DYNAPYVTOL: A SIMULATION CODE FOR VTOL AIRCRAFT FLIGHT DYNAMICS AND CONTROL EARLY EVALUATIONS

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Abstract

This paper presents the data structure, models and methods as well as applications of DynaPyVTOL, the in-house ONERA flight dynamics tool. The primary motivation for its creation is to be able to model the flight dynamics of any aircraft configuration composed of rotary and/or fixed wings from the earliest point in the conceptual predesign stage. For this purpose, it has been built in such a way that it can adapt its modelling to the available data and compute a representative trim of the aircraft even in the case of an over-actuated, complex configuration. The overview of its applications includes: steady flight performance with optimal trim computation for any configuration, thruster failure analysis, stability and controllability assessment through model linearization, attainable control set exploration, dynamic flight time simulation, and additional methods for assisting with early design and evaluation of an aircraft and its control laws.

1. NOTATION

Symbols:

R	Rotor radius, m
$P_{induced}$	Induced power, W
$P_{profile}$	Profile power, W
Ω	rotor speed of rotation, rad/s

Acronyms:

AoA	Angle of Attack
BEMT	Blade Element Momentum Theory
CREATION	Concepts of Rotorcraft Enhanced Assessment Through Integrated Optimization Network
eVTOL	Electric Vertical Take-Off and Landing
MDAO	Multidisciplinary Design Analysis and Optimization
SLSQP	optimizer is a Sequential Least SQuares Programming algorithm which uses the Han-Powell quasi-Newton method
UAS	Uncrewed Aircraft System
VRS	Vortex Ring State

2. INTRODUCTION

DynaPyVTOL is a flight dynamics simulation code dedicated to the study, at the early predesign stage, of the flight performance and of the control laws of any kind of VTOL aircraft configurations using rotary and/or fixed wings. This code is the flight dynamics versatile tool of the numerical workshop CREATION (Ref. 1 and 2). It has been developed by the “Rotorcraft, Flight Dynamics, and Systems (RFDS)” research unit of ONERA. It is primarily written in Python for flexibility with rotor-level solvers written in compiled Fortran for more computational efficiency. Compared to other well-known codes with years of development like HOST (Ref. 3) or FlightLab (Ref. 4), it is less demanding in terms of inputs data with a less rigid data structure allowing it to easily model any kind of aircraft, including rotorcraft, fixed-wing aircraft, or hybrid configurations. In this regards it is comparable to the conceptual design tool HYDRA developed at DEVCOM ARL and used in Ref. 5.

3. BACKGROUND

In response to the growing interest in Advanced Air Mobility with eVTOL (about 1000 new concepts since 2016 referenced in Ref. 6) and in UAS, this tool has been created for the study at the early presizing and evaluation stages of new, unconventional aircraft configurations.

In the UAS sector particularly, the number of operators and registered aircraft continues to grow by millions, as regulations are put in place to govern the higher risk levels of operation. While the vast majority of civil UAVs are still limited to operations requiring only low levels of verification (below "Specific Assurance Integrity Level" SAIL III), the road has been mapped out to gradually reach levels requiring certification by the authorities. In the process, UAVs with designs as varied as the industrial imagination allows will eventually have to comply with increasingly stringent requirements. Flights over population, operations beyond direct line of sight, degrees of autonomy, etc., enable access to higher value-added markets, but require safer and more efficient platforms. As a result, new aircraft concepts need to be on course to meet these requirements from the predesign stage. In the military sector this is even more obvious, as new concepts are being developed every day to meet greater capability and performance requirements.

Therefore, DynaPyVTOL was previously developed in the context of the numerical workshop CREATION (Ref. 1 and 2). Originally, each vehicle design was modelled with a dedicated flight dynamic simulation corresponding to its general configuration (e.g. conventional helicopter, compound helicopter, tiltrotor, etc.). With the emergence of eVTOLs and UAS, novel hybrid configurations became more common. An initial Matlab framework was developed to provide a more flexible and simple flight dynamic toolbox. It was able to define rigid-bodies with "articulated bones" that were combined with simplified rotor/propeller, wings and aerodynamic components models. The initial results were used for example in a study conducted by ONERA and SAFRAN on new distributed electric lift and propulsion architectures (Ref. 7). The main purpose was to fill the gap between predesign analysis tools and comprehensive flight dynamics tools.

On one hand, classical performance tools for pre-design usually applied simple analytical models and methods (e.g. power balance or energy method), and were therefore limited to rough assessment of the required power. This left them without true trim capabilities necessary to evaluate complex aircraft concepts and without abilities for flight dynamics assessments. On the other hand, the more comprehensive flight dynamics tools such as HOST (Ref. 3) or FlightLab (Ref. 4), require detailed data input which are not available at early presizing stages.

Thus, DynaPyVTOL has been built to provide a more flexible tool for steady and dynamic flight performance evaluation as early as possible in the presizing process. This increased modelling flexibility also enables new analytical capabilities. For example, DynaPyVTOL could be aligned with the eVTOL BADA model proposed in Ref. 8, in order to increase modelling fidelity for flight dynamics tasks when required.

4. DATABASE STRUCTURE

DynaPyVTOL is built on a general data structure developed by ONERA called MANGROV ("Modular and Adaptable Notation for Generalized Representation Of Vehicles" see Ref. 9 for more details). It has been developed in order to address to the need of a common and dedicated vehicle description in the design process of an aircraft, where many disciplines are involved. Its primary goal is to provide a well-defined tree structure which contains all needed parameters for describing the vehicle for use between different modelling tools. This structure provides a standalone definition of the vehicle which can be interpreted by specialized codes, such as: flight dynamics (DynaPyVTOL), aerodynamics (Aero-Multi-Body), mass assessment (MassXe), electrical and energy distribution and storage, design app (Dash application), etc.

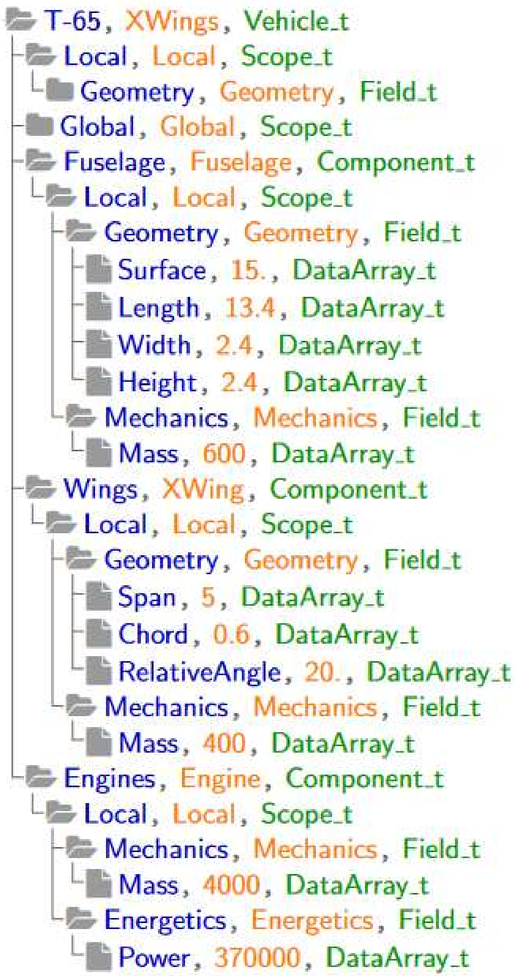

Figure 1: Example of vehicle definition tree.

The input data describing the aircraft are gathered into a hierarchical structure "Tree" containing all of the components of the aircraft (Fuselage, Rotor, Wing, etc.). It can also contain non-physical systems and other data representations, such as pilot control allocation matrices, ambient conditions and atmospheric model descriptions, and mission descriptions.

Finally, codes outputs can be stored directly in the tree, which allows the structure to be used to store results and restart points. The tree structure can be saved to hdf5 and xml file formats.

Currently, the primary implementation of MANGROV is Python-based. The versatility and large existing catalogue of open sources in Python allows for rapid development of new tools and models. For example, the browser-based interface of the DynaPyVTOL Design App leverages the Plotly Dash framework for users to visualize and modify the configuration with a user-friendly Graphic User Interface.

5. FLIGHT DYNAMICS MODELLING

This code enables the aeromechanics modelling of any VTOL configurations, including Lift+Cruise (see Figure 13), vectored thrust (see Figure 14), tilt wings, etc. as well as conventional airplanes and rotorcraft across scales starting from mini-UAVs through conventional manned aircraft. Aircraft are built element-by-element as an articulated rigid-body system. Elements are attached to each other using mechanical links with different degrees of freedom depending on their relative motion (fixed, translation, rotation) as for example in OpenVSP Parametric Geometry Tool (Ref. 10). But more general links are also possible between elements as governed by the MANGROV data structure introduced in Ref. 9.

In DynaPyVTOL, the aircraft can be composed of several types of elements: fuselage, rotor, wing, booms, hinges, motors ... Multiple levels of fidelity can be used to model the behavior of each element depending on the type of aircraft component (fixed wings, rotary wings, fuselage etc.). Thus, the modelling of the entire aircraft can be adapted to the available data, allowing initial evaluation of the flight performance in the conceptual stage. For more mature designs, the addition of specific data enables the use of higher fidelity models.

5.1. Airframe model

In addition to the position and orientation of fuselage-type elements, the user selects a drag calculation model. DynaPyVTOL provides multiple methods for implementing fuselage drag. It can be directly provided as an equivalent flat plate drag area (C_D.S) based on either a comprehensive CFD calculation or experimental data, or it can be computed in run-time from a 2D or 3D polar or analytical equation based on reference angle of attack. For example, the quadratic model gives a body-axis drag coefficient computed by the expression:

$$Cx_S = Cx_0 + Cx_1 \cdot \sqrt{|\alpha|} + Cx_2 \cdot \alpha^2$$

where Cx_i are constants and α is the angle of attack.

