STABILITY AND CONTROL SENSITIVITY OF A LIFT-PLUS-CRUISE EVTOL AIRCRAFT TO TRIM STRATEGY AND MODELING PARAMETERS

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Abstract

This paper presents an evaluation of an eVTOL configuration to provide insight into the stability of the design, depending on the trim strategies used, and accounting for the impact of interactions. The particular eVTOL configuration is an overactuated Lift-Plus-Cruse platform, and the paper focuses initially on examining trim and stability for different sets or groups of control inputs. Control strategies include power-optimal trim, pitch-level trim, low-speed "helicopter mode" and high speed "airplane mode". Primary considerations and tradeoffs between power optimal trim during transition and more controllable trim is attributed to the thrust sensitivity of the RPM controlled rotors. Two different models are used in the trim and stability studies; a low-fidelity flight dynamics analysis with built-in optimization capability, and a medium-fidelity comprehensive analysis. The paper also includes an initial examination of aerodynamic interaction between the wing and the lifting rotors. The impact of wing interference is primarily to increase the down-wash on the rear lifting rotors, which increases the power requirement and reduce the stability of the short period oscillatory mode.

1. INTRODUCTION

Novel electric Vertical Take-Off and Landing (eVTOL) configurations are being developed, with many having reached the prototyping and flight test stages of design. These aircraft benefit from battery and electric motor developments which allow designs that would not have had sufficient range until recently. With such rapid development cycles, many of these configurations have outpaced a rigorous analytical investigation in the open literature. These aircraft introduce stability and control challenges which should be well investigated to ensure safety, reliability, and proper pilot training tools exist prior to their widespread adoption.

The generic Lift-Plus-Cruise (L+C) configuration offers a platform well suited to perform initial studies of several flight modes without the added complexity of moving/tilting propellers. The flight regimes can be loosely grouped into a hover or low-speed "helicopter mode", a high-speed "airplane mode", and a blended control mode for transition and other low-to-moderate-speed maneuvers. Handling qualities analysis and control system design for this configuration is an active research area, especially recently.

Ref. [1, 2, 3] examine piloting issues and handling qualities of over-actuated vehicles. Research focused on L+C control system design and testing includes Ref. [4, 5]. The transition mode control problem is the focus of Ref. [6], while Ref. [7] and Ref. [8] look at more detailed aerodynamic analyses of components such as propellers or wings. Finally, Ref. [9, 8] focus on the overall design of L+C aircraft and various trim strategies. Many of these related efforts are in the early research stages, and in general there is a lack of public domain validation data.

This paper seeks to examine the stability of a representative eVTOL aircraft, using a generic Lift + Cruise configuration introduced in Ref. [9]. Building upon this and similar work Ref. [8, 10], the focus is primarily on the locus of the eigenvalues of the open-loop system/bare airframe, and its evolution with different modeling parameters. The final aim of this stability study is to identify key points of interest concerning the stability of eVTOL configurations

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to define their control laws.

2. MODELING AND ANALYSIS

2.1. Configuration

The Lift + Cruise configuration shown in Figures 1 and 2 incorporates 12 canted lifting rotors and a pusher propeller augmenting a fixed wing aircraft configuration with 5 control surfaces: two flaperons acting collectively or differentially, two rudders active collectively, and an elevator.

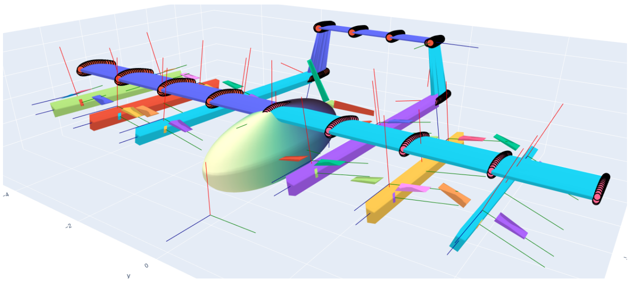


Figure 1: Lift + Cruise configuration model in DynaPy

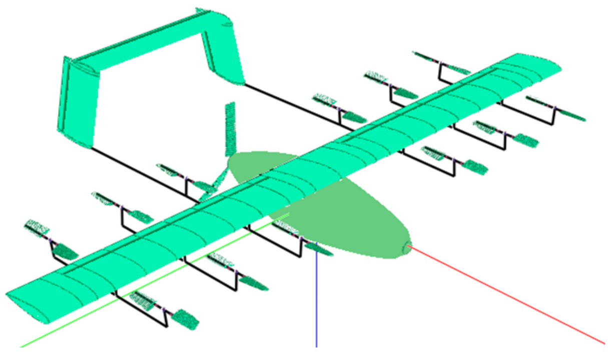


Figure 2: Preliminary RCAS model representation

The design cruise speed is 50 m/s. The aircraft has a gross weight of 1200 kg, with a center of gravity (CG) assumed initially to be positioned at the geometric center of the 12 lifting propellers.

This work is being conducted in cooperation between France and the U.S., and characteristics of two numerical models of this aircraft will be compared. The first approach uses ONERA's flight mechanics code DynaPyVTOL, and the second uses the United States' Rotorcraft Comprehensive Analysis System (RCAS).

2.2. DynaPyVTOL

DynaPyVTOL is a comprehensive analysis tool for flight dynamics simulation of any aircraft developed and maintained at ONERA. DynaPyVTOL is used here for its steady state trim solver and optimization framework, as well as linearization capacities. This software is predominantly written in Python, while the blade-element momentum theory rotor calculations are performed in a Fortran sub module and empirically corrected based on a higher-order free-wake model Ref. [11].

DynaPyVTOL includes an aerodynamic interference model that adds the shed wake from the wing to the inflow and free stream components of the velocity at the rear lifting propellers, horizontal and vertical tails, and pusher propeller. While not initially used, its impact on the results is examined in the last section of this paper.

2.3. RCAS

The RCAS model was developed from design data from Ref. [9]. The lifting rotors and propeller are modeled with rigid blades and uniform or 3-state dynamic inflow options. Control surfaces such as flaps, rudders and elevator are modeled using the RCAS "elevon" option, which used Theodorsen theory to calculate the aerodynamic loading from the control surface. The wing flaps and ailerons are combined into "flaperon" controls.

The trim procedure for RCAS is based upon usage of the direct time integration method to find a solution for the time-domain equations. RCAS applies a trim spring/damper force to the 6-DOF system to bring the aircraft forces and moments into an equilibrium state. The trimming function perturbs the trim variables, computes a trim matrix, runs a periodic solution and tests the trim solutions against the user-specified constraints.

