DEVELOPMENT OF AUGMENTED CONTROL LAWS FOR A TILTROTOR IN LOW AND HIGH SPEED FLIGHT MODES

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Abstract: Tiltrotors present unique features with respect to both conventional helicopters and fixed wing aircrafts. The use of traditional cockpit flight controls, particularly if complemented by standard albeit Fly-By-Wire stabilisation and command augmentation systems, may cause a high piloting workload as the pilot is required to manage the thrust vectoring and the flight path control manually. This paper presents a novel control strategy for a future Tiltrotor which aims at reducing the piloting effort, and it is enabled by the combined use of state-of-art active stick technology and highly augmented control laws. The paper focuses on the control functions investigated so far, namely Translational Rate Command for hover and low speed (helicopter configuration), and flight path control for high speed (airplane mode) operation. Both control strategies embed peculiar characteristics that differentiate them from the corresponding standard fixed-wing and rotary-wing application counterparts. The paper presents numerical results of the proposed control algorithms obtained through a fully non-linear Tiltrotor simulation model developed by Leonardo Helicopter Division.

NOMENCLATURE

LH	Leonardo Helicopter Division
MIMO	Multiple Input Multiple Outputs
SCAS	Stab. and Command Augmentation Syst.
SISO	Single Input Single Output
TC	Turn Coordination
$(\delta_{\text{LAT}}, \delta_{\text{LON}})$	stick inputs
$(\delta_{\text{THR}}, \delta_{\text{DIR}})$	thrust and pedal inputs
δ_N	nacelle tilt angle
$(\theta_{1s}^s, \theta_{1s}^d)$	symm. and diff. longitudinal cyclic pitch
(θ_0^s, θ_0^d)	symm. and diff. collective pitch
(δ_a, δ_e)	aileron and elevator commands
δ_{PDS}	power demand signal
$(T_{\text{Q1,2}}, \Omega_{1,2})$	L/R proprotors' torque and angular rate
(ϕ, θ, ψ)	body Euler attitudes
(p, q, r)	body rates
(V_x, V_y, V_z)	body groundspeeds
(n_x, n_y, n_z)	body load factors
T	proprotors' thrust
W	aircraft weight
V_{T}	true airspeed
V_{C0}	C* cross-over speed
g	gravity acceleration
γ	flight path angle
α	Angle of Attack (AoA)
C^*	C-star mixed output
H_∞	H-infinity norm

1. INTRODUCTION AND MOTIVATIONS

Tiltrotors present unique features with respect to both conventional helicopters and fixed wing aircrafts. The cockpit flight controls of Tiltrotors have been so far designed by assuming typical helicopters' inceptors as reference or at most by replacing the conventional collective lever with airplane-style thrust control lever arrangement (*i.e.* the case of Bell-Boeing Osprey V22). In particular, one of the most debated issue for Tiltrotors and - generally speaking - VSTOL aircrafts has been the thrust control. By implementing a traditional piloting approach for this kind of aircrafts, the pilot is generally required to handle the inherent coupling that exists between thrust and pitch control axis for a generic thrust vector angle (*i.e.* nacelles' angle in the case of Tiltrotors). This piloting burden is indeed reduced outside conversion phase, nonetheless a conventional thrust control strategy becomes counterintuitive in either helicopter (with airplane-style thrust control lever) or in airplane mode (when helicoper collective is used as thrust control lever). In the attempt of improving the pilot's situational awareness, many innovative thrust control lever arrangements have been proposed over the years [1,2] but to date a consensus on this topic has never been reached. Future Tiltrotors' designs must indeed capitalize the experience gained so far by optimizing the Human Machine Interface while, at the same time, reducing the crew workload and maximizing the situational awareness. With the prevailing use of Fly-By-Wire technology on this kind of aircrafts, it is reasonable to assume that increasing control law augmentation will help to reduce the need for designing and validating atypical inceptors arrangements.

This subject is currently under study in Leonardo Helicopter Division, in the framework of a research project. This aims at developing an Enhanced-Flight Control System (EnFCS) concept to be deployed on future Tiltrotor products, in cooperation with Politecnico di Milano. EnFCS relies on the introduction of *short-pole* active inceptors [3] - such as sidearm sticks - in the Tiltrotor's cockpit complemented by the development of suitable augmented Fly-By-Wire control laws. These are required to ensure a satisfactory degree of decoupling between the various Tiltrotor's control axes and to provide a smooth operation across all the flight phases: hover and low speed, conversion and airplane mode. The present paper provides an overview of the unconventional control strategies that will be developed and assessed in the framework of EnFCS research activities. The paper is structured as follows: in Section 2 the possible control strategies for future Tiltrotor platforms are presented, from both a cockpit configuration and pilot's control allocation perspective. Then, Section 3 deals specifically with the control functions investigated so far (phase 1 EnFCS). These correspond to two specific flight regimes and Tiltrotor's configurations, namely: Translational Rate Command for hover and low speed (helicopter configuration) and flight path angle Rate Command Attitude Hold complemented by either Linear Acceleration Command Speed Hold or Speed Command Speed Hold for governing longitudinal response at high speed (airplane mode). Finally, Section 4 will draw some conclusions and present the roadmap towards EnFCS development completion and the following simulation assessment phase.

2. SELECTION OF CONTROL STRATEGY FOR TILTROTOR

The Handling Quality requirements followed for EnFCS development prescribe the use of highly augmented control laws, providing a satisfactory degree of decoupling between the various Tiltrotor control axes, and providing a smooth operation across the entire flight envelope. The decoupling feature provided by the control laws allows to reduce the piloting effort as the involved off-axis control tasks are carried out by the flight control system in a way transparent for the pilot. Furthermore, each primary control function could be mapped towards a different control effector, according to the selected cockpit control allocation strategy. Moreover, the use of active stick technology provides several benefits that are herein summarized:

- *Stick electrical coupling* improving crew coordination and situational awareness in dual pilot cockpit operation, helpful also for training purposes.
- *Variable force gradient* or stick force per *g*, as generally required by VSTOL aircrafts.
- *Advanced tactile cues* improving the situational awareness in critical conditions (*e.g.*. low control margin, vortex ring state proximity, engine power limits, stall condition, etc.) and generally improving the effectiveness of Fly-By-Wire envelope protection algorithms.