With the option "Polar 2D", an interpolation function gives lift, drag, and pitching moment coefficients (respectively C_L, C_D, and C_M) with respect to α using a table look-up within the polar input data file. The drag and lift coefficients are then rotated into the body frame:

$$\begin{cases} C_x = C_D cos(\alpha) - C_L sin(\alpha) \\ C_z = C_D sin(\alpha) + C_L cos(\alpha) \end{cases}$$

If the aerodynamics of the airframe have been analyzed more thoroughly, a 3D approach can be used to account for sideslip β, lateral forces and moments. An interpolation function is used based on the angles α and β and carries out the various aerodynamic coefficients: C_L (Lift coefficient), C_Y (Lateral force coefficient), C_D (Drag coefficient), C_M (Pitching moment coefficient), C_{la} (Rolling moment coefficient) and C_{na} (Yawing moment coefficient). The vector of aerodynamic forces in the body frame is then calculated as the product of the vector [C_D ; C_Y ; C_L] and the rotation matrix derived from the Euler attitude angles. The vector of the aerodynamic moments [C_{la} ; C_M ; C_{na}] is similarly rotated into the body frame.

5.2. Fixed wings models

The simplest wing model uses a rectangular (constant chord) wing represented by a single polar of aerodynamic coefficients (for lift, drag, pitching moment) with respect to the angle of attack. The typical airspeeds of helicopters and eVTOL aircraft do not exceed 100 m/s (i.e. Mach < 0.3), so polars without compressibility effects are generally used (no Mach dependency for fixed wings) and the 2D polar is generated for a Reynolds number representative of the scale and reference airspeed of the aircraft. Aerodynamic coefficients are usually obtained over a range of angles of attack between approximately -20 and 20 degrees, from which a full wing polar is then generated by:

- extending to the full 360 degrees range of angles of attack in order to model maneuvers such as vertical climb/descent and rearward flight in hover,

- applying a Prandtl correction accounting for 3D effects due to the finite span of the wing.

A higher fidelity model for fixed wings is available in the “Aero-Multi-Body (AMB)” code from the CREATION numerical workshop. It will be briefly described in the “Induced Velocities models” part hereafter.

A linear wing flap model can be used to include the variation of the wing lift, drag forces and pitching moment due to flap deflection. For this model, the wing definition requires additional input data for the derivatives of the wing lift, drag, and pitching moment coefficients with respect to the deflection angle of the flap.

5.3. Rotary wings models

The low-level model for the rotor is a rotor disc model based on momentum theory with global aerodynamic coefficients, called “Rotor Performance Model” hereafter. Providing additional input data for the rotor allows the use of a simplified BEMT model (Ref. 11), with a generic description of the blades and of their aerodynamic coefficients. Further improvements of the BEMT model towards a more general lifting line approach are also available with a more detailed blade description (including airfoils, twist and chord variations along the blade span etc.). The incremental stages of input data fidelity enable greater fidelity in the modeling approach. Through this general process, the computation can be adapted to the available data. In order to improve modeling where performance data is available, DynaPyVTOL also features methods which allow fitting a model to reference data.

The improvement of simulation fidelity can therefore by accomplished directly or indirectly:

- Directly through the use of more detailed geometry and models (e.g. a rotor BEMT model instead of a rotor disc model),
- Indirectly by identifying model parameters to match reference data (e.g. propeller thrust and torque) coming from measurements or from high-fidelity simulation. The later may be too computationally expensive for flight dynamics purposes, but can improve the quality of the lower order models.

<u>Rotor Performance Model</u>

The “Rotor Performance Model” is the simplest rotor or propeller model in DynaPyVTOL. It is based on the power balance or energy method to provide the required power as a sum of the blade profile drag power and the induced power (including the power for climb or descent) and thus the resulting torque.

The thrust expression is:

$$T = \frac{\rho}{6} \sigma S V_{tip}^2 Cz_m$$

and the torque is given by: $Q = \frac{P}{\Omega}$

with the power P *(eq.1)*:

$$P = P_{profil} + P_{induced} \\ = (1 + 4.65\mu^2) \cdot \frac{\rho}{8} \cdot b \cdot c \cdot R \cdot V_{tip}^3 \cdot C_{xp} \\ + T(\kappa \cdot V_{im} - V_z)$$

It takes as inputs:

- the main rotor characteristics (diameter *2R*, number of blades *b*, mean chord *c*, mean lift coefficient C_{zm} and mean blade profile drag coefficient C_{xp}),
- either the rotor revolution speed *Ω*, or the rotor thrust *T*,
- the flight conditions, i.e. the 3 components of the airspeed seen by the rotor and the air density *ρ*, (*μ* is the advance ratio, which is the ratio of the aircraft velocity to the tip blades rotational speed).

For the mean lift coefficient *Czm*, it depends on the type of rotor-propeller.

If it is a constant pitch propeller, the *Czm* is imposed as a characteristics which can be fitted to data (measurements or computations by a higher fidelity model). Then the blade tip speed due to rotor revolution speed ($V_{tip}= \Omega R$) can be found as a function of thrust *(T)*. w.r.t. this *Czm*:

$$V_{tip} = \sqrt{\frac{6 \cdot T}{\rho \cdot B^3 \cdot \sigma \cdot S \cdot Cz_m}}$$

Where:

B is the blade tip loss factor which represents the percentage of the blade radius that is considered efficient,

σ is the rotor solidity,

S is the rotor disk surface.

If it is a variable pitch propeller, the blade tip speed is fixed and *Czm* is calculated as a function of thrust *(T)* and this blade tip speed using the classical definition of *Czm*:

$$Cz_m = \frac{6 \cdot T}{\rho \cdot B^3 \cdot \sigma \cdot S \cdot {V_{tip}}^2}$$

When the calculated *Czm* is above the maximum Czm_{Max} given for this rotor, then the *Vtip* is recalculated to match this Czm_{Max}.

The classical coefficients allowing a good approximation of required power (see *eq. 1* on previous page) i.e.: the inflow factor *κ* for the induced power $P_{induced}$ (applied on the mean inflow for correcting the momentum theory) and the mean profile drag coefficient Cx_p for the profile drag power $P_{profile}$ are calculated with a "grey model". This means that analytical models are used considering the physics underlying the variations of these parameters *κ*; Cx_p with physical inputs like the horizontal and vertical components of the advance ratio, the Mach number at the blade tip, the air density etc. and rotor inputs like solidity *σ*, *Vtip*, *Czm*. These analytical foundations are the ones of the CREATION workshop and are comparable to the models described e.g. in Ref. 12.

From these analytical models based on physics, a surrogate model fitted on a database is generated by a least-squares algorithm. This reference database depends on the considered aircraft to be simulated and on the availability of experimental data. For helicopters, the database can be composed both of flight test measurements and on simulation data. The simulation reference data are computed with the high fidelity models within the HOST code that most closely match the flight test points. More refined technics for generating the surrogate models have been used in CREATION, such as kriging methods (Ref. 13-14). For better accounting for the different levels of confidence of the data within a hybrid database, the use of multi-fidelity gaussian processes (e.g. Ref. 15) will be explored.

<u>Rotor BEMT model</u>

The rotor is discretized in elements distributed radially and azimuthally covering the different positions which can be occupied by a blade element along the blade span and during the blade rotation around the rotor mast. Each element or 3D blade segment is defined by two 2D sections. Each section is defined by a radial position and characterized by a chord and twist angle. The values of twist and chord at the middle of each segment are linearly interpolated between the values of its two sections.

The "rotor BEMT" model is a reimplementation from a prototype Matlab version (DynaMatVTOL), which was first validated by comparison with the "rotor Perfomance" model to ensure a continuity between models and then with experimental data (e.g. UIUC propellers database Ref. 16) as shown for example on Figure 2.

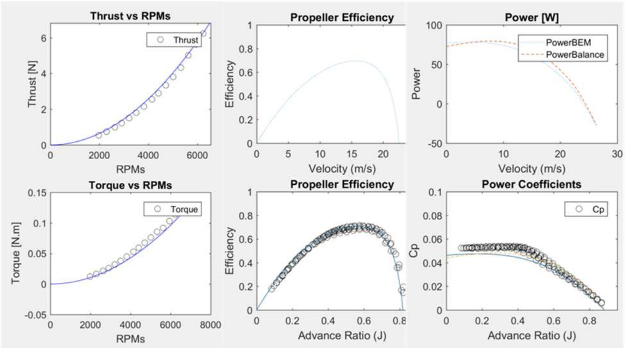

Figure 2: example of comparisons between the “Rotor Performance” model (in red), the “Rotor BEMT” model (in blue) and propeller measurements of UIUC database (circles, Ref. 16).

Other good comparisons have been performed, for instance with Flightlab propeller model and *Mejzlik* propellers data.

Three kinds of “Rotor BEMT” models are available. One is implemented in python and is a “classical version” of the BEMT able to use any polar data. The two other models are intended for more rapid evaluation, and are therefore coded in Fortran.

A key feature of this implementation is to avoid using table look-up and interpolation for aerodynamic coefficients, thereby reducing the computational cost. It has been observed that most of the lifting line approaches rely on such time-consuming numerical interpolation within airfoil polar tables (generally based on 2D quasi-steady polar data measured in wind-tunnel).

Instead, an analytical aerodynamic model of the blade airfoil coefficients is used, which incorporates an extension to the full range of angles of attack [-180deg; 180deg] using a general analytical method inspired from the one presented in (Ref. 17). This blade airfoil analytical model uses 7 parameters (“*Cn1, Cn2, Cn3, Cn4, RelativeThickness, DragAt90 and FrictionDrag*”) to calculate the lift and drag coefficients (CL, CD) on the full range of AoA (angles of attack), see for example a comparison for the NACA5405 on the Figure 3 and Figure 4. In Ref. 17, the analytical formulation is used only at high AoA beyond stall, for the extension to the full AoA range, while table look-up interpolation is still applied for accuracy at low AoA. In DynaPyVTOL, an analytical modelling is desired for use over the entire range of AoA for rapid computation.

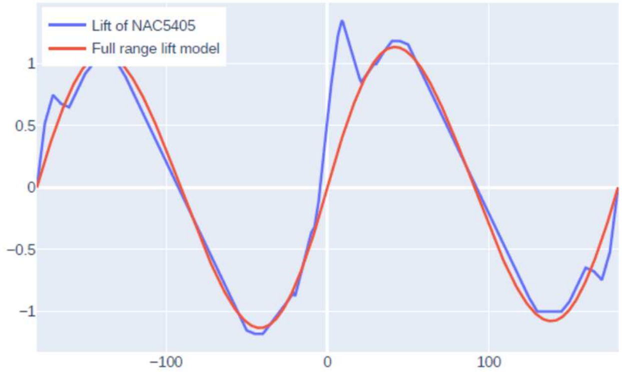

Figure 3: comparison of the lift coefficient versus AoA (deg) between the NACA5405 polar reference data and the “Full range analytical model” extended to low AoA.

