Exploration of distributed propeller regional aircraft design

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1. Introduction
   - The big picture

FIGURE 1 – ESAero NASA X-57 Maxwell [2] [1]

FIGURE 2 – Vahana, the self-piloted, EVTOL Aircraft from A3 by Airbus. [2]

1. NASA Illustration, *Scalable Convergent Electric Propulsion Technology Operations Research (SCEPTOR) project*, https://www.nasa.gov/centers/armstrong/features/CAS_showcase.html, Feb 2017
2. Vahana, the self-piloted, EVTOL Aircraft from A3 by Airbus, https://www.airbus.com, Jun 2018

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- Multiple propellers distributed along the wing span
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- Wing area reduced/Shorter Takeoff Field Length
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Issues : Unconventional configuration

- No semi-empirical formula
- Need cheap prediction tools ⇒ low fidelity

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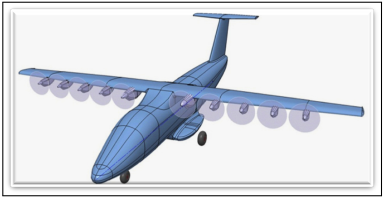
Transformation



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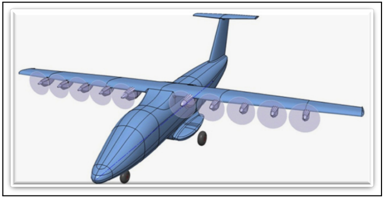

Objectives :

- Determine the viability of a concept and optimize it in a limited domain
- Monitor a large number of parameters and interaction between disciplines
- Estimate the aircraft performance for a given mission
- Reduce the number of late modifications

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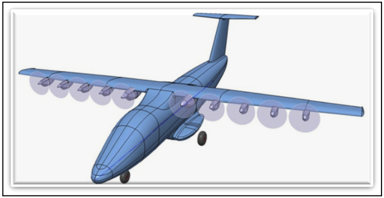

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Expected outcomes :

- New weight distribution
- Propellers-wing interaction,
  Propellers-control surfaces interaction
- Specific modules integration

2. Multidisciplinary Design Analysis (MDA)
   - General framework
   - Fixed-wing Aircraft Sizing Tool - FAST

General multidisciplinary analysis framework[3] [3]

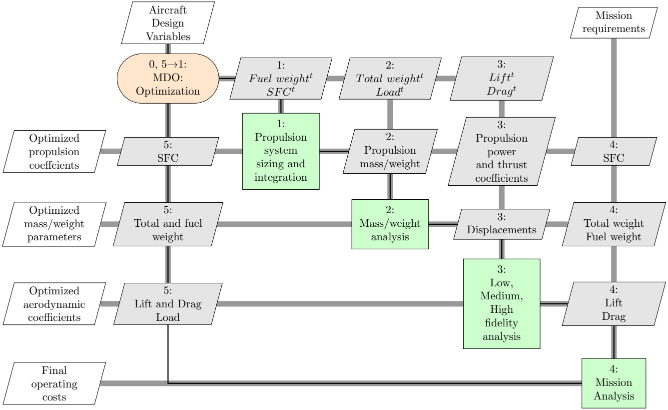

FIGURE 3 – Multidisciplinary design analysis workflow.

3. A.B. Lambe et al., *Extensions to the Design Structure Matrix for the Description of Multidiplinary Design, Analysis, and Optimization Processes*, Structural and Multidisciplinary Optimization, 2012

2. Multidisciplinary Design Analysis (MDA)
   - General framework
   - Fixed-wing Aircraft Sizing Tool - FAST

In-house multidisciplinary design analysis tool for aircraft with distributed propulsion system

Specific modules :

- Propulsion module
- Geometry initialization module
- Aerodynamic module
- Mass breakdown module
- Global flight and performance prediction module

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- Aircraft geometry description
- Propulsive parameters

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Input :