Within the framework of the present research project, two main possible command strategies for a modern Tiltrotor aircraft have been envisaged, conceptually inherited from either rotary-wing or fixed-wing applications, as described below.

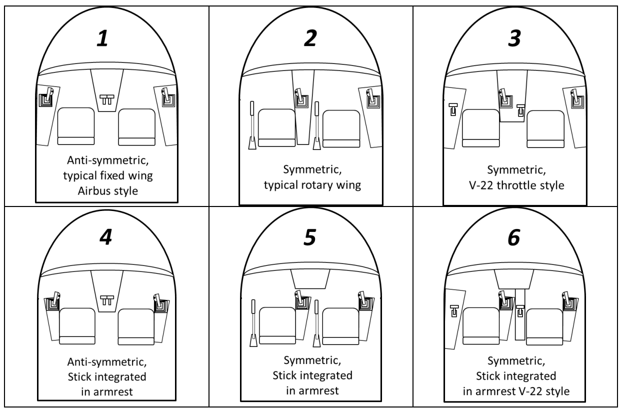


Figure 1: Tiltrotor cockpit layout options.

2.1 Airplane style control strategy

The cockpit control allocation summarized in Table 1 represents a novel solution for a Tiltrotor aircraft, and it is justified by the expected prevailing use of a Tiltrotor in airplane configuration. The envisaged cockpit layout options for this solution correspond to configurations no. 1, 3, 4 and 6 of Figure 1. In airplane mode, the pilots generally find the conventional thrust control lever (collective arrangement) rather counter-intuitive (*i.e.* pull-up to accelerate) and uncomfortable. This limitation led in the past to either adopt a linear throttle as thrust control lever (*i.e.* Bell-Boeing V22) or to implement complex power lever arrangements (*e.g.* see the Rotational Throttle Interface designed by NASA[2]). In the second case, the attempt was to constrain the direction of grip displacement to the thrust vector, in order to provide a cue of the current aircraft configuration and to prevent pilot's disorientation. As previously anticipated, the approach followed within this project is different as it implies to move the problem complexity from the mechanical domain (inceptor) to the control laws domain (software). The new power lever should be then as simple as possible (*i.e.* a linear throttle or a single degree-of-freedom sidearm controller are the best candidate options) and used to command either speed (Speed Command, Speed Hold, SCSH) or longitudinal acceleration (Linear Acceleration Command Speed Hold, LACSH), independently from aircraft nacelles tilt angle. In the following, this new inceptor will be denoted as "throttle" for sake of brevity. At hover and low-speed, the same controller would be used to command the aircraft along-heading groundspeed (Translational Rate Command, TRC and possibly Translational Acceleration Command, TAC) or differential position (Position Command, Position Hold, PCPH). The side-arm controller (sidestick) would be used to control aircraft heave axis (through longitudinal grip displacement) and roll axis (through lateral grip displacement). The control types proposed for heave / flight path response are: Position Command Height Hold (PCHH) / Rate Command Height Hold (RCHH) at hover and low speed, and either flight path angle Attitude Command Attitude Hold (ACAH) or Rate Command Attitude Hold (RCAH) in airplane mode. Roll axis would be controlled at hover-low speed according to PCPH / TRC response types, whereas in conversion and airplane mode the proposed response type is either a standard ACAH or RCAH on bank angle. As the pedal / yaw control is not considered a matter of concern on Tiltrotor, in the framework of the present research project there is no plan to develop a new pedal assembly. A standard passive, mechanically interconnected, pedal system will be then part of cockpit composition. The related response types are therefore standard, Rate Command Direction Hold (RCDH) at hover and low-speed, and Rate Command plus automatic Turn Coordination at conversion and high speed / airplane mode. The latter may be replaced by an unconventional ACAH closed on sideslip angle, which would help to provide an effective envelope protection in the lateral-directional plane at high speed.

	Throttle	Pitch	Roll	Pedal
Hover	PCPH Lon.	PCHH	PCPH Lat.	RCDH
Low Speed	TRC TAC Lon.	RCHH	TRC TAC Lat.	RCDH
Convers.	SCSH LACSH	ACAH γ RCAH $\dot{\gamma}$	ACAH ϕ RCAH $\dot{\phi}$	ACAH β RCDH RC+TC
High Speed	SCSH LACSH	ACAH γ RCAH $\dot{\gamma}$	ACAH ϕ RCAH $\dot{\phi}$	ACAH β RC+TC

Table 1: Airplane style control strategy.

	Thrust Lever	Pitch	Roll	Pedal
Hover	RCHH	PCPH Lon.	PCPH Lat.	RCDH
Low Speed	RCHH	TRC. Lon.	TRC Lat.	RCDH
Convers.	Thrust+ heave control	ACAH γ RCAH $\dot{\gamma}$	ACAH ϕ RCAH $\dot{\phi}$	ACAH β RCDH RC+TC
High Speed	Thrust control	ACAH γ RCAH $\dot{\gamma}$	ACAH ϕ RCAH $\dot{\phi}$	ACAH β RC + TC

Table 2: Helicopter style control strategy.