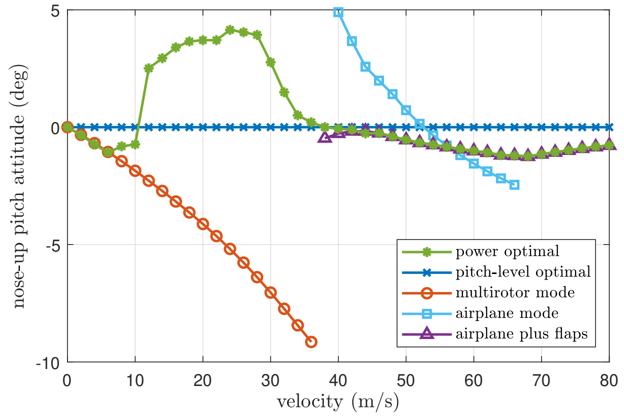
3. TRIM ANALYSIS

3.1. Trim Strategy

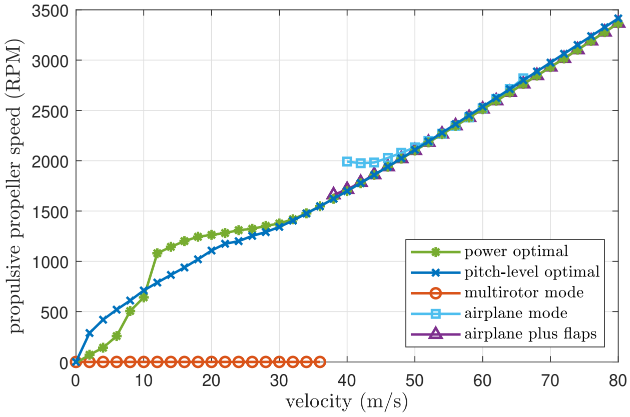
The configuration of interest in this paper is an over-actuated system, implying that the trim solution is non-unique. The trim strategy could be adapted to target any number of optimality conditions. Power optimization has been used in the past Ref. [12].

For this study, various trim strategies will be contrasted for their impacts on performance, stability, and control. Initially, these trim strategies are examined using DynaPyVTOL due to the trim optimization capabilities of the code. The solution of trim controls which correspond to the following strategies are presented in Figure 3.

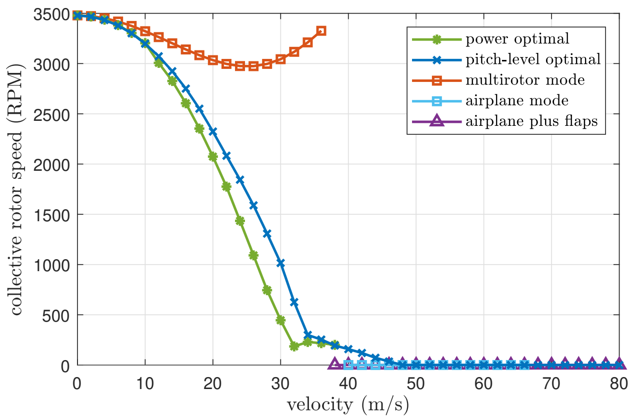
- **Power Optimal:**
  All controls available are used, and vehicle pitch attitude is a trim variable. Trim is solved within



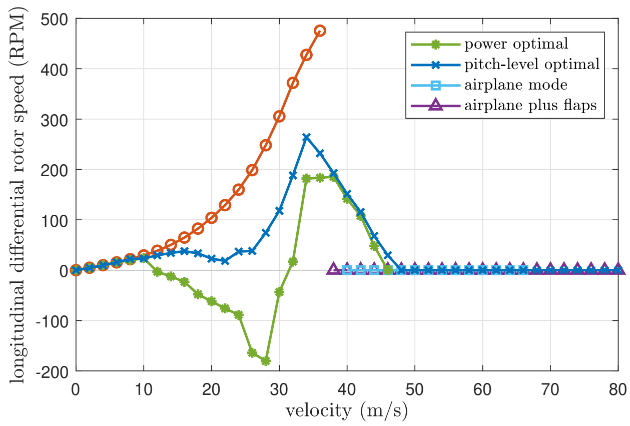
(a) Pitch Attitude (deg)



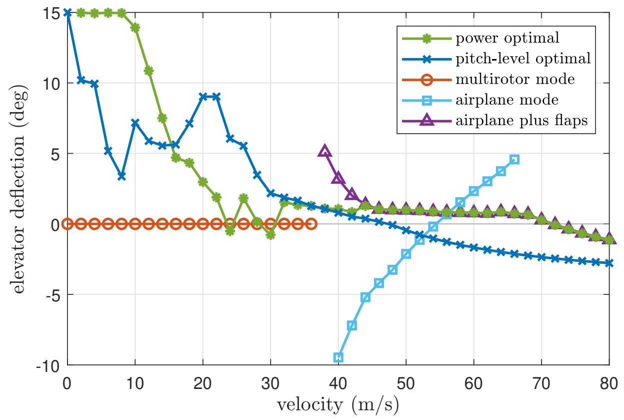
(b) Propulsive propeller speed (RPM)



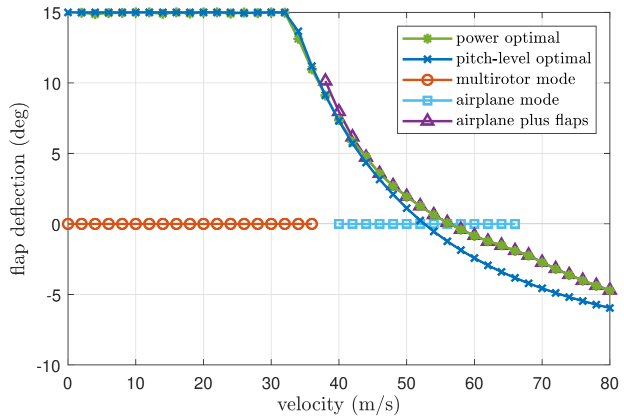
(c) Collective lifting rotor speed (RPM)



(d) Longitudinal differential lifting rotor speed (RPM)



(e) Elevators



(f) Flaps

Figure 3: Comparison of DynaPyVTOL trim control strategies over the full flight envelope

an optimization routine with total power requirement as an objective function that is being minimized.

- **Pitch-level Optimal:**
  Identical to the prior stragety, but with pitch attitude removed as a trim variable and fixed to zero degrees.

- **Multirotor Mode:**
  Only the lifting rotor commands are used, with rotor speed control in collective, lateral differential, longitudinal differential, and pedal differential modes. Pitch attitude is reintroduced as a trim variable.

- **Airplane Mode:**
  Only the traditional airplane mode controls are used, including the differential ailerons, elevators, collective rudders, as well as the pusher propeller speed, and the vehicle pitch attitude.

- **Airplane Plus Flaps:**
  Identical to the Airplane Mode trim strategy, but with the further addition of a collective flaperons control. The resulting trim routine reintroduces the power optimization routine.

Figure 3 presents the variation in trim variables and controls across the strategies. Controls with dominant effects in the lateral force axis, as well as roll and yaw moment axes are omited, and have near-zero values with the exception of differential lateral and ailerons which act to cancel the torque of the pusher propeller while maintaining a level roll attitude.