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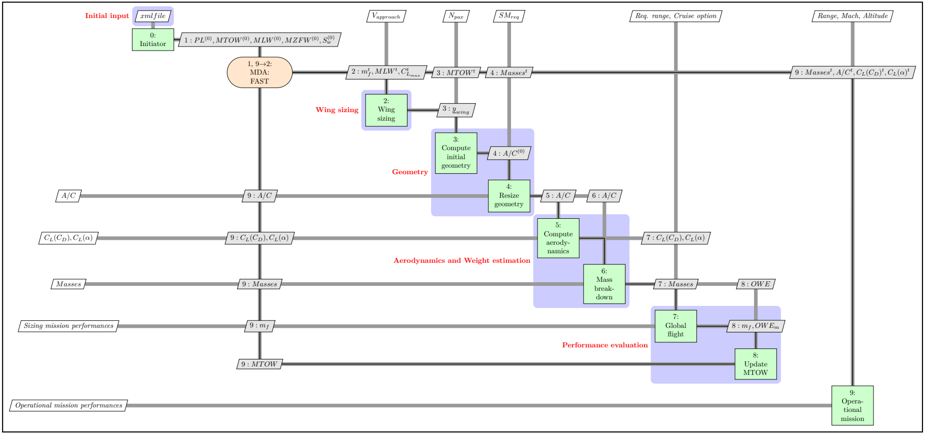
Output :

- Mission profiles
- Aircraft geometry sizing
- Aerodynamic components' characteristics
- Weight and balance

Preliminary design tool (ONERA & ISAE-Supaero)[4] [4]



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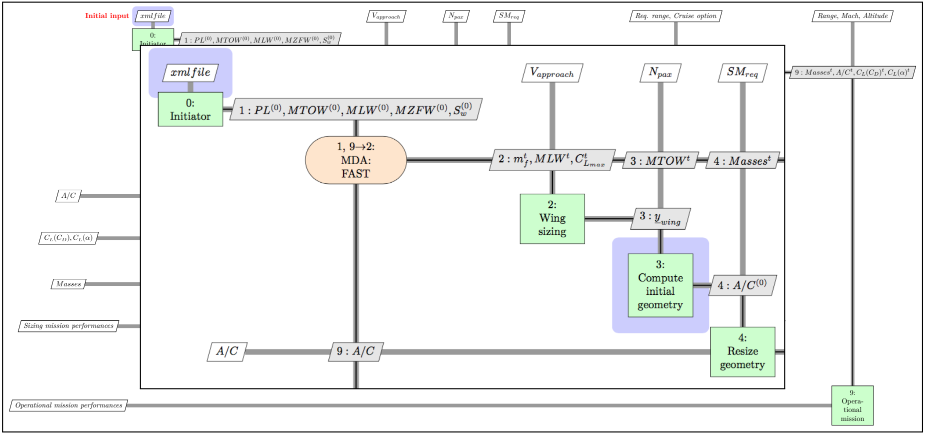

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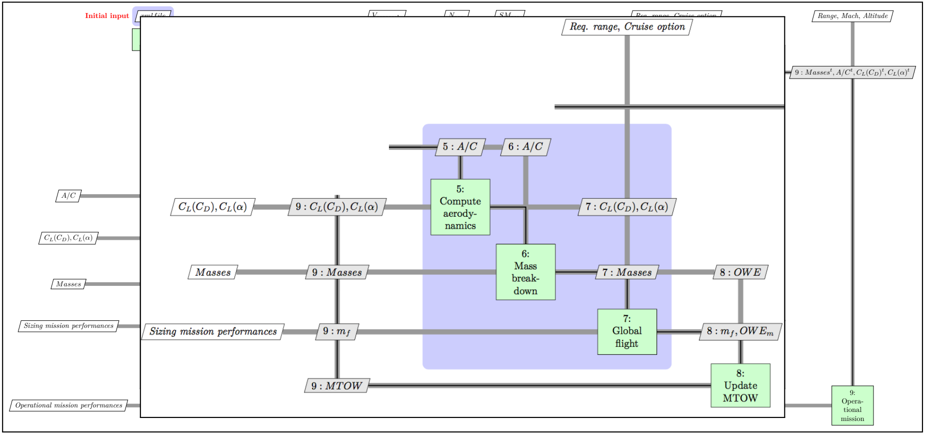