2.2 Helicopter style control strategy

The control allocation strategy summarized in Table 2 is assuming a typical Fly-By-Wire helicopter cockpit arrangement, comprising two side-arm controllers (two degrees of freedom), passive centered pedals (mechanically interconnected) and two conventional collective levers (see configurations no. 2 and 5 of Figure 1). It is herein reported for sake of completeness, as the airplane style command strategy is currently considered as the most promising solution for next generation Tiltrotor aircrafts. According to this concept, the collective lever would be allocated to thrust control with the possibility to command directly rate of climb in helicopter mode thanks to highly augmented RCHH function. Unusual thrust control lever configurations could be explored as well, provided that they solve the issues highlighted for this kind of devices[2]. The TRC function would be allocated to side-arm controller through its longitudinal and lateral axis. Starting from conversion phase till high speed airplane mode, the sidestick would be used as on a typical Fly-By-Wire transport aircraft, with control response types identical to the ones previously discussed for the airplane control strategy.

3. ENFCS CONTROL LAWS

The design of EnFCS control algorithms started from a consolidated Tiltrotor control law design, providing angular stabilisation and standard rate-command, attitude-hold response type about pitch, roll and yaw axes, and unaugmented response along thrust axis. The legacy control laws assume a conventional helicopter cockpit configuration, with trim actuated *long-pole* inceptors, *i.e.* centerstick and collective (thrust control) lever, plus a standard passive pedal. The nacelles' angle position is manually controlled by the

pilot through a thumbwheel placed on collective grip. Besides introducing the control logics described in the present paper, the software implementation of EnFCS control laws involves other practical modifications. Above all, the introduction of suitable auto-trim functions within roll, pitch, and thrust channels, as the new active inceptors will be preferably used as *unique-detent* sticks for ergonomic reasons and since the high control augmentation would not permit anyway to maintain a fixed relationship between stick and control effector position. The loss of this traditional visual cue of available control margin can be compensated for by means of tactile feedbacks thanks to active stick technology. The setup of stick active features (*e.g.* variable gradients, soft-stops, back-drive, etc.) is indeed one critical aspect that requires thorough assessments with the pilots and it is not discussed in the present paper. On the other hand, the existing thrust and power management system (*i.e.* proprotors' torque and rpm governing logics) and the gearing law between equivalent stick demands (including pilot's and flight control system contributions) and the physical Tiltrotor control surfaces (and hence actuator positions) do not need any modification to support EnFCS. The original gearing law (*i.e.* the so-called control "ganging" matrix[4]) is scheduled as a function of nacelle angle δ_N and calibrated airspeed.
The numerical validation of EnFCS design is made possible by an accurate FLIGHTLAB non-linear multibody model of medium size Tiltrotor, running in a distributed framework together with the other model components (engines, actuators, sensors, inceptors, etc.) and developed by LH Flight Mechanics team. The simulation environment (AWARE2) enables both off-line and real-time simulations.
In the following, the EnFCS control functions developed so far (Phase 1 EnFCS) and corresponding to hover and low speed (helicopter mode), and to high speed flight (airplane mode), will be thoroughly discussed.

3.1 Hover and Low Speed regime

Translational Rate Command (TRC, according to ADS-33E-PRF definition[5]) and Vertical Rate Command / Height-Hold response types are recognized as an effective way to provide satisfactory handling qualities for a rotorcraft operating nap-of-the-earth hover and low speed tasks, particularly during degraded visual conditions. Due to its intrinsic capability to minimize piloting workload and hence to increase safety when the aircraft is operating close to ground, the TRC mode has been then considered a natural candidate for inclusion within EnFCS control laws. Although TRC is a well-known helicopter response type, much less literature exists regarding TRC applied to low-speed Tiltrotor's control[6,7]. The approach presented in this paper differs from the TRC control strategy evaluated at NASA Ames[6] for the following aspects:

- The medium-small size Tiltrotor model used as reference does not provide lateral cyclic actuator, so it can rely only on differential collective for controlling roll axis at hover and low speed. This constraint does not allow to perform wings level lateral translation maneuver, *i.e.* without banking the aircraft[6,8].
- It is proposed to not use the nacelle tilt angle as a primary control variable for longitudinal translation, in order to not overstress the pylon conversion actuators with a high duty cycle and to not pose additional requirements on actuator rate limits. As on conventional rotorcrafts, the primary mean for aircraft longitudinal control would be represented by the proprotors' longitudinal cyclic pitch. Similarly to lateral translation, this choice requires the aircraft to undergo significant pitch attitude excursions during the acceleration and deceleration phases of the maneuver. Moreover, the symmetric use of longitudinal cyclic shall be also limited by the maximum allowed proprotors' flapping angles. For these reasons, we propose in this paper an enhanced version of the basic TRC scheme which exploits the thrust vectoring degree of freedom as a simple anticipation term.
- It is suggested to extend the longitudinal ground-speed range compatible with TRC mode from 40 to 60 knots, in order to ensure a smoother transition to conversion / airplane mode.
- The cockpit controls are configured as described in section 2. The nacelle angle can still be finely regulated by the pilot through the standard nacelle thumbwheel (or a discrete beep trimmer) placed on the left-hand grip. This control input allows the pilot to indirectly act on pitch attitude, as the longitudinal cyclic command is already exploited by TRC for controlling the aircraft longitudinal acceleration. It's noted that, by selecting an airplane style command strategy (Tab. 1), the pilot would be required to accomplish the TRC maneuver in the horizontal plane by coordinating the sidearm roll axis and the left inceptor (the throttle). This appears quite unusual if compared to conventional helicopter piloting practises, but not necessarily inconceivable after a proper training and thanks to the excellent control decoupling characteristics ensured by TRC. Validation of this unconventional piloting strategy will indeed require extensive ergonomic and handling assessments at simulator. As far as force feel requirements are concerned, it is envisaged to program the active inceptor system to ensure a basic (low) gradient law about all three axes, plus specific non-linear tactile cues.