The Power Optimal and Pitch-level Optimal trim strategies encompass the entire envelope from 0 to 80 m/s, with a complete transition between hover and forward flight. In both approaches, the following phases of transition can be identified based on the trim controls:

1. **0–10 m/s:**
   Trim at these speeds does not significantly differ from Multirotor Mode. Longitudinal differential rotor speed control is used to balance moments, while limited propeller thrust is also introduced. The flaps are fully deflected to increase wing lift. For Power Optimal trim the elevator is fully deflected while the aircraft pitches nose-down to use the lifting rotors to overcome some drag. For Pitch-Level Optimal trim the elevator is active at a lower speed, reducing the nose-down pitch moment and maintaining a level aircraft. In this case, the lifting rotors produce no propulsive thrust, so the rear propeller must trim to a higher RPM.

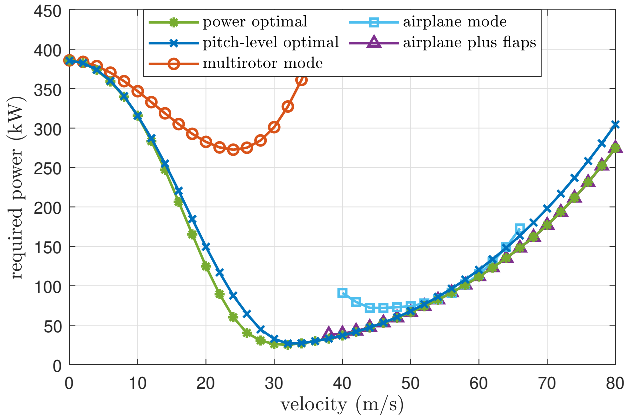


Figure 4: Comparison of power requirement for different trim strategies using DynaPyVTOL

2. **12–32 m/s:**
   The rotor collective reduces throughout this phase as the optimal trim strategies deviate from Multirotor Mode. The elevators further reduce their angle as the dynamic pressure increases, and the fixed wing control surfaces gain control authority. The Power Optimal strategy uses nose up pitch attitudes to offload the lifting function to the wing as early as possible, reducing the collective pitch at a faster rate than the Pitch-Level Optimal strategy.

3. **34–48 m/s:**
   The longitudinal differential rotor speed control matches the collective rotor speed as it reduces from about 200 to 0 RPM over this range of speeds. This corresponds to shutting down and locking in place the rotors ahead of the wing; operating with just the rear set of rotors to provide lift and pitching moments until the stall speed of 40 m/s has been surpassed by enough of a margin to efficiently offload the rotors entirely.

4. **50+ m/s:**
   The lifting rotors are entirely off. The Power Optimal strategy is identical to the Airplane Plus Flaps strategy, while the Pitch-Level Optimal strategy trims with nose level pitch and more negative (upward) elevator and flap deflection angles.

Figure 4 contrasts the power requirement of the aircraft computed using DynaPyVTOL while incorporating the five different trim strategies. As velocity increases through transition, the rotors operate more efficiently due to a reduction in induced power, while the wing begins to produce greater

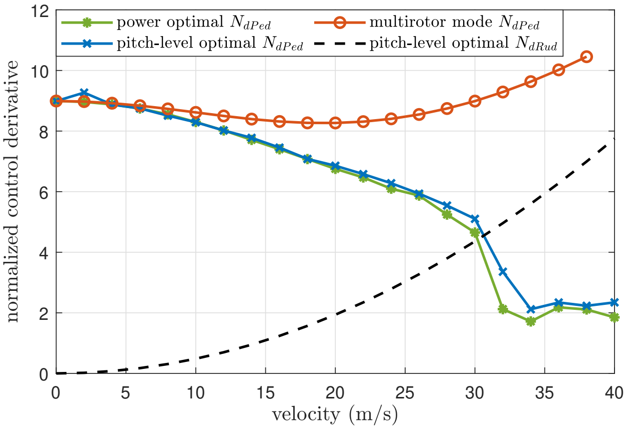


Figure 5: Comparison of normalized yaw axis control derivatives for different trim strategies and controls using DynaPyVTOL

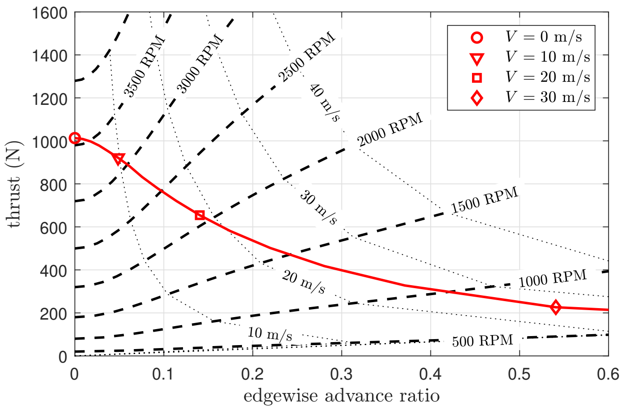


Figure 6: Contours of constant RPM showing the impact of edgewise advance ratio on thrust sensitivity to RPM, L+C Pitch-Level Optimal trim sweep for reference.

lift. Near the design cruise speed of 50 m/s, there is limited difference between the Power Optimal trim strategy and the unique trim of the Airplane Mode strategy. For speeds further from the design cruise speed, it becomes more efficient to incorporate the flaps to help the wings produce additional lift, or reduce camber at high speeds.

Controllability

This discussion will focus on the yaw response of the Lift + Cruise configuration, which has the most control deficiency across all flight speeds due to its low control derivates and motor speed response lag Ref. [13]. This deficiency has been partially mitigated due to the cant angles of the lifting rotors which introduce a coupling between reaction torque and thrust in the yaw axis, but is still a concern to ensure adequate handling qualities. Often, the approach used in the prior section of power-optimization guiding trim can impose penalties on handling qualities.

Figure 5 compares the yaw moment control derivative as a response to normalized pedal input for three different trim strategies through the transition phase from hover to 40 m/s. The normalization is performed relative to the stick limits imposed for each control, which is a unit-less number with a range of 0 to 1. In the case of rotors the stick limits are from 0 to 5000 RPM, and for control surfaces they are from -15 to 15 degrees (30 degrees total). The yaw axis control is the focus of this discussion due to it being the axis with the least authority. Although they are omitted from this discussion for brevity, the pitch and roll control derivatives follow similar trends, though with at least an order of magnitude larger control derivatives.

For comparison, the yaw response to normalized rudder input is also shown in Figure 5. This control derivative is directly related to dynamic pressure and increases with the square of velocity. By 32 m/s it has greater authority than the minimal or pitch-level optimal trim strategies, yet it still has a less sensitive response than the lifting propellers only trim strategy pedal response. A full examination of the aircraft handling qualities is likely to present an even more limiting picture, as the RPM controls will approach their lower saturation limit as the collective control approaches zero at the end of transition (46-48 m/s). In this circumstance, the control derivative may be non-zero, but the ability for the aircraft to generate moments is severely limited by the total acceleration that the control can impart.