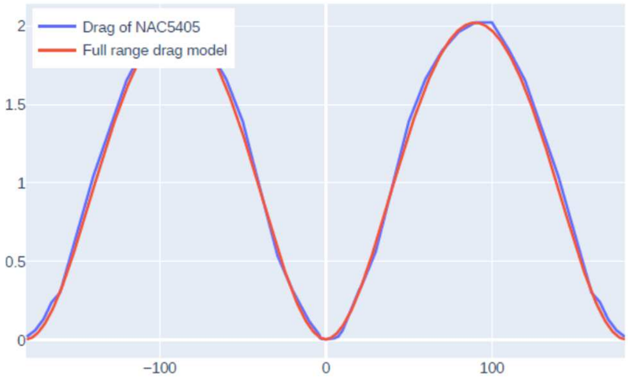

Figure 4: comparison of the drag coefficient versus AoA (deg) between the NACA5405 airfoil polar reference data and the “Full range analytical model” extended to low AoA.

An improvement to the analytical shape function for this full range model has been used to better account for the lift and drag variations within the linear regime at low AoA (see Figure 5-Figure 6). Again in Ref. 17 at low AoA, table look-up interpolation within airfoil polar reliable data is done, but here the goal is to get a full range analytical model for the entire range including low AoA.

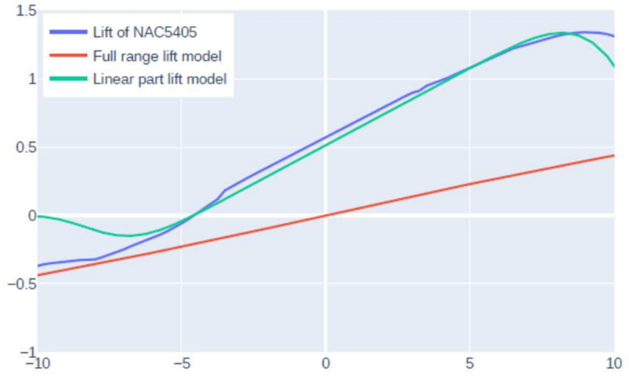

Figure 5: comparison of the lift coefficient versus AoA (deg) between the NACA5405 polar reference data (in blue), the analytical “Full range model” extended to low AoA from Ref. 17 (in red) and the improved linear part of the analytical model in DynaPyVTOL (in green).

The lift at zero AoA and the maximum lift value before stall as well as the lift curve slope are better reproduced with the improved linear regime model.

For the drag coefficient a “bucket” and phase shift parameter are also added to the analytical model in order to better account for the fact that the lowest drag may not be located at zero AoA (see Figure 6).

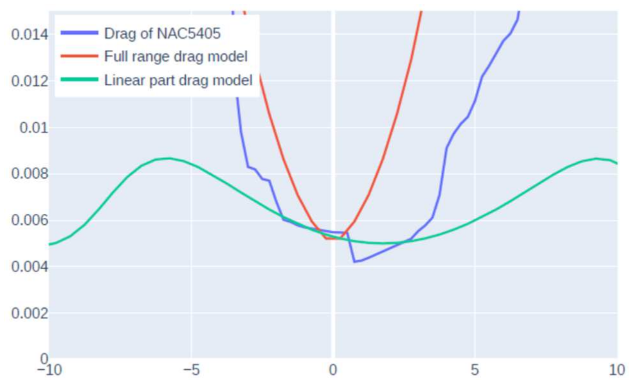

Figure 6: comparison of the drag coefficient versus AoA (deg) between the NACA5405 polar reference data (in blue), the analytical “Full range model” extended to low AoA from Ref. 17 (in red) and the added improved “bucket” & phase shift part of the analytical model in DynaPyVTOL (in green).

The blending of the original “extended range analytical model” (Ref. 17) and these improvements at low angles is performed though the addition of 6 model parameters: *AngleOfAttackNoLift, LiftSlope, LinearLiftRange, DragBucketDrop, LinearRangeFlatness and LinearRangeCenter*.

The final comprehensive analytical polar model gives a better assessment of the lift and drag coefficients than the initial model in particular in the regular range of the airfoil AoA although a deeper post-stall is produced. The resulting model allows a better fitting of the rotor BEMT model when compared to the airfoil and propeller databases (e.g. UIUC propeller database Ref. 16).

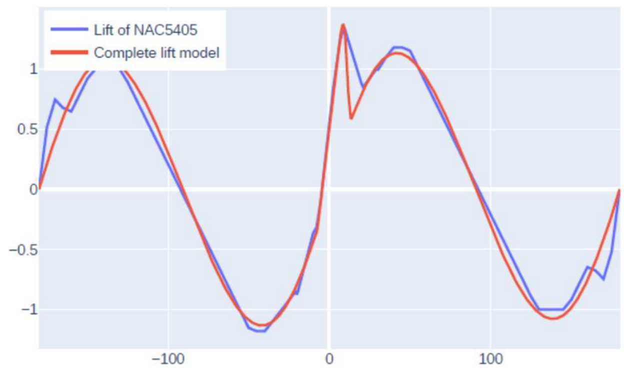

Figure 7: comparison of the lift coefficient versus AoA (deg) between the NACA5405 polar reference data (in blue) and the improved analytical “Complete model” in DynaPyVTOL (in red).

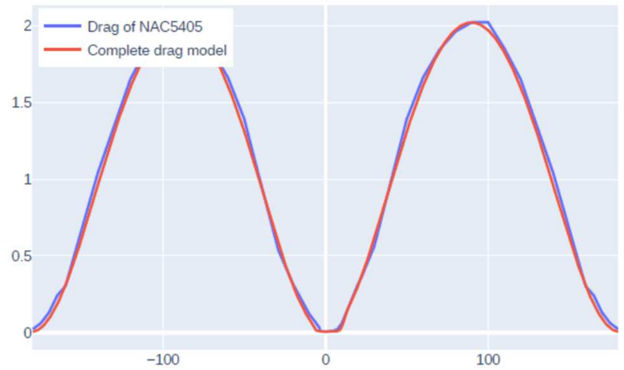

Figure 8: comparison of the drag coefficient versus AoA (deg) between the NACA5405 polar reference data (in blue) and the improved analytical “Complete model” in DynaPyVTOL (in red).

Further developments may include model improvements in accuracy (see post-stall), the formulation of analytical derivatives for use of auto-differentiation, and implementation of spanwise airfoil blending.

5.4. Induced velocity models

Uniform rotor inflow models

The two mentioned versions of Rotor BEMT models in Fortran use the momentum theory to calculate a uniform inflow through the rotor disc. One makes converge the rotor inflow on the thrust given in input with a root quartic approach (“Thrust control”), whereas the other calculates forces and moments directly from the given aerodynamic condition (“Classical control”).

In this last case thrust and rotor inflow are a corollary of the controls (RPM and/or pitch angle) and of the airspeed conditions whereas in the first one the thrust is directly controlled and the rotor inflow is converged on in accordance.

The rotor inflow model in the rotor BEMT model has been recently improved for a better simulation of the "Vortex Ring State (VRS)". The extension of the momentum theory developed in the ONERA Ph.D. thesis (Ref. 18-19) has been implemented in DynaPyVTOL. This model is based both on rotor inflow measurements in descent flights showing that the mean inflow increases beyond the prediction of the momentum theory and on French flight test data at different forward speeds and rates of descent. This will contribute to better assess with DynaPyVTOL the risks of VRS on rotorcraft concepts at early evaluation stage. It will be applied to the study of eVTOL for which one or more lifting propellers may encounter the VRS during a steep approach for example with roll motion.

An example for the case of the Dauphin helicopter is shown hereafter. Figure 9-Figure 10 illustrate that the non-linear variation, brought by this rotor inflow model on the total mean airflow speed (Vz+Vim) through the rotor (Figure 9), induces the non-linear variation of the collective pitch with respect to the descent rate (Figure 10). As explained in Ref. 20, this is required to capture the VRS instability on the heave mode. Indeed, for some values of collective, there are three equilibrium solutions: one stable on the helicopter branch, one stable on the wind-mill branch and one unstable in VRS between the two other solutions.

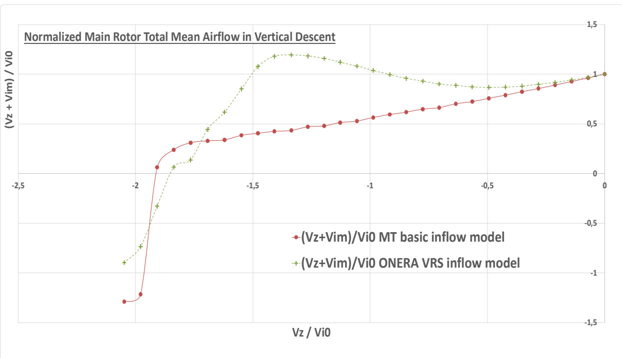

Figure 9: Main rotor total mean inflow (Vz+Vim) normalized by the mean inflow in hover Vi0 calculated for the Dauphin helicopter with the basic Momentum Theory model in DynaPyVTOL (in red) and the ONERA extended model to VRS (in green) in vertical descent flights.

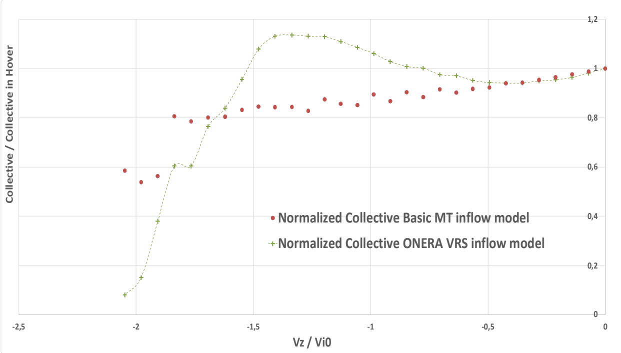

Figure 10: Collective control normalized by the collective in hover calculated for the Dauphin helicopter with the basic Momentum Theory model in DynaPyVTOL (in red) and the ONERA extended model to VRS (in green) in vertical descent flights.

