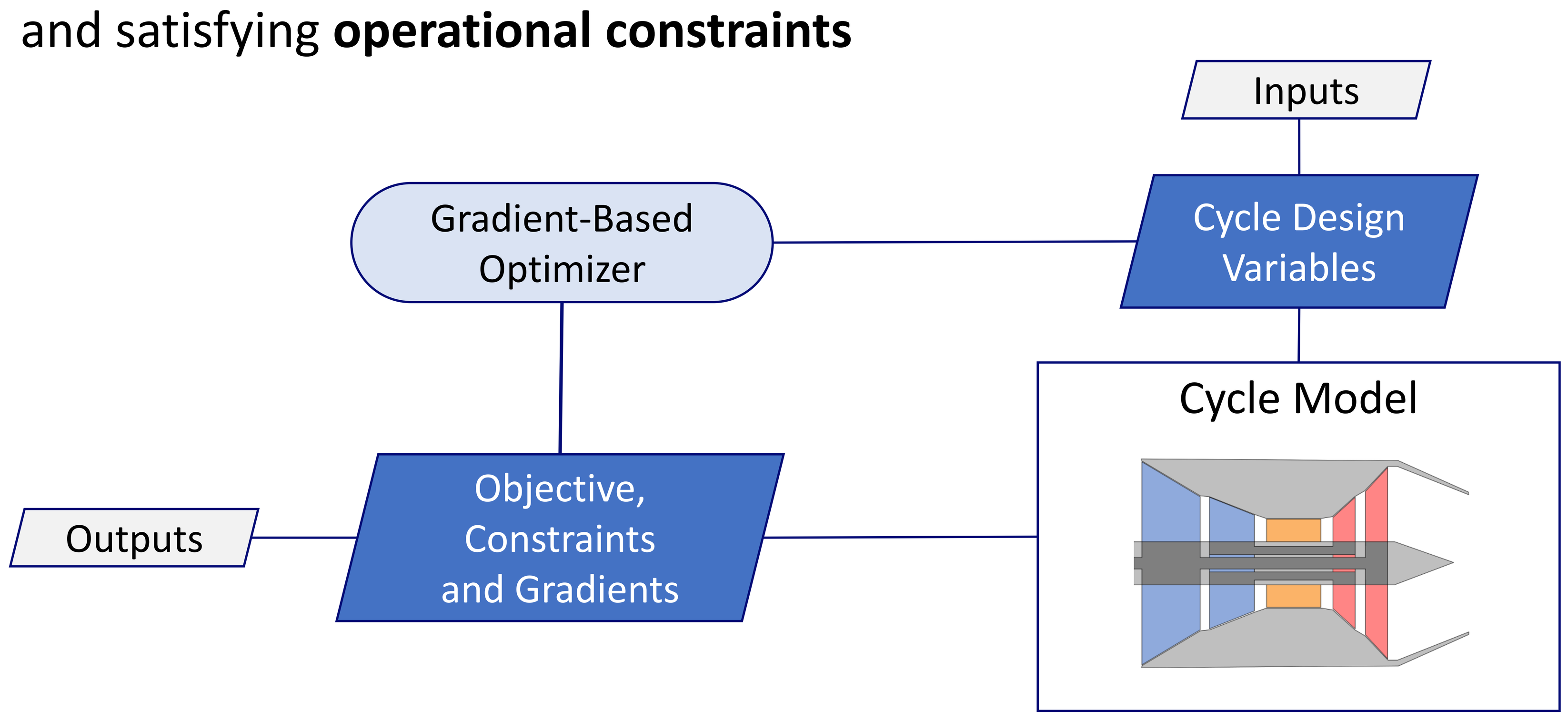
Most current methods model these subsystems in isolation, limiting optimization potential. However, novel open-source tools like **pyCycle** [3], built on **OpenMDAO** [4], enable:

- **Modular modelling** of engine components (compressor, turbine, gearbox, etc.) which allows to couple both thermal and electric systems
- **Gradient-based optimization** across coupled disciplines

Methodology

The thermal core of the Propfan engine is modelled using **pyCycle**, a component-based thermodynamic cycle analysis tool.

- Models allow simulating both **design-point and off-design conditions** at the same time they enable electrification through hybrid architectures
- Integrated with **OpenMDAO** for **multidisciplinary optimization**, leveraging **automatic differentiation** for efficient, gradient-based optimization
- Optimization focuses on **maximizing efficiency**, **minimizing emissions**, and satisfying **operational constraints**



pyCycle optimization framework overview

DISCUSSION

This research presents a novel methodology for **Propfan engine design**, combining advanced propeller aerodynamics with thermal engine optimization. Key contributions include:

- The development of **DeepONet surrogates** for accurate and efficient **aerodynamic modelling of propellers**
- **Modelling inter-blade interactions** using cascade simulations and theoretical corrections, leading to improved performance predictions
- The design and optimization of **thermal engine** using a **modular MDO framework** allowing coupling with electric components, including dual-usage RGB

These advancements provide a solid foundation for the design of **high-efficiency**, **hybrid-electric propulsion systems** in sustainable aviation.

Acknowledgements

ODE4HERA, project financed by EUROPEAN COMMISSION RESEARCH EXECUTIVE AGENCY, Ref. 2024/00026/002

IMPAD, project financed by UC3M, Ref. 2024/00732/001

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