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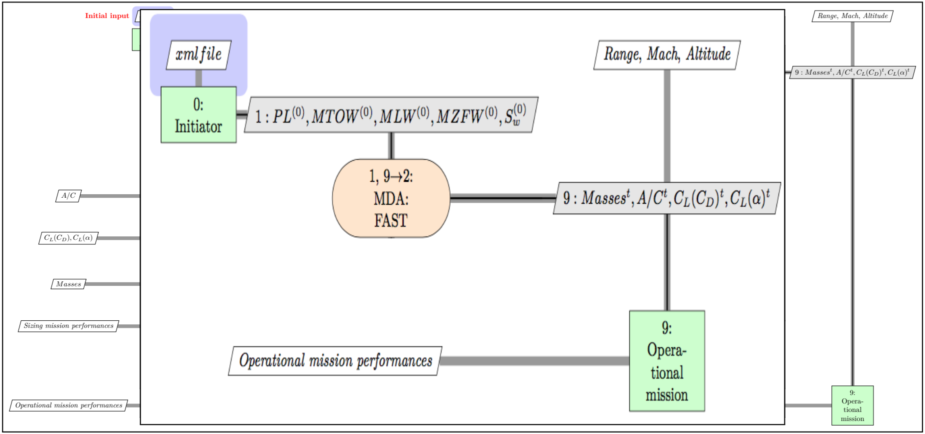


4. P. Schmollgruber et al., *Use of a Certification Constraints Module for Aircraft Design Activities*, AIAA Aviation Meeting, 2017

[Weiberg 1958]

- ✓ Wind tunnel test
- ✓ Twin-engine model with TE flap, high AR, thick and straight wing

1958

1968

[Page 1968]

- ✓ Wind tunnel test
- ✓ Four propeller STOL transport aircraft
- ✓ Wing of various AR

[Witkowski 1988]

- ✓ Wind tunnel test
- ✓ Semi empirical
- ✓ Vortex Lattice Method

1988

2001

[Moens 2001]

- ✓ Euler and 3D Navier Stokes
- ✓ Actuator Disk Model

[Veldhuis 2004]

- ✓ VLM-BEM model
- ✓ Navier-Stokes model

2004

2006

[Hunsaker 2006]

- ✓ BET combined with Momentum Conservation equations
- ✓ Lifting Line Theory

[Chatot 2014]

- ✓ Extended of steady actuator disk to unsteady flows

2014

2014

[Ferraro 2014]

- ✓ Truckenbrodt 3D lifting surface method coupled with MSES

[Agostinelli 2015]