<u>Non-uniform rotor inflow models</u>

In many cases, the application of momentum theory inflow locally on each blade element does not give satisfying results. An anticipated development of this flight dynamics tool will be to implement a dynamic inflow model, such as the well-known Pitt & Peters model in Ref. 22. The implementation in the HOST code done by ONERA of this first harmonic dynamic inflow model brought significant improvements to the helicopter flight dynamics simulation years ago (Ref. 23). These positive results encouraged further refinements of the dynamic inflow models in HOST, such as the FiSuW model (based on Peters & He extension in terms of harmonics and radial span non-linear variations Ref. 24-25), and the extension to the 3 components of induced velocities everywhere on and out of the rotor (Peters & Huang Ref. 26-27).

To date, this generalized dynamic inflow model has been implemented by ONERA both in the HOST code and in the AMB ("Aero-Multi-Body") ONERA code. AMB is the aerodynamic tool within the CREATION numerical workshop and is used to assess the aerodynamics and interferences of any aircraft configuration at early evaluation stage (see Ref. 2).

Fixed wing modeling in AMB consists of a lifting line model, with a free vortex wake model comparable to a Vortex Lattice Model. Thanks to the discretization of the wing in elements along its span, local interference velocities induced by nearby fixed or rotary wings can be taken into account.

The Rotary Wings in AMB are also modelled with a lifting line approach using different induced velocities models:

- a simplified model for predesign based on momentum theory for the axial component of the rotor induced flow Vi_z which results from rotor thrust T and on the Euler theorem for the swirl component Vi_θ which results from rotor torque Q or Power P (see Ref. 2 and 21),

- a prescribed wake model with vorticity segments advected all with the same airspeed, sum of the free airstream and of the mean rotor induced flow,

- a free-wake model, where each vortex segment induces velocities both on the blade lifting line elements and on each other.

ONERA has implemented other induced flow models in AMB, including the Peters & Huang model (Ref. 26-27) and a new model based on a spectral Galerkin method applied to the incompressible non-linear Euler equations (Ref. 28).

A "weak coupling" between DynaPyVTOL and AMB allows the use of the same python tree data for describing the aircraft through the use of MANGROV. An example of aerodynamics computation was performed by AMB on the "Lift+Cruise" eVTOL configuration for the "Project Agreement AHFIR collaboration" between ONERA and US-Army/DEVCOM (Ref. 29). For ensuring a good convection of the 12 lifting propellers wakes in HOGE (Hover Out of Ground Effect), a first initialization of wakes was done with the prescribed wake model (on the 5 first revolutions, see Figure 11) before switching on the free wake model (Figure 12).

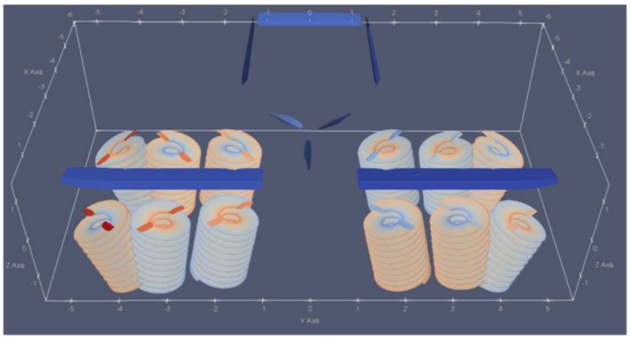

Figure 11: initialization of the 12 lifting propellers wake using the prescribed wake model in HOGE.

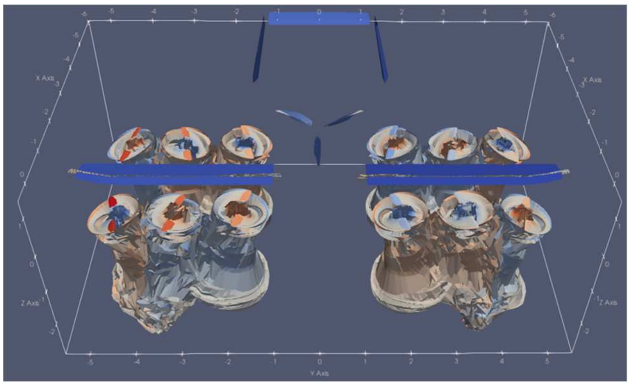

Figure 12: following computation with the AMB free-wake model in HOGE.

The hover case is always a challenging task because the only airspeed advecting the vortices are the induced velocities by the vortex wake themselves. Therefore, starting from no wake does not always result in well converged simulations. Such two phases simulation approaches are a good method for avoiding cases where the free-wake computations expand the wakes radially before the vertical wake develops. An interesting observation from these simulations has been that these 12 closely positioned lifting propellers produce beneficial aerodynamic interferences in hover. The downwash at the periphery of a propeller close to its neighbor is reduced by the upwash induced by the blade tip vortices outside of the wake of its neighbor. This upwash effect increases local angles of attack and reduces the required power. This positive interaction seems to be reinforced by the cant angles of these lifting propellers. This first assessment with AMB computation gives a reduction about 10% in the required hover power, which was then accounted for in DynaPyVTOL simulation of this "Lift+Cruise" configuration in hover by adjusting the induced flow correction factor κ within the momentum theory inflow model as part of the "grey box" modeling approach.

Further simulations have been recently performed by ONERA using higher fidelity CFD models in order to continue investigating this positive effect.

5.5. Full aircraft flight dynamics simulation

Thanks to the development of computationally efficient rotor-level Fortran libraries called by Python, DynaPyVTOL allows for efficient simulation of aircraft with numerous elements. Examples of such aircraft configurations with different combinations of rotary wings and fixed wings are shown hereafter on Figure 13 and Figure 14.

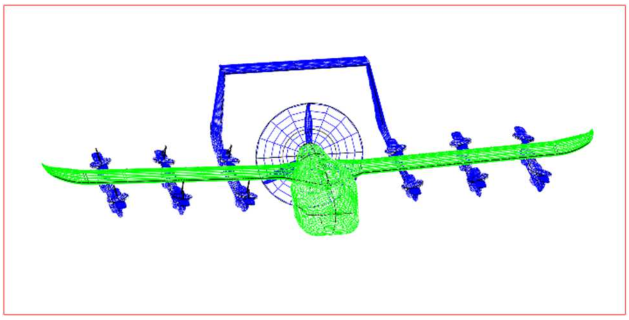

Figure 13 : Lift + Cruise example of configuration with 12 canted lifting propellers and one pusher propeller (Ref. 29 and 30)

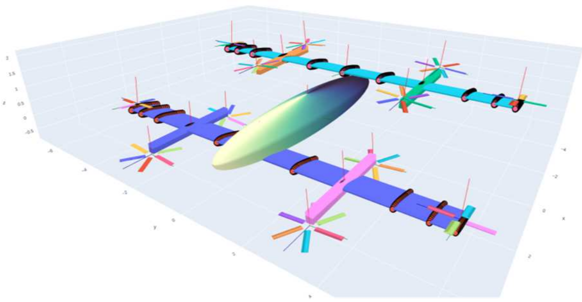

Figure 14 : The ONERA HEDWIGE tandem wing configuration with 8 lifting propellers and 4 tiltable wing tip propellers

6. STEADY FLIGHT PERFORMANCE AND TRIM

DynaPyVTOL evaluates both steady and dynamic flight performance of various aircraft configurations using cumulative data. Steady flight performance is assessed through trim computations corresponding to equilibrium points.

Many configurations are over-actuated, meaning they have more than 6 controls for piloting the 6 rigid body flight dynamics, leading to infinite trim solutions. This is particularly the case for many new aircraft concepts based on the electric distribution of lift and propulsion on many propellers (e.g. Figure 13-Figure 14). For instance, the “Lift+Cruise” or “Separate Lift and Cruise” (SLC) configuration has 17 basic controls or effectors: 13 for the RPM controlled propellers (12 lifting propellers and 1 pusher propeller), 4 control surfaces angles across the 5 fixed wings (2 wing-flaps which can be used in aileron and/or flaperon modes, 1 ganged pair of rudders on the 2 fins, 1 elevator angle for the horizontal stabilizer). In addition to these 17 effectors, one or more of the 3 attitude angles can be used as trim parameter. For example, for the case of straight steady level flights as shown on Figure 15, the pitch angle is used for allowing both the use of the lifting propellers at low forward speed for the transition toward cruise as well as for adjusting the aircraft AoA in order that the fixed wings provide 100% of the lift at higher speeds. Therefore 18 trim parameters can be used for finding the trim (6 rigid body flight dynamics accelerations equal to zero).

A first way to help finding the trims and to manage the trim strategies is to define the logics of the allocation of these basic controls (here 17 effectors) to the pilot controls. For example, in hover and low speeds, only the propellers RPM can be used. They can be grouped logically in four control mixing as for a helicopter (see red curve on Figure 15):

- Collective control: imposes the same variation (in absolute value) of the RPM on the 12 lifting propellers (considering the different revolution directions),
- Longitudinal control: imposes opposite variations on front and aft lifting propellers,
- Lateral control: imposes opposite variations on right and left lifting propellers,
- Pedals control: imposes opposite variations on lifting propellers turning in opposite directions.

At higher airspeeds, the fixed wings can be used, leading to define five airplane mode controls:

- Wing flaps imposes the same variation on the wings flaps in a flaperon mode,
- Longitudinal control imposes the variation on the horizontal stabilizer elevator angle,
- Lateral control imposes opposite variations on the wings flaps acting thus in an aileron mode,
- Pedal control imposes the variation on the vertical stabilizers flap angle,
- Thrust control imposes the variation on the pusher propeller RPM.

Even if this control allocation reduces the trim problem from 17 effectors to 9 mixed controls, there are still more control unknowns than equations (the 6 rigid body motion aircraft accelerations). Of course, in hover only the 4 helicopter mode controls can be used with the pitch and bank angles if the center of gravity is not at the centroid of the 12 lifting propellers, leading to a unique trim solution. As well in cruise, the 5 airplane mode controls and the pitch attitude can be used to give also a unique trim solution. But in the transitions at intermediate airspeeds, all the 9 mixed controls can be used leading to infinite trim solutions.