These will comprise a positive throttle soft-stop to make the pilot aware of the incoming mode transition plus a negative hard-stop to represent the impossibility to overcome a maximum backward velocity. Similarly, symmetric roll hard-stops will announce the achievement of maximum lateral ground speed (currently set to 20 knots) whereas suitable sidestick pitch hard-stops will delimit the vertical speed boundaries.

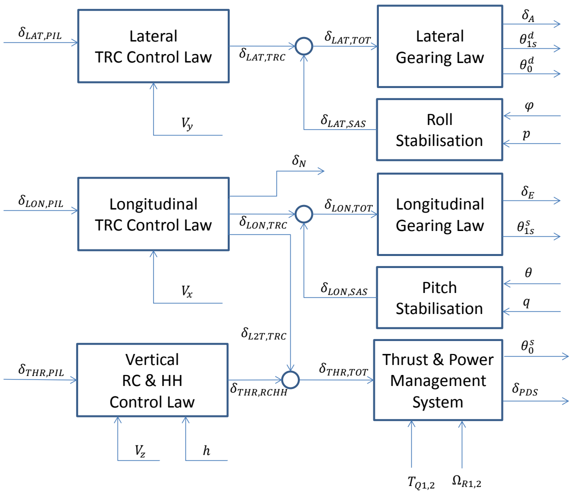


Figure 2: Longitudinal/Lateral TRC and Vertical RCHH control concept applied to Tiltrotor.

Figure 2 shows the functional diagram of the implemented TRC/RCHH control logic. Thanks to Tiltrotor symmetry, and by assuming the nacelle angle in proximity of helicopter configuration (90 deg), the bare aircraft hover and low speed dynamic responses are almost perfectly decoupled. This consideration allows to design the TRC/RCHH control laws as three independent SISO control loops. The directional law has not been depicted in Figure 2 since the proposed command strategy is still relying on the existing pedal system and the RCDH law has been deemed appropriate for the TRC implementation. The longitudinal, lateral and heave rate controllers are fed by the measured along-heading (V_x), across-heading (V_y) and vertical rate (V_z) signals and generate equivalent pitch, roll and thrust stick demands (δ_{LAT}, δ_{LON}, δ_{THR}). The groundspeed signals used as feedback typically comes from AHRS-GPS hybridisation (through complementary or Kalman filtering). The legacy full-authority SCAS, which is providing forward loop control shaping and stabilisation of pilot response (similarly to the architecture described in[9]), has been simplified to provide purely attitude (θ, ϕ) and rate (p, q) stabilisation. As previously noted, the gearing and thrust/power management laws mapping the equivalent pitch, roll and thrust stick demands to the various aircraft effectors have not required any modification. These can be briefly expressed as:

(1) $$\begin{bmatrix} \theta^s_{1s} \\ \delta_e \end{bmatrix} = g_{\text{LON}} \left(\delta_{\text{LON}}, \delta_N, V_{\text{T}} \right)$$

(2) $$\begin{bmatrix} \theta^d_{0,\text{LAT}} \\ \theta^d_{1s,\text{LAT}} \\ \delta_a \end{bmatrix} = g_{\text{LAT}} \left(\delta_{\text{LAT}}, \delta_N, V_{\text{T}} \right)$$

(3) $$\begin{bmatrix} \theta^s_0 \\ \delta_{\text{PDS}} \end{bmatrix} = g_{\text{THR}} \left(\delta_{\text{THR}}, \delta_N, T_{\text{Q1,2}}, \Omega_{\text{1,2}} \right)$$

whereas the directional rigging law can be expressed as follows:

(4) $$\begin{bmatrix} \theta^d_{0,\text{DIR}} \\ \theta^d_{1s,\text{DIR}} \end{bmatrix} = g_{\text{DIR}} \left(\delta_{\text{DIR}}, \delta_N, V_{\text{T}} \right)$$

The total pitch commands θ^d_0 and θ^d_{1s} comprise both lateral and directional contributions, i.e. $\left(\theta^d_{0,\text{LAT}} + \theta^d_{0,\text{DIR}}\right)$ and $\left(\theta^d_{1s,\text{LAT}} + \theta^d_{1s,\text{DIR}}\right)$, respectively. However, at hover and low speed the set of used effectors would reduce to the proprotors and engines control variables, *i.e.* $\left(\theta^s_{1s}, \theta^d_{1s}, \theta^s_0, \theta^d_0, \delta_{\text{PDS}}\right)$. The translational rate-command control laws include pilot command shaping and limiting, and feedback control. In order to decrease control aggressiveness about roll and pitch channels and thus moderating actuator demands and containing attitude excursions, the pilot command shaping path in roll and pitch is rate limited to 0.15 g along both lateral and longitudinal direction above 5 ft/s. The stick sensitivity has been set to allow a rate demand of 67.5 ft/s (40 knots) along and across heading, and $\pm$ 500 fpm within the operating stick strokes. It must be noted that, with respect to the typical sensitivities reported in literature[6] for conventional centersticks (10 to 17 ft/s/in), the EnFCS values would be higher as effect of using short-pole inceptors, *i.e.* with equivalent displacement in the range of $\pm$ 1.5 to $\pm$ 2.0 inches[3]. This issue is recognized by ADS-33E-PRF[5] that in fact reformulated the requirement in terms of cockpit control force above breakout. The exception may be represented by the throttle, if a linear inceptor is used instead of a rotary sidearm stick. The translational rate feedback laws are basically SISO PID (Proportional-Integral-Derivative) regulators which can be tuned through classical frequency-response based methods or modern optimization techniques. The tuning task showed that, in order to obtain a robust first-order like response as recommended by ADS-33E-PRF[5], the pitch and roll attitude stabilisation gains must be increased to maximize the damping ratio associated to longitudinal (phugoid) and lateral translation modes. The feedforward path from longitudinal control channel to thrust control channel has been introduced to minimize the cross-coupling effects appearing for