- ✓ RANS-Actuator Disk model combined with the BEMT

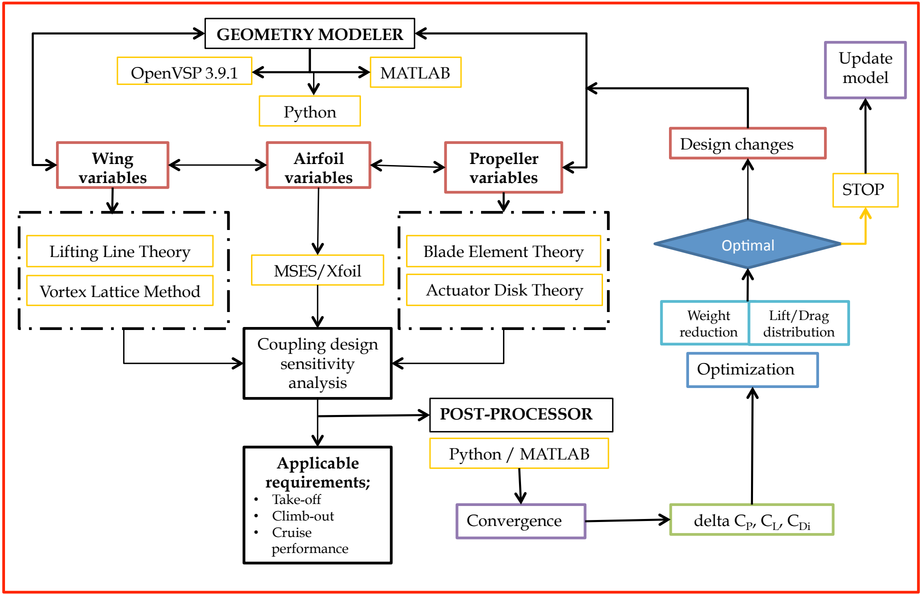
2015

2015

[Borer 2015]

- ✓ Blade shape profile and airfoil shape using MATLAB® and then fed into Xfoil

3 Aerodynamic Module
- Modeling Frameworks


GEOMETRY MODELER
OpenVSP 3.9.1
MATLAB
Python
Wing variables
Airfoil variables
Propeller variables
Lifting Line Theory
Vortex Lattice Method
MSES/Xfoil
Blade Element Theory
Actuator Disk Theory
Coupling design sensitivity analysis
POST-PROCESSOR
Python / MATLAB
Applicable requirements;
• Take-off
• Climb-out
• Cruise performance
Convergence
delta C_P, C_L, C_{Di}
Optimization
Weight reduction
Lift/Drag distribution
Optimal
Design changes
STOP
Update model

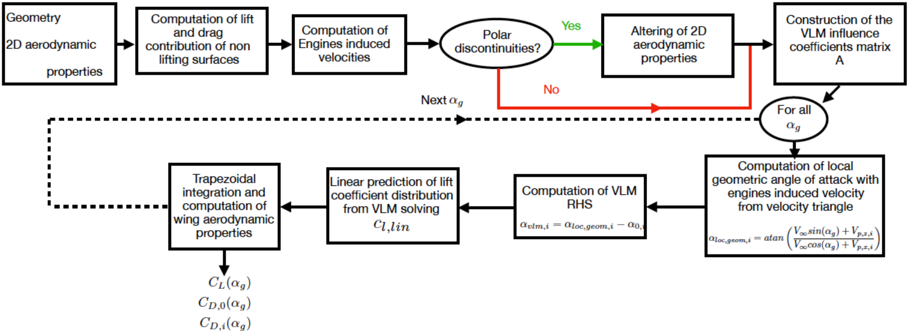


FIGURE 5 – Workflow of aerodynamic module (linear)

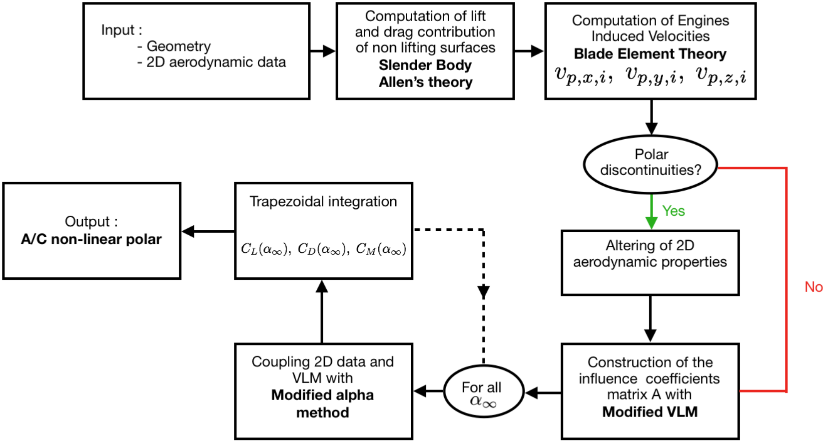


FIGURE 6 – Workflow of aerodynamic module (non-linear with high lift devices)