The challenge lies not in finding any equilibrium, but in identifying the optimal one. Conventional optimizers struggle with local minima and flat solution spaces (Ref. 31), making them inefficient. The SLSQP algorithm is recommended in Ref. 5, but requires a good starting point which may not be available for unknown configurations. To address this, a custom optimization process based on a gradient approach has been developed. This method exploits the control matrix kernel to efficiently and robustly find optimal trims, especially during complex phases like VTOL transitions. The custom algorithm is particularly effective in transition phases where all effectors, such as rotary wings and wing flaps, are active. This DynaPyVTOL optimal trim algorithm has been successfully applied to find the trims minimizing the required power of many over-actuated aircraft (e.g. Figure 15, Ref. 30) and also to find the optimal redistribution of thrusts in case of thruster failures (Figure 16, Ref. 32 and 30), showcasing its versatility and reliability in design optimization processes.

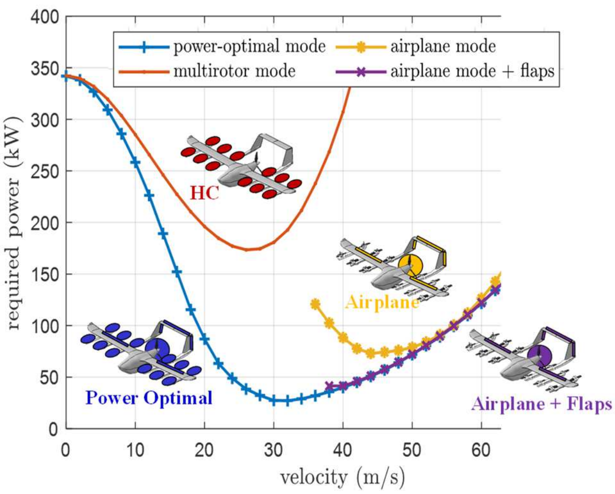

Figure 15 : Effect on the evolution of required power with forward speed of different trim strategies, the “Power optimal” blue curve result is obtained by the optimal trim algorithm with a minimizing Power criterion.

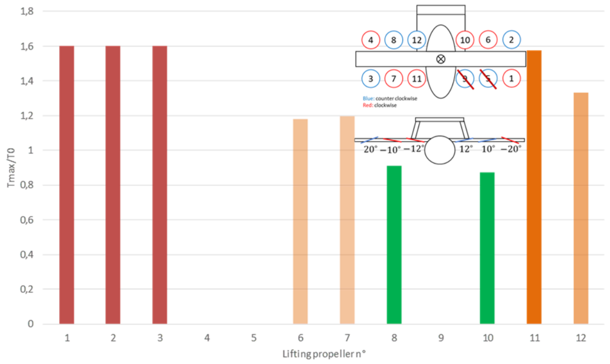

Figure 16: example of optimal trim minimizing the Maximum Thrust on the 10 operating propellers after the failure of the front left inner n°9 and middle n°5 propellers.

A detailed description of this in-house algorithm would require a dedicated paper or technical note. For the sake of brevity here only the key ideas are exposed.

First, close to any trim solution, the flight dynamics can be considered through its linear form:

$$\dot{X} = f(X, U, t) \approx [A].X + [B].U \qquad \text{(eq. 2)}$$

where *X* is the state vector and *U* the control vector. Of course, finding the optimal trim w.r.t. to a given criterion (e.g. minimize the required power) means that among the infinite space of trim solutions (zero accelerations on the 6 motion degrees of freedom of the aircraft: 3 translations, 3 rotations), we are looking for the best one respecting this criterion.

The key idea is to reduce the space of possible solutions by focusing the search into the subspace corresponding to the kernel of the control matrix *[B]*. Within this subspace of solutions, any change on the controls will give a new solution respecting the trim constraint at a given precision *p*:

$$\|\dot{X}\| \leq p$$

Then the optimization problem respecting this constraint is reduced to one criterion (e.g. minimize the power) and can be dealt with a gradient based method (within this “tube” of radius *p* respecting the above trim constraint). The initial solution can be either a first trim or any random solution (optional number of multi-starts given by the user). The direction toward a better solution can be looked for by computing the power gradient (or criterion gradient) and choosing the steepest one or by exploring all the directions and choosing the one giving the best next point or both by alternating the two approaches. Obviously the gradient one is the least costly but tends to get trapped in a surrounding local minimum. Once the direction of search selected, a line search method using a dichotomy approach or a quadratic approach is applied for finding the best next point in this direction of course without going out the subspace of kernel solution respecting the above trim constraint. Therefore, the precision *p* must not be too small for allowing a search within a not too narrow acceptable domain of trim solutions. That is why several successive calls of the trim algorithm can be required in difficult cases by adjusting the trade-off between the parameters (step size, number of iterations, search method and precision etc.) for progressing “like in a funnel” towards the global optimal solution.

7. STABILITY

Once the aircraft is trimmed, its natural stability can be studied by computing the linearization of its flight dynamics (in the form of the state *[A]* and control *[B]* matrices) around the trim point. The matrix *[B]* provides the control derivatives giving a first insight on the maneuverability of the aircraft. The *[A]* matrix allows an initial assessment of the stability of the aircraft, considering the evolution of its eigen-modes with respect to the variation of some design parameters. An example is shown hereafter for the case of a Lift+Cruise quadrotor configuration with opposite cant angles on the right/left lifting propellers. The effect on the aircraft stability in hover is calculated with DynaPyVTOL (see Figure 18) when varying the cant angles from -10° inboard (dihedral in blue) to 10° outboard (anhedral in green).

From a natural aircraft stability perspective, a -5° cant angle is a favorable compromise. It enhances roll subsidence stability (with respect to the uncanted case) while still keeping the "lateral phugoid" mode on the stable side (negative real part). The "lateral spiral" mode becomes also less unstable with an inboard (dihedral) cant angle. However, the phugoid (longitudinal swing) and "lateral spiral" modes remain unstable regardless of the cant angle. Indeed, the heave and longitudinal modes (longitudinal phugoid, pitch subsidence) are of course minimally affected by lateral tilt angles on the lifting propellers. Therefore -5° of dihedral cant angle turns out to be a good trade-off considering this eigen-plot and also the fact that keeping the cant angles low reduces the increase of the required power in hover and low speeds as illustrated on Figure 17. With -5deg of cant the increase of required power for hovering out of ground effect is lower than 1% w.r.t. to the uncanted case for this configuration.

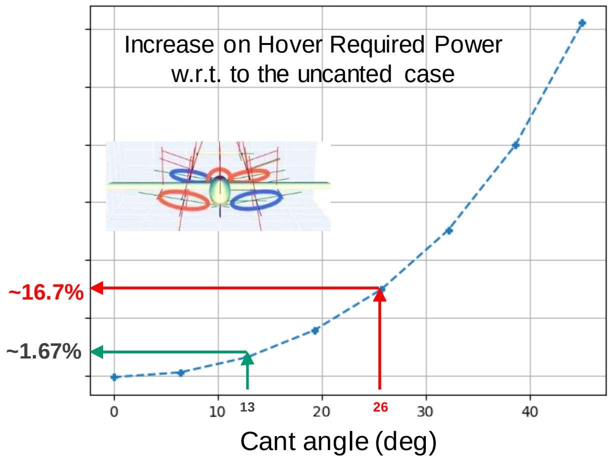

Figure 17: relative increase of the required power for hovering w.r.t to the uncanted case for the Lift+Cruise quad-rotor configuration (from Ref. 30).

This non-linear increase of the required power in HOGE is simply due to the geometrical relationship between the cant angle *d* and the thrust *T* on one hand:

$$T = \frac{Tz}{\cos(d)} = \frac{Cste}{\cos(d)} \approx \frac{M.g/4}{\cos(d)}$$

and the relationship between the required power *P* and the thrust on the other. In hover, the required power is mainly driven by the induced power *Pi* which varies according to the momentum theory as $(T)^{3/2}$, therefore the non-linear variation of the required power with the cant angle is as the one of $(\cos(d))^{-3/2}$:

$$P \sim P_i \sim T^{3/2} \sim \frac{1}{\left(\cos(d)\right)^{3/2}}$$

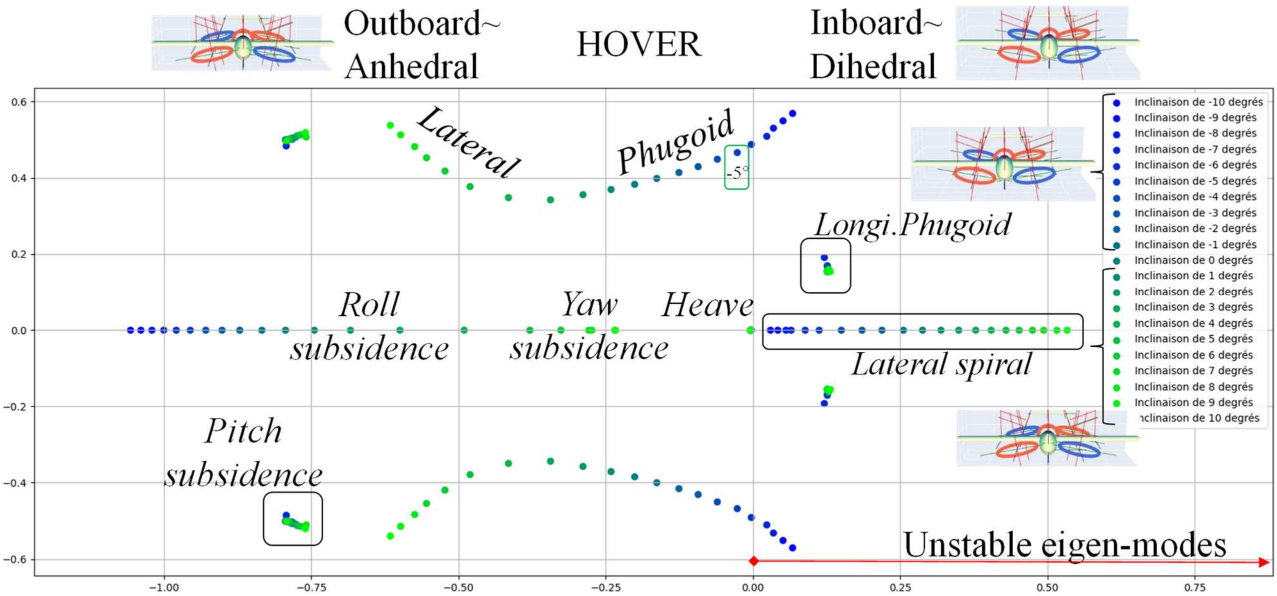

Figure 18: Example of study of the impact of rotor cant angles on the aircraft stability considering the variation of the eigenvalues of a Lift+Cruise quadrotor with different cant angles.