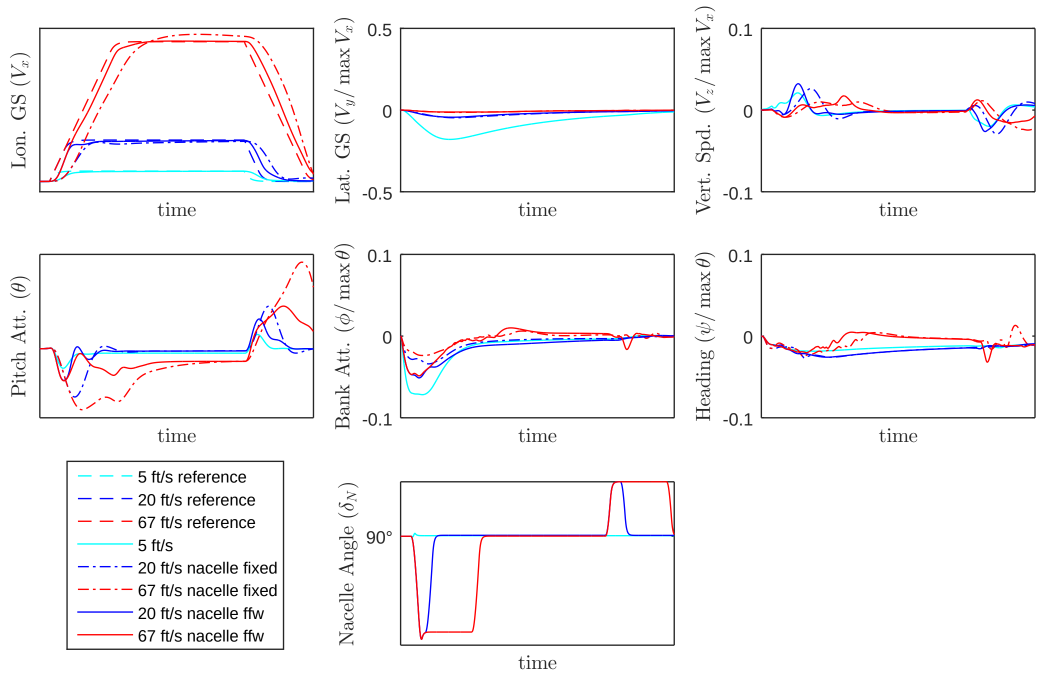


Figure 3: TRC longitudinal responses, commanded vs. fixed nacelle angle.

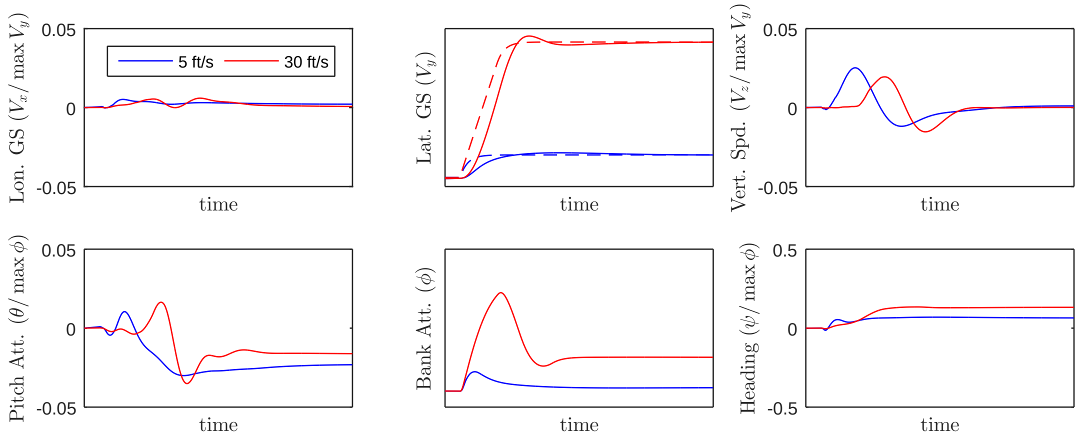


Figure 4: TRC lateral responses.

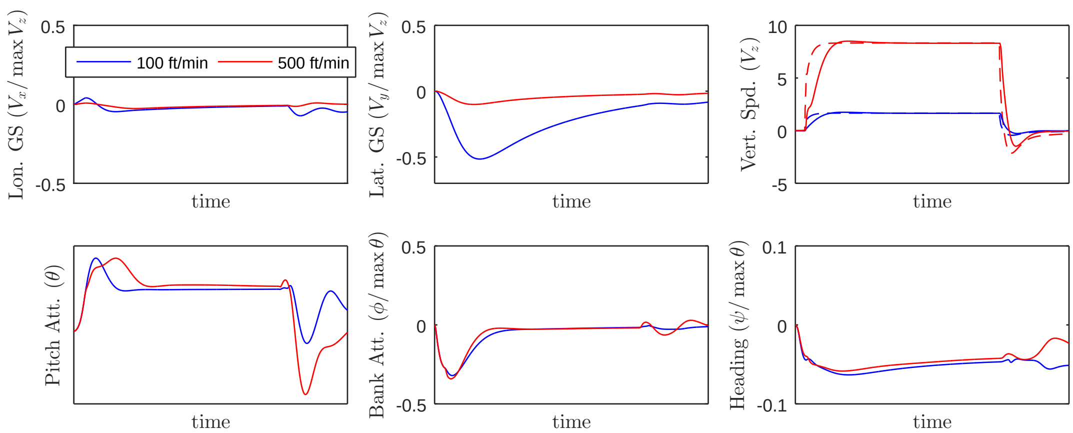


Figure 5: Vertical RCHH responses.