Propellers induced velocity :

- Uniform blade loading
- Froude and Blade Element Theory

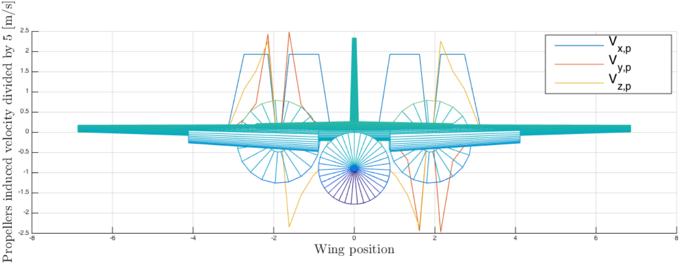


FIGURE 7 – Example of propellers induced velocities with the BET

- Reduced computational costs ⇒ avoid chord-wise discretization
- Lift curve slope fixed by distance between vortex bound and collocation point
- Zero-lift angle in the VLM right-hand-side term
- Additional mesh for defining the wake path [7] [5]

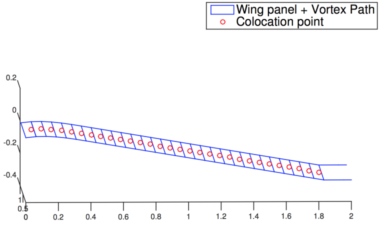


FIGURE 8 – Classical VLM configuration

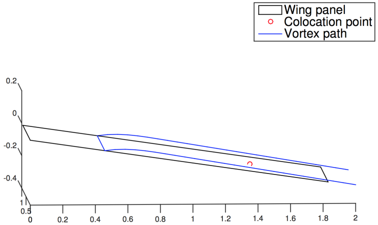


FIGURE 9 – Modified VLM configuration

5. Yahyaoui, M. and al., Generalized Vortex Lattice Method for Predicting Characteristics of Wings with Flap and Aileron Deflection, International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering ; Vol. 8, num. 10, 2014

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TABLE 1 – Specifications of the model [5].

Dimension	**Short wing span**	**Medium wing span**
Span, *m*	13.21	14.61
Area, m^2	30.6	32.8
Mean aerodynamic chord, *m*	2.38	2.32
Aspect ratio	5.71	6.52
Taper ratio	0.554	0.507
NACA airfoil section	632-415	632-415
Sweep of leading edge, *deg*	2.88	2.88
Root chord, *m*	2.98	2.98
Tip chord, *m*	1.65	1.51

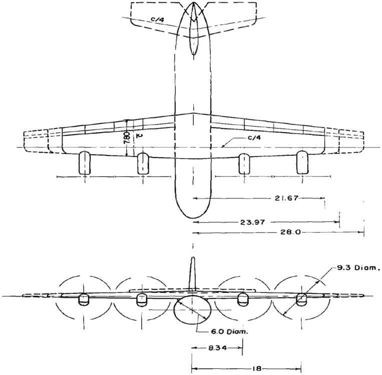

FIGURE 10 – Geometry model [5]

6. Page et al., Large-scale wind-tunnel tests of a deflected slipstream STOL model with wings of various aspect ratios, NASA TN D4448, 1968