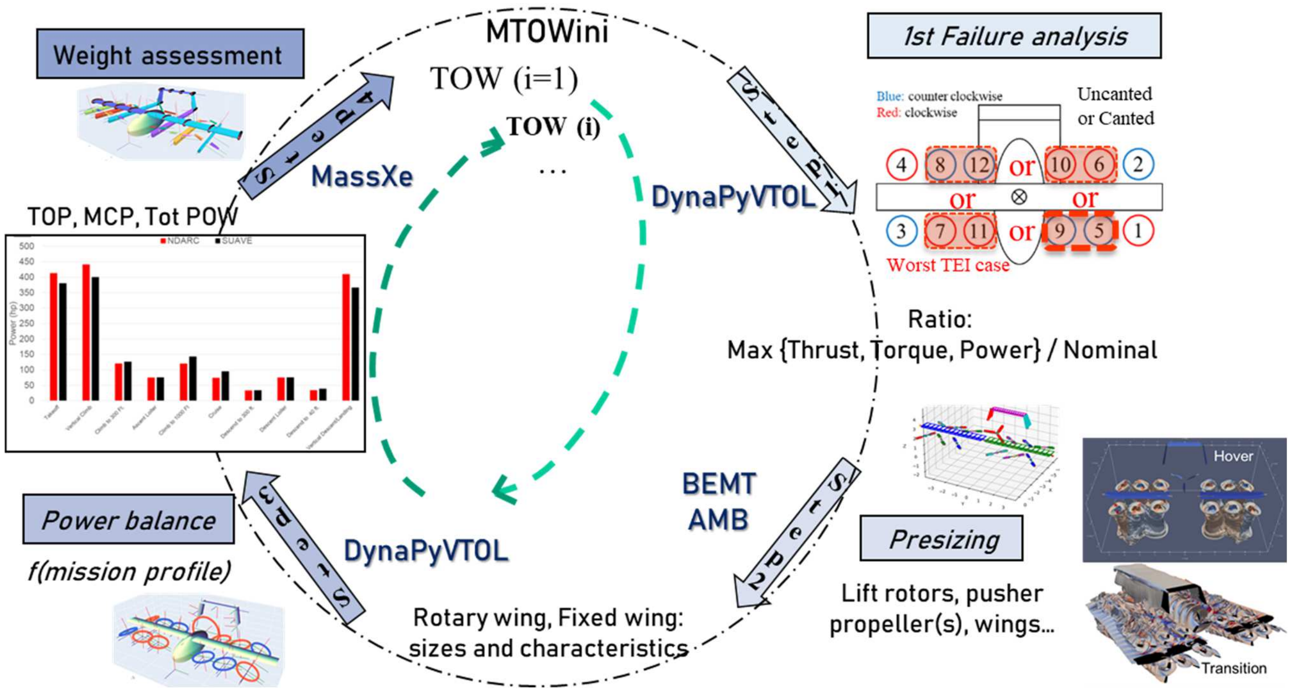

Figure 19: Predesign first loop for "Mass & Performance" convergence.

8. TIME SIMULATION AND CONTROLLED FLIGHT

In addition to steady flight performance and stability, DynaPyVTOL can also be used for open-loop or controlled time simulations, from simple to complex waypoint-following tasks (see Figure 20). A versatile control method, adapted from Ref. 33, and based on the dynamic inversion of the control matrix, is applied for a fast-initial assessment of the aircraft control potential. This method rapidly provides an initial view of the aircraft closed-loop behavior, focusing on evaluating its platform capabilities rather than delivering robust and very efficient control laws.

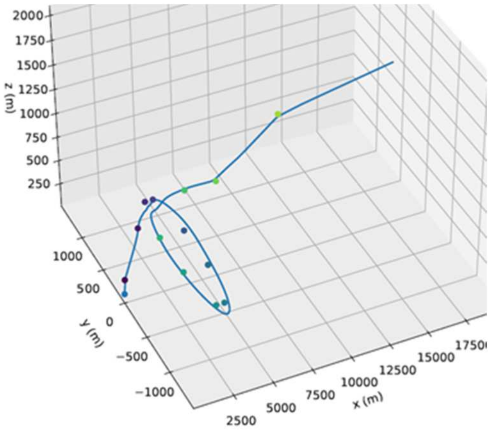

Figure 20 : Trajectory of a conventional helicopter (blue line) following waypoints.

At each point of the trajectory, the linearized system is considered (see eq. 2). The desired time derivative of the state vector $(\dot{X})$ is calculated with a PID. Then the approach consists in calculating the control variations to be applied in order to reach the desired state dynamics. The solution in terms of control variations is searched such that it minimizes the L2 norm of these control variations.

The main method used for the finding this control solution is the JPI (Jacobian Pseudo Inverse) method. This method is used to control redundant or over-actuated systems. In such cases, the number of degrees of freedom in terms of controls is greater than necessary, the Jacobian matrix is not square and is therefore not invertible in the classical sense. The pseudo-inverse of the Jacobian matrix is then used to find an approximate solution that minimizes the error between the desired position and the actual position (or state vector X) of the aircraft. The pseudo-inverse is calculated using singular value decomposition. Optimization by minimizing criteria such as power or control variations enables control redundancy to be managed. This method remains flexible for complex motions and provides stable solutions for over- and under-actuated systems. However, near singular trajectory waypoints, it can lead to excessive speeds. For example, when an aircraft has to change suddenly from climb to forward flight, the computed trajectory may overshoot the trajectory to be followed. In addition, solutions may depend on the path followed and are not always repeatable (Ref. 34). A Discrete Jacobian Pseudo Inverse (DJPI) method is also available in a discrete-time context. Four other control methods are also currently available in DynaPyVTOL:

- LQR: Linear Quadratic Regulator
- MPC: Model Predictive Control
- LMI: Linear Matrix Inequalities
- OLR: Open Loop Response

With the option LQR (Linear Quadratic Regulator), we first compute the linearization of the system at the given point, then we solve the associated Riccati equation in order to find the adequate controller. These controls will minimize a given cost function defined by the user which can be related to the required power.

The MPC (Model Predictive Control) is an optimal control technique that uses a prediction of the system's future behavior over a given time horizon and the model equations as well as the possible control actions. The difference with LQR is that the optimal control is calculated by integrating the non-linear equations over a time prediction horizon of several time steps. Then, the process is recalculated at each time step with the new state (receding horizon or time window).

The LMI (Linear Matrix Inequality) tries to find a command law of the type $U = KX$ in order to ensure that the system $\dot{X} = (A + BK)X$ is stable. A is the state matrix, B is the input matrix and K is the feedback gain matrix that should be determined to stabilize the system. The LMI formulation is such that: $(A + BK)^T P + P(A + BK) \prec 0$ and should be solved with $P \succ 0$.

The last and simplest option is OLR (Open Loop Response). It consists in computing the reaction of the aircraft to a given command, without considering any feedback. It is used to access rapidly the influence of a set of control parameters.

An example of application of the OLR option consists of exploring the accelerations capabilities of the aircraft by calculating the maximum reachable acceleration of the aircraft rigid-body flight dynamics in response to all the combinations of max/min values of all the controls. For instance, in hover on the Lift+Cruise configuration with 12 lifting propellers, this will require a large number of dynamic evaluations $(\dot{X})$: $2^{12} = 4096$ (see Ref. 30). In the case of the quad Lift+Cruise, the number of acceleration evaluations is of course much smaller: $2^4 = 16$. The multi-propellers configuration with only lifting propellers or propellers pointing all in the same direction and no tilt propeller are known to suffer from a lack of authority in yaw. As explained in Ref. 30, the cant angle by providing a lateral force means can improve the yaw authority as well as the tolerance to lateral wind in hover and low speeds. The Figure 21 shows the improvement brought on the quad Lift+Cruise example on the yaw attainable acceleration. In hover with no bank or roll angle, this kind of configuration cannot produce any lateral force or lateral acceleration whereas it is possible with cant angles as illustrated on Figure 22.

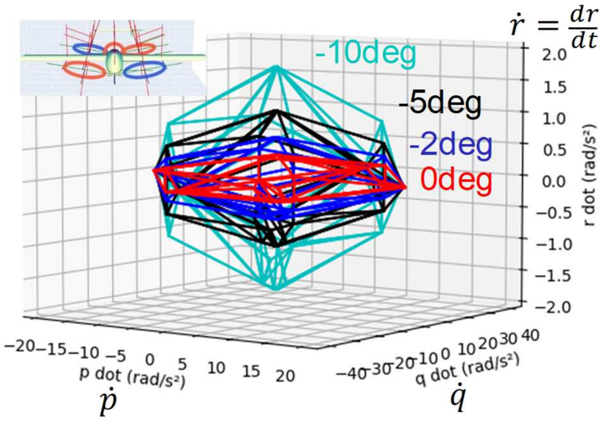

Figure 21: Attainable yaw acceleration domain in hover for a typical quad Lift+Cruise configuration with no cant (red), -2deg (bleu), -5deg (black), -10deg (cyan) of dihedral cant on the four lifting propellers.