larger longitudinal command amplitudes, and behaving as a large disturbance on heave channel. Differently from longitudinal and lateral channel, the vertical rate controller embeds a height-hold function that enables height capturing and keeping when the heave stick (*i.e.* sidearm pitch axis) is released. Figure 3, 4 and 5 show the AWARE2 off-line simulation results corresponding to different rate amplitudes for longitudinal, lateral and vertical maneuvers, respectively. The obtained time histories have been analysed to check that the ADS-33E-PRF[5] guidelines applicable to this response type have been met. Particularly, rotorcraft handling quality guidelines recommend an equivalent rise time comprised in the range 2.5 to 5.0 seconds which corresponds, according to the definition provided by Franklin *et al.*[10] *i.e.* based on the 45 deg phase margin from stick input to translational rate frequency response, to a bandwidth ranging from 0.2 to 0.4 radians per second. These figures apply to moderate and small input amplitudes, as non-linear effects appear dominating for the larger amplitudes. For longitudinal and lateral channels the responses above 5 ft/s are lagged by the presence of the rate-limiters previously mentioned, that prevent the aircraft attitudes from exceeding acceptable values during the acceleration and deceleration transients. This effect is quite evident on longitudinal response, whilst the lateral rate shows a departure from the ideal first order model as indicated by the small overshoot present in the 30 ft/s case. The bandwidth requirement appears satisfied by the three control loops, although as expected the tuning enforced on longitudinal and lateral axes involve significant attitudes during the translated maneuvers at the highest commanded rates (in the range of $\pm$ 10 to $\pm$ 15 degrees). It must be also noted that the longitudinal response shows the highest equivalent time constant (in the order of 4.0 seconds), although some room for improvement through tuning optimisation would still exist. Furthermore, simulations confirm that the achieved dynamic responses are well decoupled and not showing objectionable overshoots or damping issues. Differently from lateral control, for which a limited performance improvement can be foreseen through the optimization of feedforward (command shaping) and feedback (PID gains) paths and without implying unacceptable bank attitudes, the longitudinal control could take large benefit from the suitable use of thrust vectoring feature provided by Tiltrotor technology. The idea, assessed in the framework of EnFCS development, is to command the nacelle tilt with a dedicated feedforward path driven by the pilot's longitudinal demand exceeding the threshold for linear control operation (5 ft/s) and hence feeding also the rate limiter. The relation between commanded along-heading acceleration and nacelle tilting, *i.e.* approximately the control derivative X_{δ_N}, can be extracted either numerically from the model or simply by perturbing the nacelle angle of the hovering aircraft in the earth referenced system as shown in Eq. 5, 6 below.

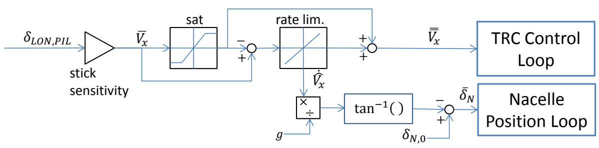


Figure 6: Nacelle command anticipation term.

(5)
$$T \sin\left(\delta_N + \theta\right) = W$$
$$T \cos\left(\delta_N + \theta\right) = \dot{V}_x \frac{W}{g}$$

Therefore, by indicating the hover trim condition with the subscript 0 we have:

(6)
$$\left.\frac{\partial \dot{V}_x}{\partial \delta_N}\right|_0 = -\frac{g}{\sin^2\left(\delta_{N,0} + \theta_0\right)}$$

It is noted that the same expression is obtained by perturbing the pitch attitude, for instance 9 deg of nacelle forward rotation starting from levelled aircraft would achieve roughly 0.15 g acceleration as 9 deg pitch down maneuver. The expression shown in Eq. 6 does not take into account the effect of flapping derivative, however the default pitch control laws already include a crossfeed path from nacelle rate to equivalent longitudinal stick command δ_{LON} which helps compensating the flap-back and hence the "non-minimum phase" effect experienced when the nacelles are tilting forward (and vice-versa)[6,7]. The same feedforward command aims at mitigating the inertial coupling between nacelles and fuselage, which would induce a pitch attitude perturbation in the same direction of flapping. Therefore it is reasonable to expect that a suitable split of the pilot's acceleration demand between TRC control loop and the nacelle control system could dramatically reduce the required pitch attitude during the maneuver or, equivalently, decrease the response lag for the same pitch attitude. The idea is therefore to command the nacelle position forward and backward during the acceleration and deceleration phase, respectively, at the default rate of 8 deg/s. The commanded nacelle angle excursion is driven by the derivative of the longitudinal groundspeed command exceeding the 5 ft/s threshold, that is subject to the rate limit constraint (see Figure 6). The advantage of this approach is that thrust vectoring feature is exploited during the transient in a feedforward way, without putting the additional constraints on pylon conversion actuators that a translational-rate command control based on primary nacelle actuation would imply (*i.e.* higher duty cycle, shorter fatigue life, etc.). Figure 3 reports the comparison between longitudinal responses (depart/abort) achieved with the