There is a direct correlation between the three contrasted trim states power requirement and pilot pedal response (N_{dPed}). Because of the reduced rotor RPM of the lifting propellers, the rotors are operating at a high advance ratio. It is well known that rotor thrust sensitivity to collective pitch reduces as advance ratio increases, leading to an eventual control reversal at $\mu = 1.0$ [14]. However, the thrust sensitivity of the rotor to RPM increases with advance ratio, and this sensitivity is higher with higher RPMs. This can be seen on Figure 6, which displays the thrust generated by a rotor for different RPMs and its evolution with advance ratio. For a given advance ratio the change in thrust (y-axis) between the constant RPM lines (dashed lines) when compared along contours of constant flight speed (dotted lines) tends to increase with advance ratio.

For a trimmed L+C configuration, which are represented by the red markers on Figure 6, the aircraft offloads the lifting function to the wings as velocity increases, resulting in a reduction of the lifting rotor RPMs. As velocity increases at each of the four identified trim states, the vertical space between contours of constant RPM increases, indicating a reduced sensitivity of thrust to RPM. The impact of the RPM reduction is the dominant effect of the two, reducing in the total sensitivity of the thrust with respect to the RPM command seen in Figure 5.

Stability

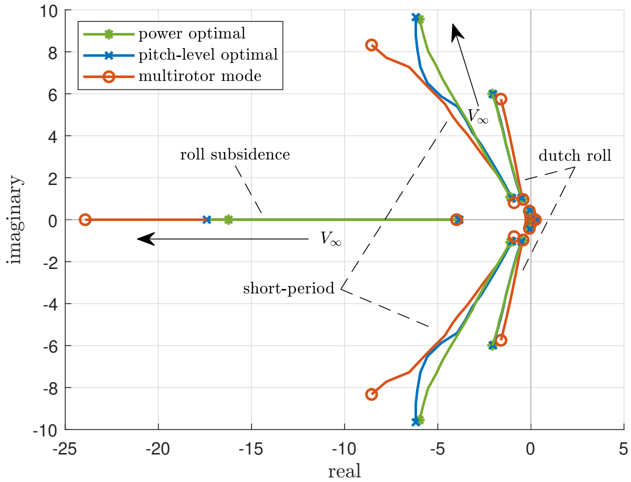


Figure 7: Open-loop stability through transition from 6 to 30 m/s using different trim strategies in DynaPyVTOL

As was shown in Figures 3 and 4, the trim controls converge to an identical, unique trim solution in hover (to within trim precision), and thus the power requirements, control derivatives, and stability characteristics are also identical. These strategies begin to deviate from each other as trim redundancy becomes available with the increase of dynamic pressure available in forward flight. Figure 7 presents the evolution of the dynamic modes of the aircraft from low speed flight at 6 m/s through transition to 30 m/s.The classical modes of aircraft can be identified, and tracked through conversion into fixed-wing aircraft modes in cruise for each of three different trim strategies; Power Optimal, Pitch-Level Optimal, and Multirotor trim strategies. These results are truncated at 30 m/s to illustrate the trends through transition clearly.

Starting at 6 m/s, the high frequency modal characteristics are similar to those most commonly associated with those of an airplane, including dutch roll, short period, and roll subsidence modes. As flight speed increases the natural frequency of these modes increase with a fairly constant damping ratio. All of the low-frequency modes near the origin have minor differences between the trim strategies. Critically, with the modeling approach used, transition does not appear to be the limiting case for aircraft stability, with hover generally being less stable for most modes.

The dutch roll mode is the least stable high frequency mode on Figure 7, and the Pitch-Level Optimal and Power Optimal trim strategies have similar behavior, however the Multirotor trim strategy has less damping. The Power Optimal and Pitch-Level Optimal trim strategies also exhibit fairly similar behavior for the short-period mode, except for a range of transition velocities between 20-30 m/s, where the damping of the Pitch-Level Optimal Mode damping increases. Compared to these two modes, the Multirotor trim strategy is always more damped, and is significantly more stable at higher velocities.

The net impact of reduced stability at lower speeds, and reduced controllability at higher speeds can be shown by examination of the transfer function in the frequency domain. Figure 8 shows the yaw response to pedal input at 30 m/s, which corresponds to the terminus of the evolution on Figure 7 contrasting the same three trim strategies. While the response of the motor is not being modeled, the motor can be assumed to have ideal behavior at low frequencies. The significant 20° cant angle is also expected to mitigate the impact of the motor dynamics at medium frequencies, shifting the dynamics of the torque response to higher frequencies Ref. [13]. The primary impact of trim strategy is to the magnitude of the response. The low frequency response is the highest in magnitude for the No-Pitch Optimal trim strategy, which is has a universally higher gain than the power optimal, and is only surpassed by the response of the Multirotor Mode trim strategy at frequencies above 1 rad/s.

The net effect of trim strategies has been shown to have a significant impact on the performance, stability, and control characteristics of the aircraft. There are significant differences between trim strategies; primarily a tradeoff between beneficial handling qualities and minimum power trim objectives, which can be attributed primarily to the significant change in the operational edgewise advance ratio of the lifting rotors. The extremes of these objectives are respresented by the Multirotor Mode and Power Optimal trim strategies. The No-Pitch Optimal trim strategy represents a strategy that attempts to make a compromise between the two extremes without any formal optimization between the two criteria. The total impact is a strategy that trims to within 20 kW of the Power Optimal trim strategy, while improving the yaw response to pedal by 10 dB for low frequency pilot commands in transition.

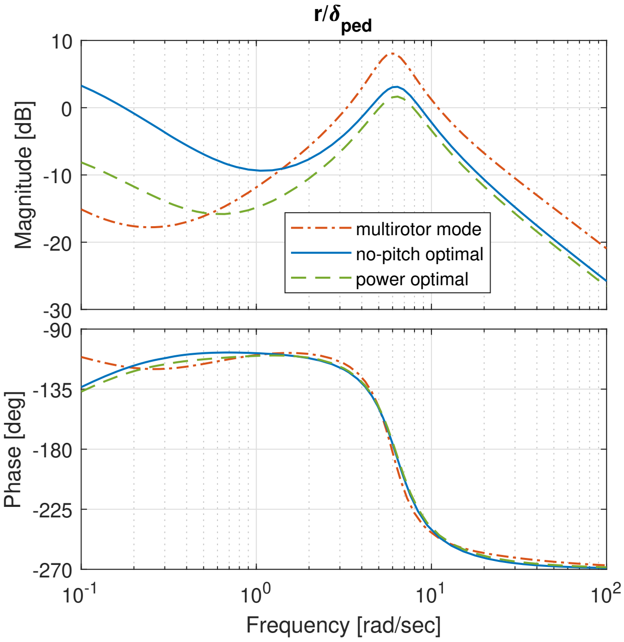


Figure 8: Frequency response of the yaw response to pedal input for different trim states during transition at 30 m/s.

4. C.G. TRAVEL

Although eVTOL configurations are not expected to encounter as much of a change in their center of gravity position during flight as fuel-burning aircraft, it remains a necessary consideration due to passenger or payload variation.