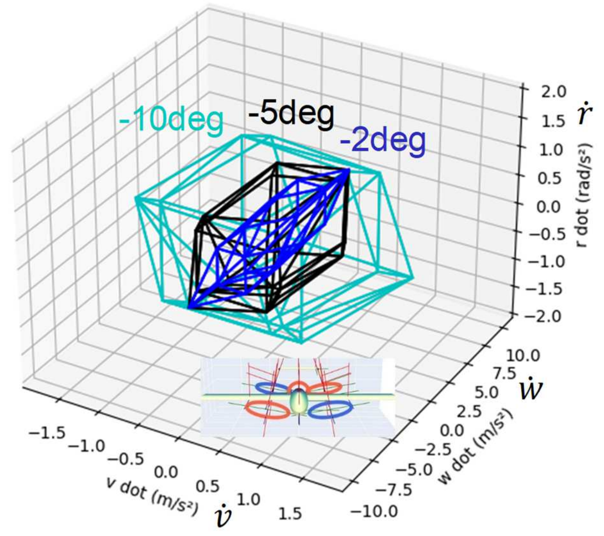

Figure 22: Attainable control set on lateral, vertical and yaw dynamics in hover for a typical quad Lift+Cruise configuration with -2deg (bleu), -5deg (black), -10deg (cyan) of dihedral cant on the four lifting propellers.

The acceleration values depend on the range of RPM variation (min-max), on the inertia and dimensions of the aircraft. By normalizing these absolute values by those of the uncanted case, the effect of the canting can be better appreciated in relative terms, as shown on Figure 23. Only the lateral acceleration *(dv/dt)* is not normalized, because the uncanted configuration generates zero lateral acceleration (in hovering horizontal flight). The improvement in the yaw and lateral acceleration capabilities is demonstrated clearly in these figures.

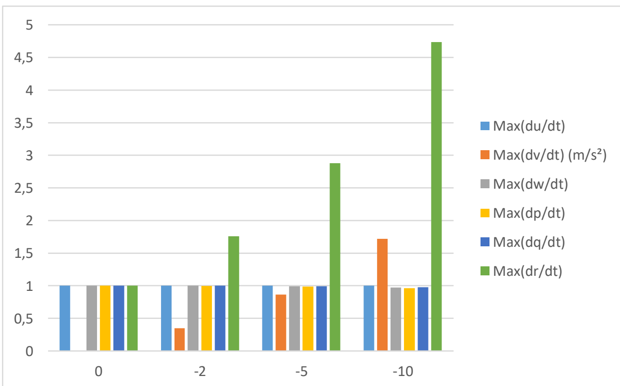

Figure 23: maximum aircraft 6 rigid body accelerations normalized by the values obtained for the uncanted quad Lift+Cruise (except for the lateral speed acceleration which is null for the uncanted case)

DynaPyVTOL can be used for further studies dedicated to the development of control laws adapted to a new aircraft concept at the preliminary conceptual stage, see for example Ref. 35.

For that purpose, it has been coupled to Matlab Simulink© for easing early design and evaluation of control laws. A dedicated Simulink© model has thus been developed, integrating specific functionalities required to develop and study a complete Flight Control System (FCS). This Simulink© model, called "ESSENCE" for Evtol SyStems dEsigN struCturE (see Figure 24), integrates pilot controls (emulating stick deflections and buttons), a FCS, a control allocation block, an actuator dynamics block and, as a flight dynamics code, DynaPyVTOL or its linear models. One of the objectives is the implementation of DynaPyVTOL in the ONERA real-time simulator PycsHel in the medium term, so specific blocks were introduced to emulate cockpit push-button and data transfer functions available in the simulator.

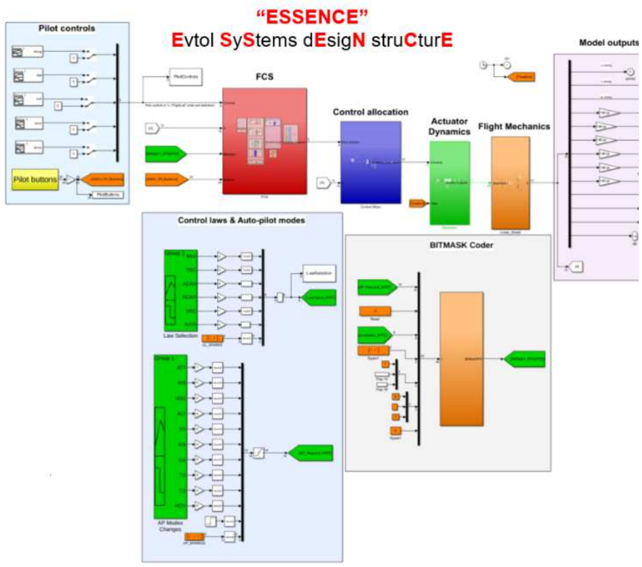

Figure 24 : ESSENCE model for eVTOL systems design.

This Simulink© model enables the development of all components of a new aircraft concept and its systems:

- **FCS**: flight control laws and autopilot modes controllers,
- **Control allocation**: conversion of primary pilot control (sticks) or FCS controls to rotor RPM, elevator, flap, ailerons, propeller controls,
- **Actuator Dynamics**: electric motors and other actuators dynamics,
- **Flight Dynamics**: linear models, DynaPyVTOL code, and maybe RCAS code in the future,
- **Pilot controls**: stick deflections and buttons,
- **Control laws & autopilot modes**: emulating the engagement/disengagement of flight control laws and autopilot modes.

As developed in the framework of the AHFIR cooperation between ONERA and US-Army/DEVCOM (see the Task presented in Ref. 35), "ESSENCE" will be soon shared with US Army with the goal to couple it with RCAS comprehensive analysis code.

In this simulation structure, DynaPyVTOL inputs correspond to the effectors settings such as propeller RPM or flaps/ailerons/fins deflections. Motor models that drive the propellers speeds are included in the Simulink© actuator dynamics block. Actuator dynamics for aerodynamic elements such as ailerons or flaps will be implemented in the future, based on simple transfer functions or more accurate models.

If DynaPyVTOL is able to find the optimal trim w.r.t. to a given criterion, the optimal control allocations among all available effectors or to perform controlled time simulations based on the dynamic inversion of the control matrix, these capabilities are not used in this simulation structure and the code is used solely as a flight dynamics code. In that manner, FCS, control allocation block or actuator dynamics can also be easily developed and modified outside the DynaPyVTOL code.

Prior work has established a reasonably low power control strategy that can be attained with pitch-level trim across all flight conditions between hover and cruise (Ref. 30, Ref. 35). This sweep provides guidance for determining the desired values of controls as a function of flight speed, and can guide the design of control scheduling for the aircraft performed in the "ESSENCE" control allocation block.

On the base of the Lift + cruise configuration shown in Figure 13, several augmented flight control laws have already been implemented and tested:

- SAS: Stabilization Augmentation System
- TRC: Translational Rate Command (longitudinal and lateral speeds)
- ACAH: Attitude Command - Attitude Hold
- VRC: Vertical Rate Command
- ACVH: Acceleration Command - Velocity Hold
- RCHH: Rate Command - Heading Hold

- ATT: Attitude Hold

As an example, a simulation of the ACAH and VRC control laws is shown in the following Figure 25. Pitch down, right roll, yaw rate and vertical speed variations are successively performed. The red dashed lines correspond to the parameter targets (Pitch angle TETA, roll angle PHI, yaw rate R, vertical speed Vz) while the blue lines show the aircraft responses. It can be seen that the aircraft precisely follows the attitude commands on pitch and roll. The yaw rate and the vertical rate are also very well matched.

In a general manner, the gains of each flight control law or auto-pilot mode could be first set thanks to the use of linear models generated by DynaPyVTOL. Then, they could be tuned through simulations involving the full non-linear model. With this specific aircraft configuration, the gains did not require any adaptation between linear and non-linear models.

Up to now, flight control laws have been tuned for low airspeed flight conditions. It is planned to investigate cruise conditions and the transition phase. Control allocation will be part of these studies as the aircraft controls have to switch from helicopter mode to airplane mode involving more non-linear flight dynamics during the transitions.

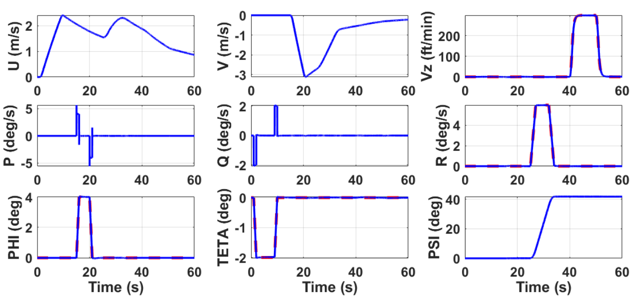

Figure 25 : Coupled Simulink© / DynaPyVTOL code simulation involving ACAH and VRC control laws.

9. COUPLING WITH OTHER SPECIALZED CODES

DynaPyVTOL is also able to perform flight dynamics computations (sum of forces and moments, time integration etc.) and to control the aircraft while letting other codes run the simulation of part or all of its elements physics. This enables its coupling to higher fidelity codes. This also allows accounting for other physics not “natively” proposed in DynaPyVTOL, such as structural loads, noise assessment or complex aerodynamic interferences, powertrain energy chain within the eVTOL framework. Furthermore, the computational cost of DynaPyVTOL models is low enough to be used in an iterative MDAO pre-design process or even to be integrated within a technical operational simulation environment (such as SimLabs at ONERA), procuring a physics engine for rotorcraft flight dynamics in the simulator.

A masterpiece for easing these couplings with external codes relies on the general comprehensive data structure MANGROV presented in Ref. 9. Indeed, as soon as the database can be parsed and understood by all codes, the coupling becomes easier. One code can retrieve explicit data from the database, regardless who writes these data.

On top of the comprehensive data structure comes the python implementation of it. This implementation relies mainly on CGNS/Python standard so the database itself does not rely on any library except for Numpy. The data is stored into a hierarchical interlocking of Python lists. Thanks to that simple implementation, every code can access all data and pointers to data from this tree. The use of the data pointers of the data Tree within the code provides an easily implementable approach for code coupling.

Demonstrations of this coupling approach have been done. A proof-of-concept coupling was a live view of selected parameters during a time-dependent mission computation. The computation was completely done by DynapyVTOL while charts and plots where done with a plotly dash app.

Another coupling demonstration and use with an aero-structure-flight dynamics coupling has been perfromed using AeroMultiBody, MassXe and DynapyVTOL; each of which are in-house ONERA codes. All three codes can use the same Python dynamic Tree to share data. The data flow is managed by the coupling algorithm and rely on a safe read/write sequence to protect against data compromise. Examples of interpretations of the same data Tree (here the Lift+Cruise configuration) by these three different codes are shown in Figure 26 to Figure 28.