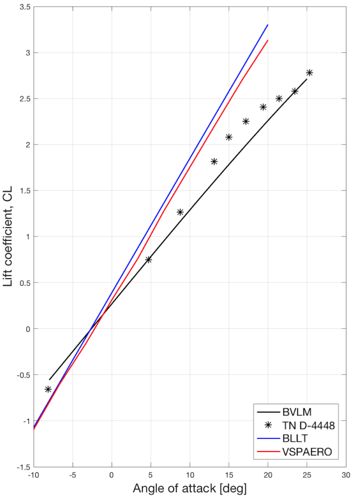

FIGURE 11 – Tc' = 1.0

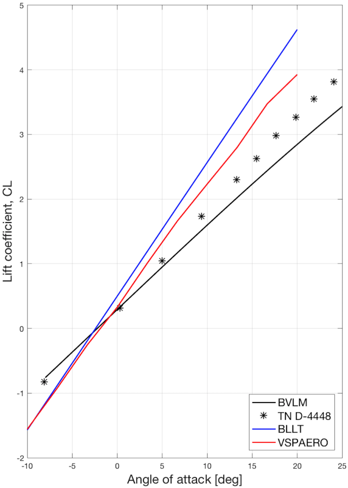

FIGURE 12 – Tc' = 2.4

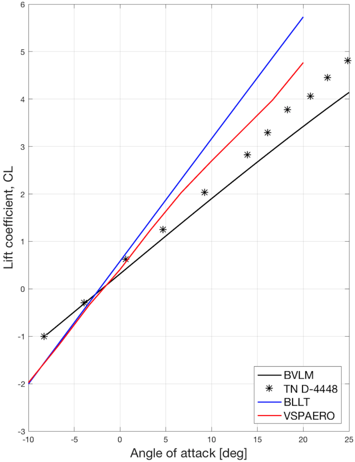

FIGURE 13 – Tc' = 3.8

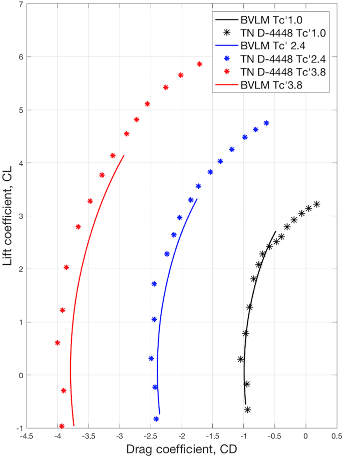

FIGURE 14 – $C_L - C_D$ curves for 3 Tc'