Figure 9 presents the labeled eigenvalues of the hovering L+C configuration as identified using DynaPyVTOL. As is common for multirotor aircraft, the dutch roll mode from Figure 7 has been replaced by a lateral phugoid mode. From hover, the center of gravity is shifted forward to a location just behind the center of rotation of the front row of rotors, and then aft to a location just ahead of the center of roation of the rear rotors. Trim cannot be identified outside of these limits in hover due to an inability to find an equilibrium in pitching moment.

The dominant impact of the center of gravity variation in hover is to reduce the stability of the aircraft. This is expected, as the center of gravity offset causes disturbances to produce a non-symmetric moment response of the rotor about the center of gravity. The lifting rotor cant and angled tails introduce axis couplings which causes this effect to be seen for both the pitch and roll axes (see the longitudinal and lateral phugoid modes and pitch and roll subsidence modes in Figure 9). For the heave and yaw modes, this impact is minor due to less coupling and sensitivity of vertical forces and yaw moments to the longitudinal center of gravity offset.

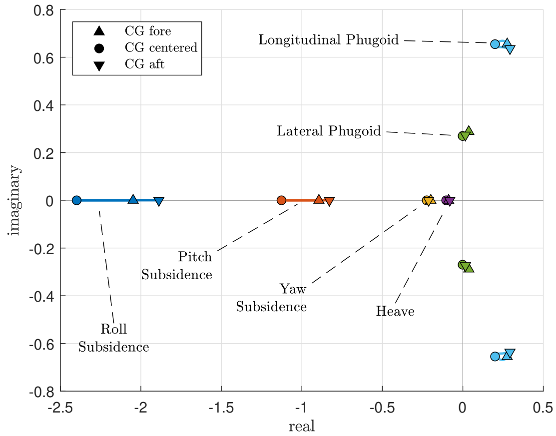


Figure 9: Eigenvalues evolution with CG location in hover

Figures 10 and 11 show the same evolution with respect to center of gravity, but relative to the cruise condition at 50 m/s using the Zero-Pitch Optimal trim strategy. In these figures, the dominant impact is to the short period longitudinal mode, while the roll subsidence, dutch roll, and the lower frequency modes in Figure 11 change to a lesser extent. At the extreme forward limit of CG travel, the short period mode becomes unstable and aperiodic. The forward limit of the CG also reduces the stability of the dutch roll mode. These results suggest that the aircraft is more tolerant to a CG shift rear of the geometric center of the lifting rotors, driven by the cruise behavior.

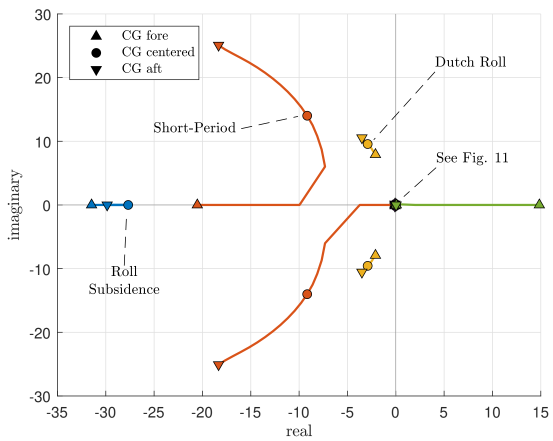


Figure 10: Eigenvalues evolution with CG location in cruise

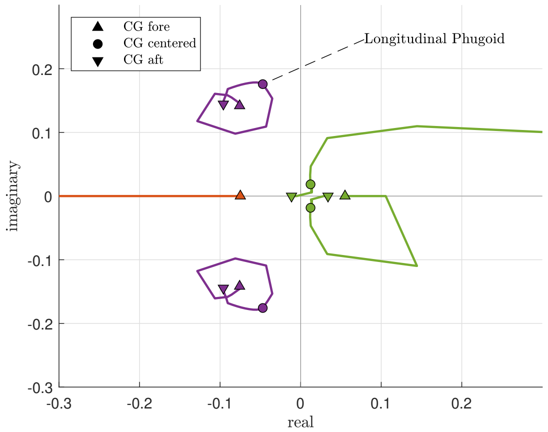


Figure 11: Eigenvalues evolution with CG location in cruise (zoomed into origin)

5. AERODYNAMIC INTERACTION

A final comparison of interest for this configuration is the impact of aerodynamic interactions. A point of interest is the impact of the main wing wake on the rear aerodynamic parts of the aircraft, which will be impacted by the wing downwash. This interaction is to be accounted for mostly during the transition phase, when the wing generates a significant wake and the rotors are still required to generate lift.

To account for this, the wing wake is modeled using a prescribed wake model, which is added to the velocities at the rotor disk in the blade element momentum theory calculation for rotor forces and moments. A cross section of the induced velocity in the plane of the outboard rotors and boom is presented in Figure 12.

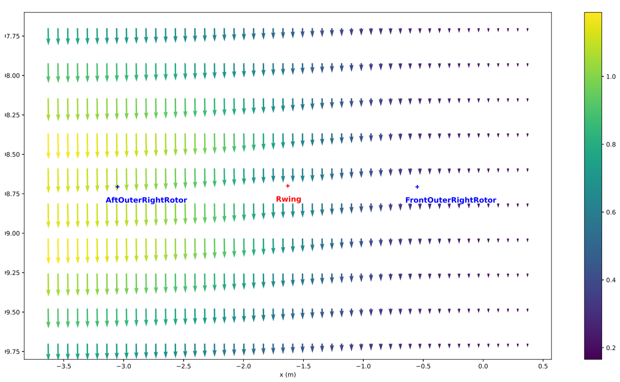


Figure 12: A view of the wing induced velocities in the plane of the outboard rotors.

The evaluation of the state matrix requires two steps; a trim computation under the influence of the wake, and then a finite differences computations in order to linearize the system and solve for the state matrix. For both cases, the wake model is fully converged for each computation. This method will, however, filter out the dynamic evolution of the wake with the state evolution. for the purposes of this study, this is assumed to be an acceptable approximation of the lower frequency modes, as the lack of motor dynamics is already preventing the model from accurately capturing the dynamics at higher frequencies. Alternative methods may be an area to investigate further in a later study to account for higher frequency interactional aerodynamics.

The aircraft is initialized using the results from the No Pitch Mode trim sweep. Similarly to the previous computations, the trim is computed with a power minimisation algorithm, with zero pitch and zero roll attitude. The results were generated for a range of velocities from 6 to 32 m/s, every 2 m/s. There is a gap between the interference trim states, where trim solutions could not be found, for 24 and 26 m/s. These results are shown in Figures 13–15, with dashed lines in red for the lower speed converged trim with wake interference and blue for the higher speed trim results. The No Pitch Mode results without interference are also shown in solid black as a point of comparison.