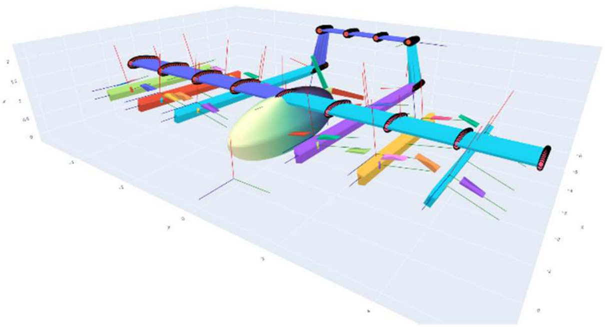

Figure 26 : View of mass interpretation of the tree (MassXe code).

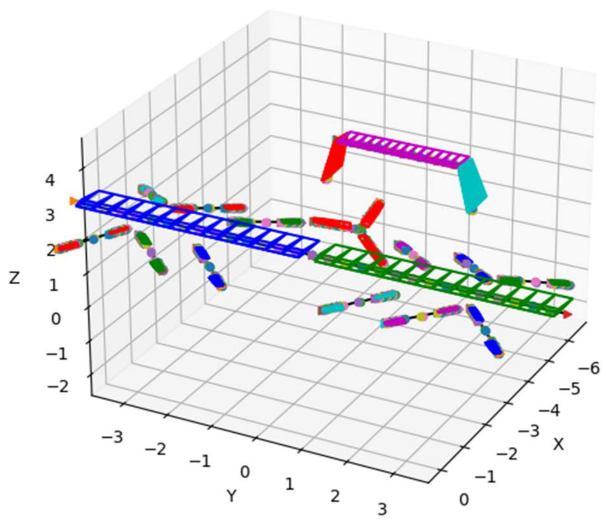

Figure 27 : View of aerodynamics interpretation of the tree (AMB code).

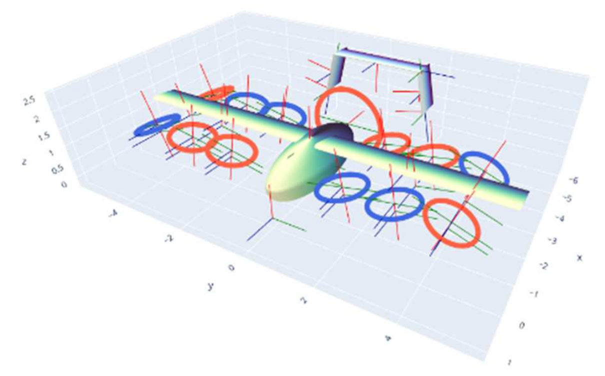

Figure 28 : View of flight dynamics interpretation of the tree (DynaPyVTOL code).

10. PREDESIGN FOR VTOL AIRCRAFT CONCEPTS EARLY EVALUATION

Evaluation of a new aircraft concept requires some initial presizing tasks, sometimes from scratch. As demonstrated in this paper, this is the main reason why DynaPyVTOL has been created. In order to assess the flight performance of a new concept, it must of course be sized and described, i.e. by estimating the input data required by the appropriate models for such evaluation.

Before considering optimization of its characteristics, an initial convergence loop between "Mass & Performance" must be performed. As expected, the flight performance is the primary driver of any aircraft design. Environmental impacts, in terms of noise and air pollution, are other criteria which can of course have significant effects on the aircraft design. The primary goal, however, is to design the aircraft with such flight performance that it is able to perform its missions in a safe and efficient way.

An example of such "Mass & Performance" convergence loop is shown in Figure 19.

Such presizing loop provides a good example of how DynaPyVTOL can interact with other disciplines and their corresponding tools. Indeed, even at this early stage of an aircraft concept evaluation, not only the flight performance but also the weights, structures, power-energy generation as well as more refined aerodynamics computation may be required.

Starting from a rough initial estimate of the Gross Weight, a first step consists in assessing the maximum Thrust (T), torQue (Q) and Power (P) by considering the worst case of thruster failures (due to the breakdown of an element of the chain between the source of energy and one or more propeller(s)). Depending on the type of missions and concept of operation of the considered aircraft, it may be relevant to design it to be resilient to failures of up to two engines (e.g. when considering missions over populated areas: TEI on Figure 19 means Two Engine Inoperative) or only one (One Engine Inoperative). The worst case scenario must be considered for the aircraft to be able to fulfill the certification requirements. The failure cases are generally the most demanding for the flight performance and sizing of the aircraft. A first example with an early version of this method was presented in Ref. 36 for three archetype examples of eVTOL. Then the method to compute the optimal redistribution of thrusts whatever the number and position of lifting propellers has been described in Ref. 32.

It is important to underline that this STEP 1 "Failure initial assessments" can be performed before the sizing of the aircraft thanks to the proposed method. Indeed, the method focuses on the aircraft concept, i.e.

the type of VTOL configuration, in terms of number of lifting propellers and provides the maximum thrust T_{max}/T_0, torque Q_{max}/Q_0, and power P_{max}/P_0 ratios with respect to the nominal operation conditions (All Engine Operative). In this manner, the instanced configuration in terms of dimensions is somehow "normalized" and the first estimate of propellers sizes and characteristics do not impact these ratios.

They can be then used in the propeller sizing routines in terms of maximum thrust, the sizing of the motors in terms of maximum torque or power, and as a first estimate of the any other powertrain and supplier components. This STEP 2 "presizing" can be performed using DynaPyVTOL models or with higher fidelity models and methods like the ones available in AMB (AeroMultiBody) if aerodynamic interferences are expected to be impactful, or with a Blade Element Momentum Theory (BEMT) dedicated tool for the optimal predesign of propellers.

Once the aircraft components have been all presized and described to the level of detail required by the DynaPyVTOL models, the STEP 3 of flight performance assessment can be conducted.

It is at this STEP 3 that DynaPyVTOL plays its primary role. Its ability to compute the trim whatever the aircraft concept and whatever the flight phase makes it particularly useful at this step. In the case of an overactuated aircraft, it can find the optimal trim minimizing a given criterion (e.g. minimal required power) as shown for example on Figure 15. The required power is calculated on a typical mission flight profile that this aircraft must be able to perform. For this purpose, the trims are computed on the different mission phases, e.g.: hover, vertical climb, oblique climb cruise or loitering flights, descents, hover landing, etc.

With the required power and time duration of the different mission phases, the energy needed to perform the mission can be then calculated. Knowing the amount of energy and the maximum power (both on the nominal mission from Step 3 and on the worst failure case to cope with from Step 1), the energy-power system can be sized in the subsequent STEP 4. For example, for sizing of the batteries, a special sizing sub loop is performed within MasXe, our tool dedicated to weights assessment connected with DynaPyVTOL through the MANGROV tree data structure.

The weights of all the aircraft components are calculated taking into account the structural constraints imposed on some of them in order the aircraft be resilient to the failure cases studied in Step 1. That is for example the case for the booms supporting the lifting propellers and the wings carrying the booms. They must able to resist to the maximum forces and moments generated by the remaining propellers in the worst failure cases in order to allow the aircraft keep flying safely until an emergency landing be possible.

This Step 4 provides a new, more realistic assessment of the Design Gross Weight (DGW). The process given by steps 3 & 4 (and step 2 if needed) is repeated until the vehicle mass and performance have converged using a fixed point method.

This first basic presizing loop on steady flight performance and weights is required before going further on stability and flight dynamics assessments (e.g. considering secondary impacts of cant angles of the lifting propellers in Ref. 30) which will provide other criteria for more detailed optimization of the aircraft. DynaPyVTOL has been implemented in a MDAO presizing process dedicated to eVTOL, and in doing so has contributed to produce the HEDWIGE concept predesign shown on Figure 14. DynaPyVTOL will also be used as the flight dynamics engine within another MDAO framework in the CREATION workshop for the presizing and evaluation of rotorcraft concepts (i.e. VTOL concepts not based on the electric distribution of lift and propulsion eVTOL principle, but on using larger articulated rotors able of autorotation).

11. CONCLUSIONS AND PERSPECTIVES

This paper presents an overview of the data structure, models, and methods of DynaPyVTOL, the in-house ONERA flight dynamics tool, as well as a summary of prior and current research efforts and applications of the tool. Beyond the interest of providing to ONERA a tool which can be used for any studies (which is not the case with a proprietary code like HOST or STORM), its main technical interest is its ability to model steady flight performance and flight dynamics of any kind of aircraft concept at early evaluation stages.

Such a level of adaptability is based on the implementation of models which can function with limited available data, and makes it well suited for the presizing of a new aircraft configuration even from scratch. This is thanks to a range of models from simple (rotor disc models) to more detailed ones (like lifting line models), and to the ability to refit these models on reference data, if available.

A key motivation is that many new advanced configurations based on distributing lift and propulsion on numerous propellers have more degrees of freedom in terms of controls than the 6 rigid body flight dynamics. A flight mechanics tool is therefore needed for computing a representative trim of the aircraft which impacts significantly the required power and control threshold. Another significant motivating factor in the creation of DynaPyVTOL was also to account for the impact of thruster failure tolerance on the initial sizing.

Starting with these first crucial needs, in a more general way, a wide range of potential applications has been illustrated, including:

- steady flight performance, with power or other objective optimal trim for any configuration, including over-actuated ones,
- failures analysis with the computation of the optimal redistribution of thrusts in case of one or more thruster failures,
- stability assessment based on model linearization,
- attainable domain in terms of peak accelerations or forces and moments generation at control limits,
- dynamic flight time simulation, including over a specified flight trajectory,
- multiple uses for assisting with early design and evaluation of an aircraft and its control laws.

Concerning perspectives, in addition to the improvement the modeling capability of the tool in terms of modeling adaptability to any aircraft and in terms of improved modeling fidelity, further developments will also be motivated by:

- coupling with other specialized codes (such as noise assessment),
- generalizable design optimization through its inclusion within MDAO processes,
- identifying and adding ways to improve the codesign process of sizing the aircraft and designing its Flight Control System simultaneously.

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