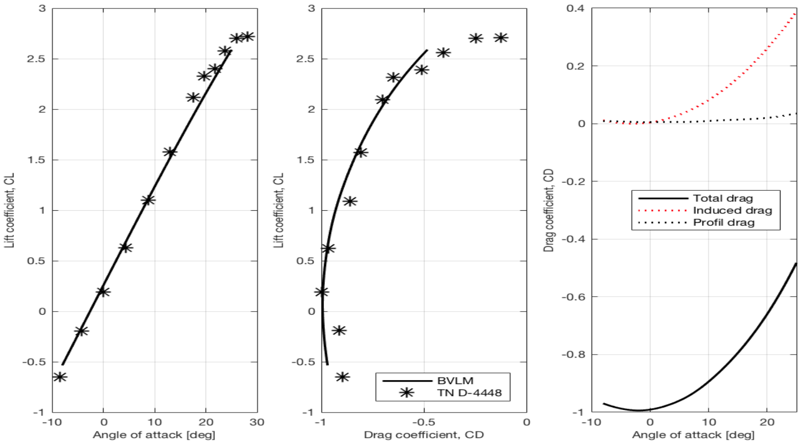

FIGURE 15 – Tc'=1.0

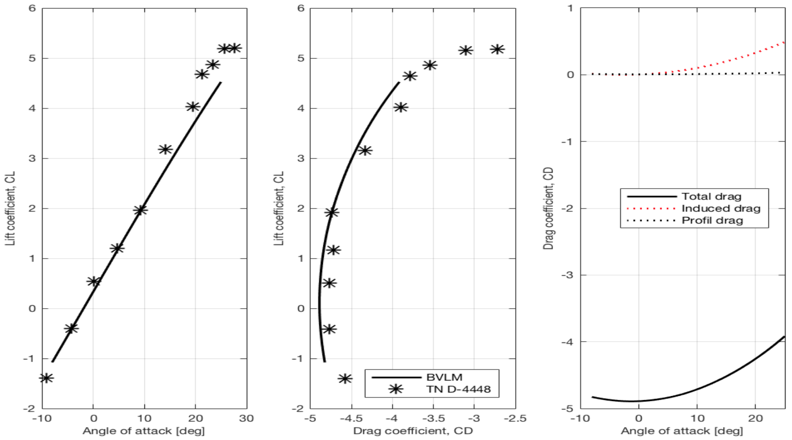

FIGURE 16 – Tc'=4.9

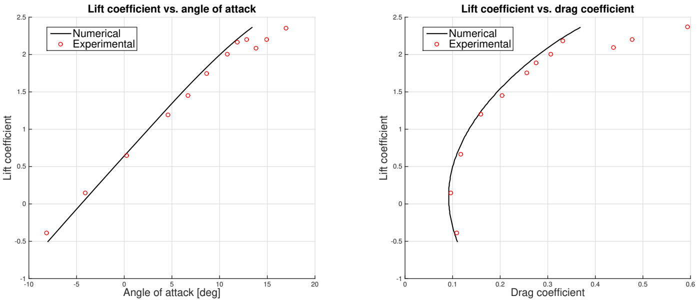

FIGURE 17 – Full a/c configuration - no flaps - Tc = 0.90 - NACA TN 4365 [6][7].

- Validation of the model for propellers' induced velocity : $\epsilon_{\%, c_{l,max}} = 8\%$
- No convergence for steep stall

7. Weiberg and al., Large scale wind-tunnel tests of an airplane model with an unswept, aspect-ratio 10 wing, two propellers and area-suction flaps, NACA TN 4365, 1958

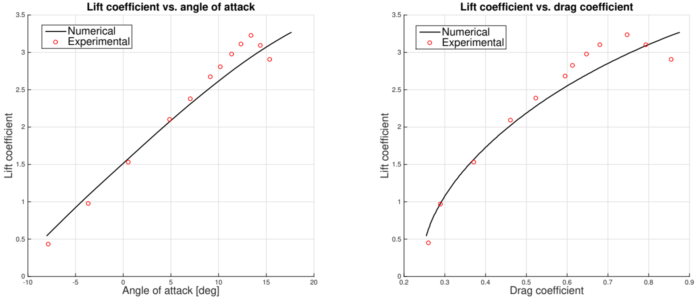

FIGURE 18 – Full a/c configuration - flaps 40° - Tc 0.75 - NACA TN 4365 [6] [11].

- Lack of accuracy on $\alpha_{L,max}$, but not on $c_{l,max}$: $\epsilon_{\%,c_{l,max}} = 1\%$

7. Weiberg and al., Large scale wind-tunnel tests of an airplane model with an unswept, aspect-ratio 10 wing, two propellers and area-suction flaps, NACA TN 4365, 1958

4 Verification and Synthesis Results
- Validation - Aerodynamic model
- Propeller-Wing Interaction -Linear
- Propeller-Wing Interaction - Non-linear with high lift device
- Validation - FAST

Number of passengers	70
Range	825 NM
Cruise Mach number	0.4
Approach speed	117.5 kts

TABLE 2 – Test case ATR 72-600 [1] [7]

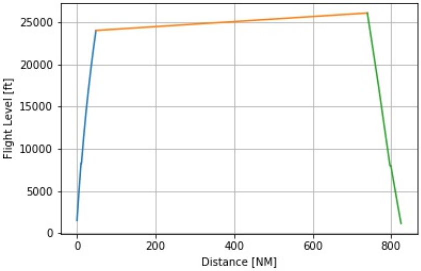

FIGURE 19 – Flight mission profile

Output	ATR 72	FAST
Wing surface [m^2]	61	61.1
Wing span [m]	27.05	27.08
MPL [kg]	7850	7770
OWE [kg]	12950	12801.8
MTOW [kg]	23000	24278.9
MLW [kg]	22350	21801.9
MFW [kg]	5000	4324.23
Mission fuel [kg]	2750.1	2689.1