From the trim results in Figure 13, it can be seen that the inclusion of the wake interference model causes the rotors to trim to a higher collective rotor speed, as well as a greater longitudinal differential collective rotor speed. The net result on power is to cause a significant increase in power requirement for speeds where the rotor is more offloaded, with the predicted power requirement doubling at the velocity of best endurance (32 m/s) relative to the trim without interference. While the propeller thrust requirement increases slightly, nearly all of this increase can be attributed to the rear rotors, which are spinning up to 200 RPM faster and consuming up to 1.7 kW additional power per rotor more than the front rotors, for a total increase of 11 kW. The additional drag generated by these rotors is also the dominant contributor to the increased propeller RPM and the remaining added power requirement.

Figure 14 demonstrates the impact of the interference on the stability of the aircraft. Although part of the difference of the eigenvalue evolution is due to the fact that the trim solutions are different, their evolution with velocity is notably impacted. The main impact can be seen on the short period oscillation. The mode is strongly affected, resulting in a decreased damping ratio, which offsets more as velocity increases.

The explanation for this behaviour is that the wing generated downwash on the rear elements

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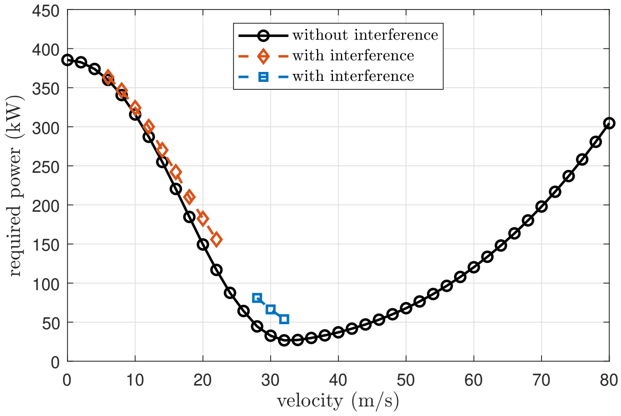
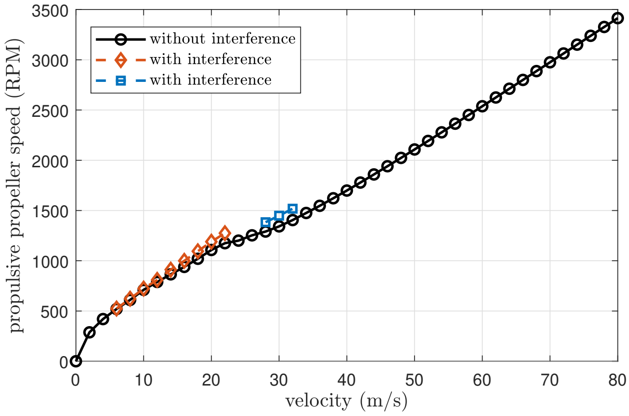
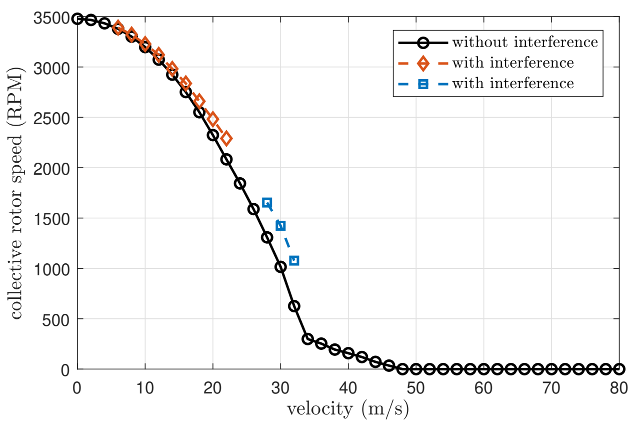


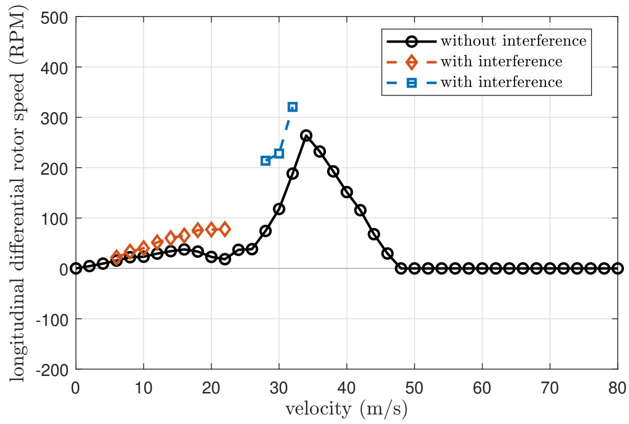
(a) Power requirement (kW)



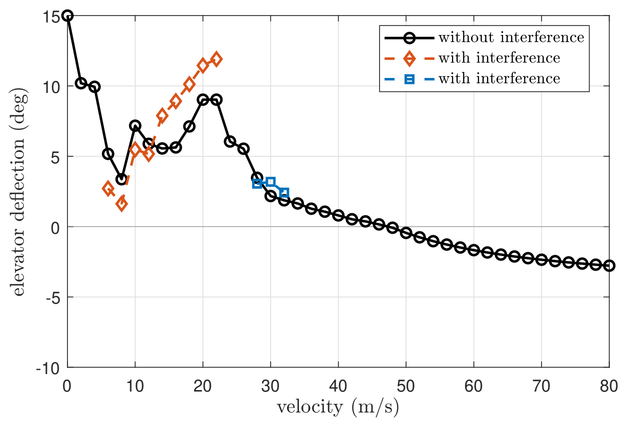
(b) Propulsive propeller speed (RPM)



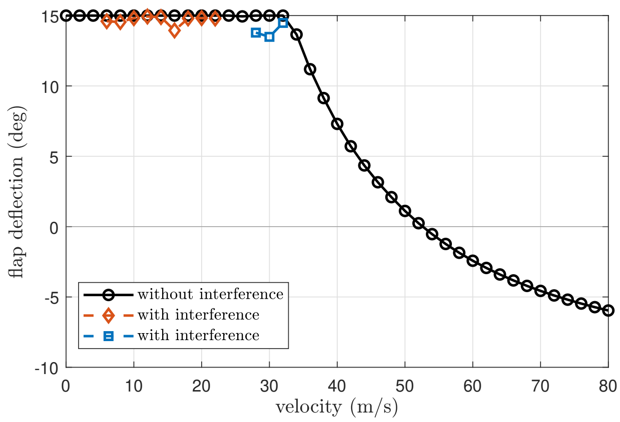
(c) Collective lifting rotor speed (RPM)



(d) Longitudinal differential lifting rotor speed (RPM)



(e) Elevators



(f) Flaps

Figure 13: Comparison of DynaPyVTOL trim with isolated aerodynamics versus trim with wing wake interfering with the rotors