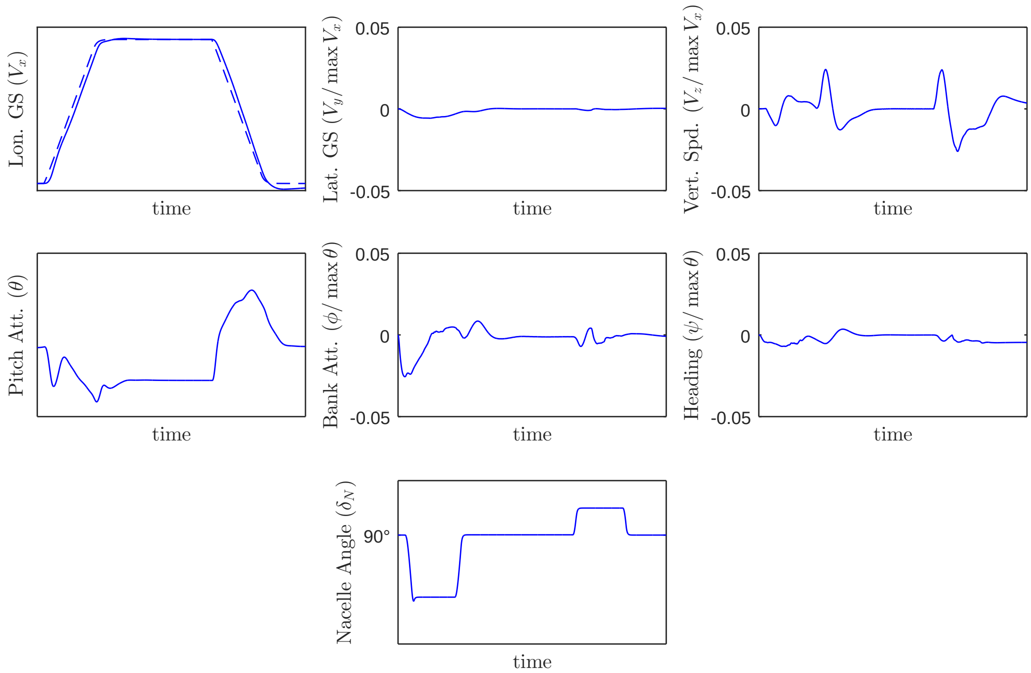


Figure 7: TRC longitudinal control extended to 60 knots.

standard rotorcraft TRC control strategy and the enhanced TRC logic just described. The improvement in terms of reduced response lag, particularly for the higher commanded speed (40 knots), is rather impressive. It is also observed almost 50% reduction of pitch attitude during the transient, which is now comparable to the results reported in reference[6]. This promising approach allowed also to investigate the extension of TRC groundspeed limit from 40 to 60 knots. Although well beyond the typical rate limits used for conventional rotorcraft TRC applications, it is believed that the proposed boundary would allow to fully exploit the TRC capability in a typical up-and-away condition and an easier mode transition from TRC to conversion mode. In order to ensure the robustness of control loop up to 60 knots the longitudinal and heave control loop gains have been scheduled with airspeed, whereas the system responsiveness has been improved by increasing the longitudinal acceleration command limit to 0.2 g. The simulated response, which is reported in Figure 7, shows an overall satisfactory performance, with still an acceptable pitch attitude excursion (within $\pm$10 degrees).
In summary, the validation at engineering simulator of the proposed TRC function will require to:

- Thoroughly assess the airplane style cockpit control allocation strategy (Table 1) at hover and low-speed, both from a functional and ergonomic perspective.
- Assess the proposed control law from a handling quality perspective, by validating with pilots the acceptability of achieved bandwidth and delay for each axis.
- Implement a Position-Hold (PH) feature around the existing longitudinal and lateral control loops, to ensure a more robust hover hold capability in presence of external disturbances.
- Possibly extend the lateral TRC controller to support wing-levelled translated flight, by assuming that the reference Tiltrotor vehicle will be equipped with lateral cyclic actuators.

Finally, it should be investigated the feasibility of a novel TAC - Translational Acceleration Command response type, which would simplify the logic transition between low and high speed regime whether LACSH is associated to left hand inceptor (throttle) in airplane mode instead of SCSH response type.

3.2 Airplane mode

The proposed control functions for airplane configuration discussed in the present paper focus on the longitudinal and heave dynamics. The lateral-directional control strategy reported in Table 1 presents more conventional characteristics, whereas the flight path control associated to throttle and right sidestick pitch axis is indeed innovative for a Tiltrotor aircraft. The first problem addressed during the airplane mode design has been the selection of an appropriate flight path angle rate command scheme. Rate command has been preferred to attitude command in order to use the sidestick controller as a unique-trim inceptor, and to provide better agility characteristics. The solution implying less modifications to the existing longitudinal SCAS would consist in feeding back the signal $q - \dot{\alpha}$, *i.e.* the derivative of flight path angle γ in level flight. The additional feedback term $\dot{\alpha}$ can be computed by processing the measured angle of attack with a high pass filter. Nevertheless, there is a big lack in knowledge regarding this type of command response system and the few available data do not allow to draw any conclusion. Therefore, it has been decided to follow a less risky approach by choosing a pitch command scheme well-known in the civil airplane industry, that is the so-called C* control algorithm[11]. According to C* definition, the feedback variable is given by a linear combination of pitch rate and vertical load factor:

(7)
$$C^* = \Delta n_z + \frac{V_{\mathsf{C0}}}{g} q$$

where Δn_z denotes the incremental load factor (with respect to trim condition) and V_{C0} is generally denoted with "cross-over" airspeed, *i.e.* the airspeed at which the two contributions, respectively the vertical load factor and the centripetal term associated to pitch rate, are equally weighed. The C* criterion asserts that pilot is likely to use pitch rate in the low speed and the vertical load factor in the high speed regime as main control cues. Moreover, it is noted that the C* figure has a close relationship with flight path control, as in straight and level flight the small load factor perturbation δn_z is equivalent to $V_{\mathsf{T0}} \delta\dot{\gamma}$, being V_{T0} the trim airspeed. The existing full-authority longitudinal SCAS, enforcing model following on pitch rate command, has been therefore modified to ensure tracking of commanded C* reference. If we consider the case of wing-level flight, and if we denote with $\bar{q}\,(V_{\mathsf{T}})$ the output of pitch rate command model (typically scheduled with airspeed in order to provide a constant g-sensitivity per inch of stick), we can express the C* command law as:

(8)
$$\bar{C}^* = \frac{\bar{q}\,(V_{\mathsf{T}})}{g} V_{\mathsf{C0}} \left(\frac{V_{\mathsf{T}}}{V_{\mathsf{C0}}} + 1 \right)$$