TABLE 3 – Test case ATR 72-600 [1]

7. ATR 72-600, www.atr-aircraft.com/datas/download_center/27/fiche72_27.pdf/, Feb 2017

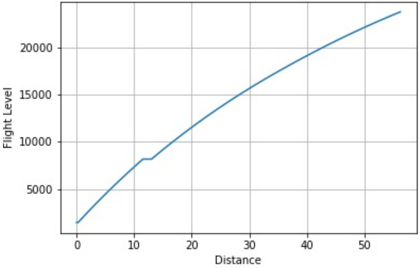

FIGURE 20 – Climb profile

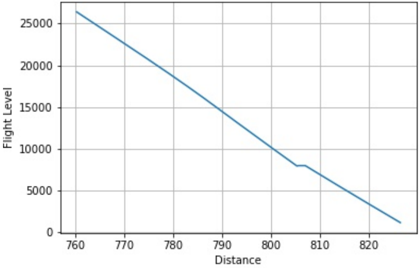

FIGURE 21 – Descent profile

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5. Conclusions and Future Works
   - Conclusions
   - Future Works

We have seen :

- Linear prediction of BVLM code in the presence of slipstream is very well predicted and validated
- The effects of the spanwise variation of propeller thrust on longitudinal characteristics
- Non-linear with high lift device aerodynamic analysis for the propeller wing interaction with a very minimum computational costs
- FAST has been validated for regional aircraft with conventional propulsive systems (A320 & ATR72-600)
- Aerodynamic module provides results good in agreement with experimental measurements for preliminary design step
- Both FAST and aerodynamic module are able to take multiple propellers along the wing

Limitations of aerodynamic module :

- High dependency in 2D aerodynamic data
- Post-stall convergence if soft stall

In the future :

- To integrate the updated specific modules, aerodynamic, mass, etc. with FAST
- To continue with the MDO process focusing on the optimzation of the propeller numbers, location and size along the wing span.
- To expand the current aircraft model to hybrid electric configuration.

- All models are wrong, and the value of any model is only to the extent to which it supports the purpose for which it was built.- George E. P. Box

ATR.
ATR 72-600.
https://www.atr-aircraft.com/datas/download_center/27/fiche72_27.pdf/.

NASA Illustration.
Scalable convergent electric propulsion technology operations research (sceptor) project.
https://www.nasa.gov/centers/armstrong/features/CAS_showcase.html,
Available online since 11/4/15, consulted the 16/12/17.

Lambe, Andrew B. and Martins, Joaquim R. R. A.
Extensions to the design structure matrix for the description of multidisciplinary design, analysis, and optimization processes.
Structural and Multidisciplinary Optimization, 46(2) :273–284, 2012.

A. Sgueglia S. Defoort R. Lafarge N. Bartoli Y. Gourinat P. Schmollgruber, J. Bedouet and E. Benard.
Use of Certification Constraints Module for Aircraft Design Activities.
In *AIAA Aviation Forum*, number AIAA 2017-3762, 2017.

V. Robert Page, Stanley O. Dickinson, and Wallace H. Deckert.
Large-scale wind-tunnel tests of a deflected slipstream STOL model with wings of various aspect ratios.
Technical report, National Aeronautics and Space Administration, Washington, D. C., 1968.

Weiberg James A., Friggin Roy N. Jr.Florman Georges L. .
Large scale wind-tunnel tests of anairplane model with an unswept, aspect-ratio 10 wing, two propellers and area-suction flaps.
NACA Technical Note, 4365, 1958.

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