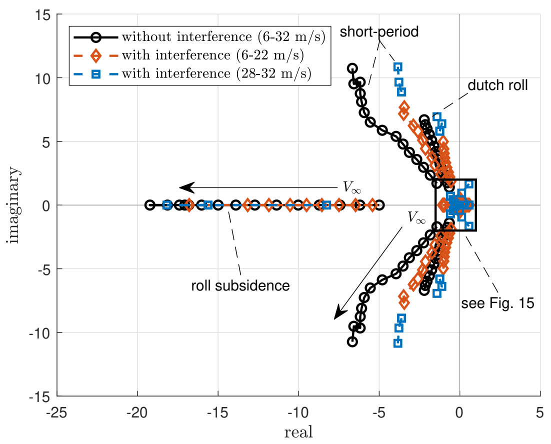


Figure 14: Comparison of stability with and without wake interaction from 6–32 m/s

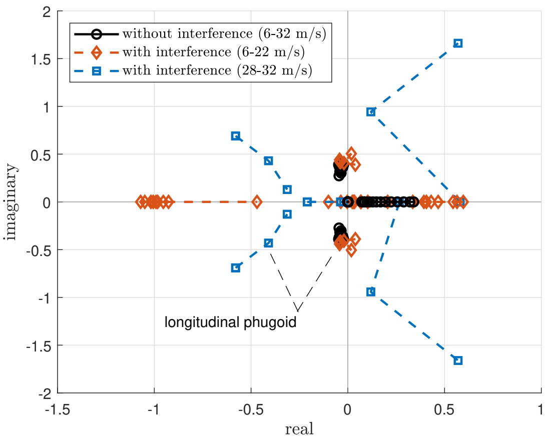


Figure 15: Comparison of stability with and without wake interaction from 6–32 m/s, low frequency modes

increases with pitch attitude. For the rotors, this tends to decrease the generated lift, thus creating a pitch down moment. The total anticipated impact is therefore to destabilize the short period oscillation mode. The dutch roll mode is affected to a lesser degree, while the roll subsidence mode is only slightly impacted. The behaviour of those modes might also be partly explained by the difference in trim solutions, which is similar, yet not identical to the original trim state that was used to seed the interference trim solutions.

Figures 14 and 15 compares the results of the interference model against the values obtained without the wake model for the Zero-Pitch mode, with trim states provided every 2 m/s over the range of 6–32 m/s. Relative to the no-interference trim cases, the inclusion of wing wake interference acts to destabilize the short period and dutch roll modes, reducing the damping ratio, while the natural frequencies of the modes stay consistent.

There is notably a small region of velocities from 24–26 m/s for which trim did not converge. This is shown in Figure 14, where the final few velocities with interference are labeled separately. They follow the same trend as the earlier velocities, with increasing frequency as velocity increases for the dutch roll and short period modes, while for the roll subsidence mode there is a significant reduction in stability after the non-trimmable set of velocities. In Figure 15 this effect is especially pronounced for the longitudinal phugoid mode, which shifts to considerably higher damping ratios at 28 m/s.

The impact of the wake on the stability of the aircraft is notable at low speed, and even more so during the transition (at around 30m/s). This highlights the need to account for the interaction in the stability analysis for those kind of configuration. In order to render accurately the behaviour and the dynamic of the aircraft during simulations, as well as for the development of an efficient controller, the aerodynamic interference must be modelled.

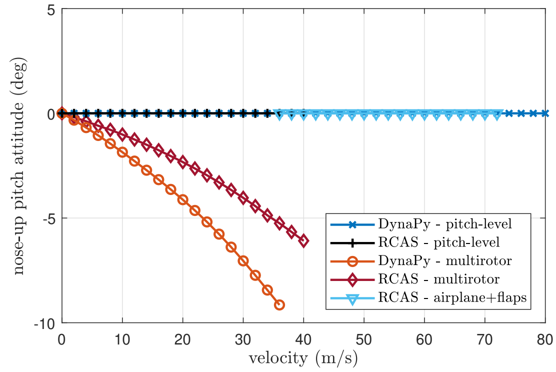
6. DYNAPYVTOL AND RCAS COMPARISONS

While the DynaPyVTOL and RCAS modeling approaches and parameters differ significantly, a comparison is performed in order to quantify the impact of these trim approaches. It is important to note that RCAS trim results are not optimized for power or any other parameter. Instead, the Pitch-Level Optimal trim solutions from DynaPyVTOL are used to inform an allocation of trim controls and scheduling of non-trim controls in RCAS.

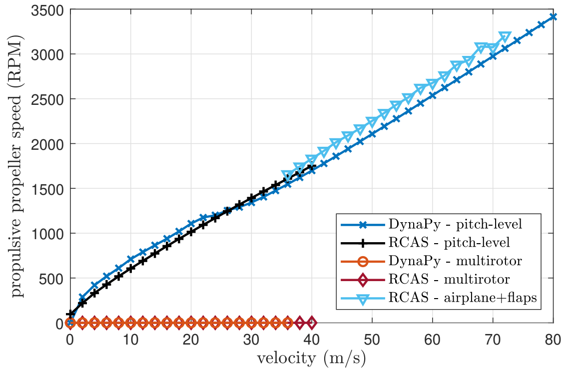
Table 1 shows the flight mode, trim variables, and trim targets. In each control mode, some of the available controls are constrained in order to calculate a unique trim solution. The constraints for each case are also in the table.

Four distinct trim procedures were used in RCAS; only the first three are shown in Table 1 and in the results in this paper. The first is a low speed Multirotor mode where only the lifting rotor RPM is used as control inputs while vehicle attitudes are used to trim out longitudinal and lateral forces. It is directly comparable to the DynaPyVTOL Multirotor mode.

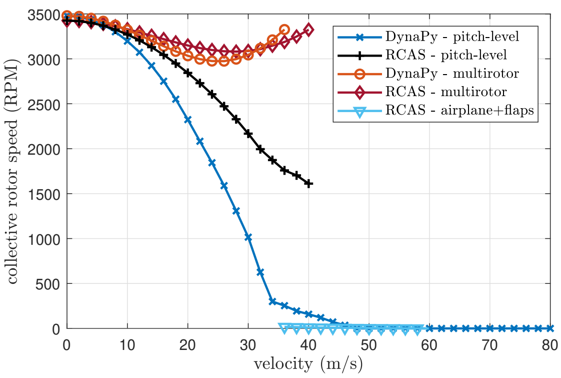
The second is a low speed Pitch-Level mode where lifting rotor collective and longitudinal differential RPM are used along with propeller RPM; flaps and elevator are scheduled in this mode. Heading and roll trim are provided by lifting rotor lateral and directional differential RPM (while aileron and rudder inputs are set to zero). These strategies correspond to the optimized control settings found using



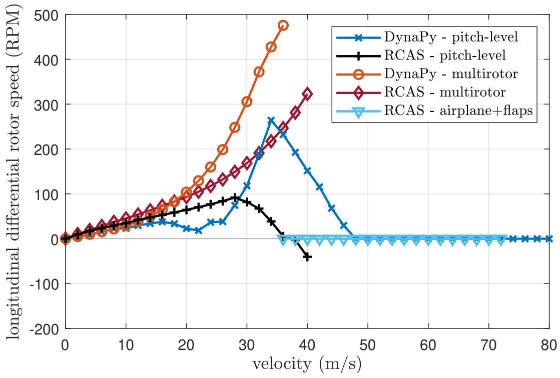
(a) Pitch Attitude (deg)



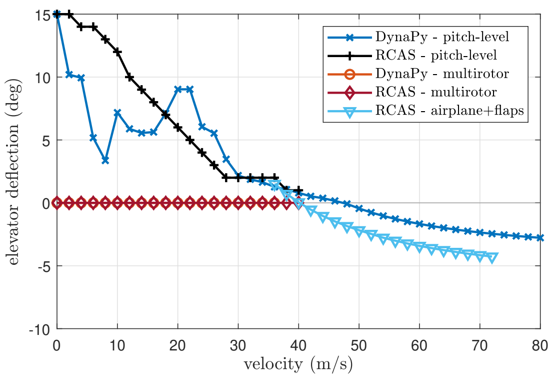
(b) Propulsive propeller speed (RPM)



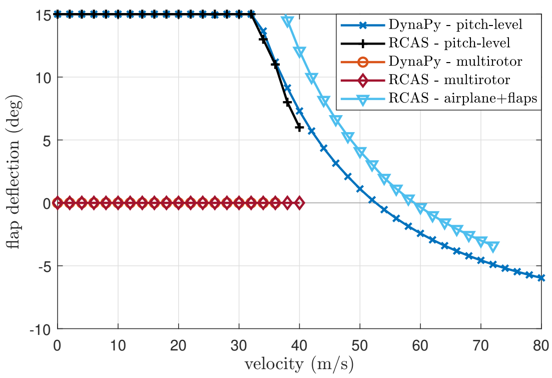
(c) Collective lifting rotor speed (RPM)



(d) Longitudinal differential lifting rotor speed (RPM)



(e) Elevators



(f) Flaps

Figure 16: Comparison of RCAS and DynaPy models with similar trim strategies over the full flight envelope

Table 1: Controls used to solve trim in RCAS

Target	Multirotor Mode	Pitch-Level	Airplane + Flaps (Pitch-Level)
F_x	Pitch Attitude	Propeller RPM	Propeller RPM
F_y	Roll Attitude	Roll Attitude	Roll Attitude
F_z	Collective RPM	Collective RPM	Flaps
M_x	Lateral RPM	Lateral RPM	Ailerons
M_y	Longitudinal RPM	Longitudinal RPM	Elevator
M_z	Pedal RPM	Pedal RPM	Rudder
handling of redundant controls:			
	Propeller Off	Flaps and Elevator Scheduled	Lifting Rotors Off
	Control Surfaces Zeroed	Pitch Attitude Fixed	Pitch Attitude Fixed

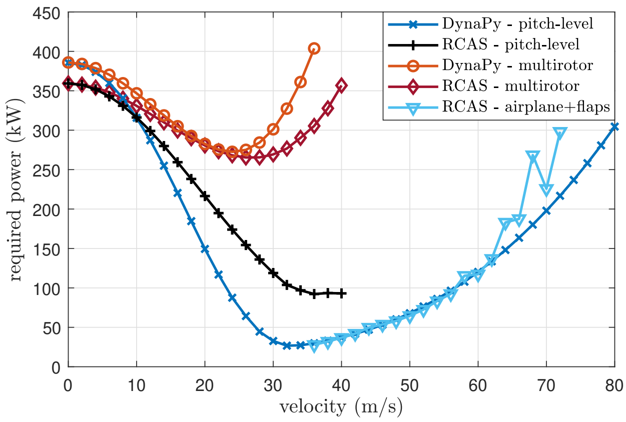


Figure 17: Comparison of power requirement between RCAS and DynaPyVTOL

DynaPyVTOL as part of the Pitch-Level trim strategy.

The third mode is a high speed Pitch-Level mode, which uses flap deflection in place of pitch attitude as a control input. The other trim controls in this mode are traditional airplane controls. The lifting rotors are all off. This mode is most comparable to the DynaPyVTOL Pitch-Level Mode at speeds above 50 m/s.

Figure 16 shows the resulting comparison between RCAS trim controls and relevant DynaPyVTOL trim controls using the most comparable trim strategies. Figure 16 compares the required power for the same trim cases. For the Multirotor mode, it is clear that there is a difference in nose-down pitch attitude that increases with airspeed, and this difference directly impacts the total power. Further investigation is warranted, but lifting rotor and wing aerodynamic modeling differences likely play the largest role.

For the pitch-level modes, the propeller speed control is very close between the two models. There are differences in low speed for the lifting rotor behavior, again likely due to rotor and wing aerodynamic modeling differences. At high speed the main difference is the use of relatively large flap angles in RCAS to trim vertical force with a pitch-level attitude, where DynaPyVTOL shows a comparative reduction in flap setting across all airspeeds. Note that for moderate speeds (35-45 m/s) DynaPyVTOL is still using some lifting rotor control while this RCAS mode has the lifting rotors turned off. The scheduled redundant controls optimized using DynaPyVTOL most likely does not correspond directly with the optimal schedule for the RCAS model, resulting in the increase in power shown in Figure 17.

7. CONCLUSION

A preliminary investigation of control strategies for an overactuated eVTOL configuration leads to several observations. The net effect of trim strategies has been shown to have a significant impact on the performance, stability, and control characteristics of the aircraft:

- Strategies which seek to maximize wing lift share and drive down rotor speed tend to minimize power, but also reduce the control derivatives and maximum force and moment generation of the lifting rotors. This can be primarily attributed to the impact of the significant reduction in RPM during transition, and the consequential reduction in control sensitivity for RPM controlled rotors.
- A pitch-level trim approach is shown, which represents a compromise between the two extremes without any formal optimization routine. The total impact is a strategy that trims to within 20 kW of the Power Optimal trim strategy, while improving the yaw response to pedal by as much as 17 dB for low frequency pilot commands in transition.
- A number of physical phenomenon have a significant impact on the stabiliity analysis of the

aircraft, which requires a deeper understanding in order to account for the essential and neglect what can be neglected. These include center of gravity travel, aerodynamic interaction between wings and rotors, and rotor inflow modeling.

- The impact of wing wake interaction on the rotors is shown to predominantly impact the rear set of lifting rotors behind the wings. The downwash increases the power requirement, and reduces the stability of the short period oscilatory and dutch roll modes.

Two different physics models of varying fidelity were used in this analysis and in some cases they produce trim control predictions that differ significantly from each other. Of note:

- Many eVTOL configurations are novel and existing analysis software has not been extensively validated in the open literature. There is little or no available test data to use for validation of analytical models.
- When two models of the same configuration produce significantly different trim results for the same flight condition, it indicates that certain modeling assumptions or analysis options are in disagreement between the codes.
- For preliminary and detailed design of these novel configurations, it is important to avoid relying on a single physics model. It is equally important to resolve differences between different models.

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