It is straightforward to see that by tracking the command model, *i.e.* $C^*(j\omega) = \bar{C}^*(j\omega)$, the controller meets also the original rate command system requirement $q\,(j\omega) = \bar{q}\,(V_{\mathsf{T}}, j\omega)$ for frequency ω within the control bandwidth. The C* command model can be reformulated to include a turn coordination term $\bar{q}_{\mathsf{TC}}$ as follows:

(9)
$$\bar{C}^* = \frac{V_{C0}}{g} \left[\Delta\bar{q}\,(V_{\mathsf{T}}) \left(\frac{V_{\mathsf{T}}}{V_{\mathsf{C0}}} + 1 \right) + \bar{q}_{\mathsf{TC}}\,(V_{\mathsf{T}}, \phi, \theta) \right]$$

(10)
$$\bar{q}_{\mathsf{TC}} = \frac{g}{V_{\mathsf{T}}} \tan(\phi) \sin(\phi) \cos(\theta)$$

Once again, the tracking performance of the controller ensures that during the coordinated turn $q(j\omega) = \Delta\bar{q}\,(V_{\mathsf{T}}, j\omega) + \bar{q}_{\mathsf{TC}}\,(V_{\mathsf{T}}, \phi, \theta, j\omega)$.

The cross-over airspeed V_{C0} for the Tiltrotor has been set to 200 knots (slightly lower than jet liners), whereas the incremental load factor has been obtained by washing out the measured vertical acceleration in order to remove the steady-state contribution (*e.g.* gravity resolved through aircraft attitude). Furthermore, the commanded C* signal has been limited within the algorithm to comply with the aircraft structural limits. It can be demonstrated that the usual scaling factor $(1 + V_{\mathsf{C0}}/V_{\mathsf{T}})$ applies to these load factor limits. The C* controller hence provides also a valid "passive" envelope protection, which can be complemented in airplane mode by the inceptors active features for other important safety cues (*e.g.* stall protection). In the Laplace domain, the adopted C* control law can be expressed as reported in Eq. 11, 12, 13 below. The dependence from scheduling parameters has been omitted for sake of simplicity. The controller setup includes hence the definition of suitable washout filters ($W_{\mathsf{O,N}}(s)$, $W_{\mathsf{O,Q}}(s)$), pilot's command shaping filter $H_{ff}(s)$ and the PI (Proportional-Integral) gains K_{cp}, K_{ci}.

(11)
$$\delta_{\mathsf{LON,SCAS}}(s) = H_{ff}(s)\delta_{\mathsf{LON,PIL}} + \delta_{\mathsf{LON,SAS}}(s) + \\ + \left(K_{cp} + \frac{K_{ci}}{s} \right) \left(\bar{C}^*(s) - C^*(s) \right)$$

(12)
$$\bar{C}^*(s) = \frac{V_{\mathsf{C0}}}{g} M_q(s) \left(1 + K_{nz} W_{\mathsf{O,N}}(s)\right) \delta_{\mathsf{LON,PIL}}(s)$$
$$C^*(s) = \frac{V_{\mathsf{C0}}}{g} Q(s) + W_{\mathsf{O,N}}(s) N_z(s)$$

(13)
$$\delta_{\mathsf{LON,SAS}}(s) = -W_{\mathsf{O,Q}}(s) K_q Q(s)$$

Consistently with Eq. 8 the normal load scaling factor K_{nz} is linearly dependent on airspeed ($V_{\mathsf{T}}/V_{\mathsf{C0}}$). Furthermore, if required to improve the short period damping of the bare aircraft, the tuning process would require also the definition of the stabilisation gain K_q. The C* control logic, and particularly its integral path (which is roughly proportional to pitch attitude and vertical speed[11]), provides the favourable characteristic of strongly damping the aircraft phugoid mode. Moreover, it naturally ensures also flight path stability because when the pilot is hands-off on pitch axis the aircraft closed in loop with the C* controller is stabilised at a constant vertical speed or flight path angle, provided that the airspeed is maintained constant by an auto-throttle system. The drawback of C* algorithm is in fact the objectionable loss of natural airplane speed stability, which could be anyway artificially restored through dedicated airspeed control loops (*i.e.* C*U variant). As in airplane mode, the control strategy proposed in Table 1 involves the use of a full-time auto-thrust control law to implement either LACSH or SCSH response type, this drawback is not considered as a matter of concern. The tuning of C* algorithm and hence the setup of the relevant scheduling law has been carried out by applying classical root locus techniques to the linearized models of the reference Tiltrotor in airplane configuration at various airspeeds. The synthesis of the C* proportional and integral paths has been performed by taking care that the natural frequency of the pitch short period mode ($\omega_{n,sp}$) is not deviating significantly from the value attained by the legacy SCAS. The corresponding damping ratio ($\zeta_{n,sp}$) is slightly reduced though it is still within an acceptable range (*i.e.* close to 0.7). For the time being, the use of the additional stabilisation path reported in Eq. 13 has not been deemed useful for the considered application because the proportional path of the C* controller already contributes adequately to the damping criterion, and higher gains would push the frequency of short period mode towards impractical values. Typical fixed-wing handling quality criteria

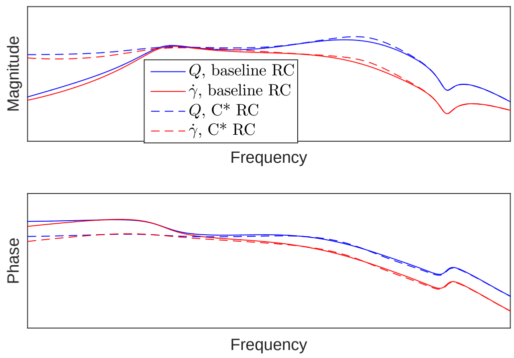
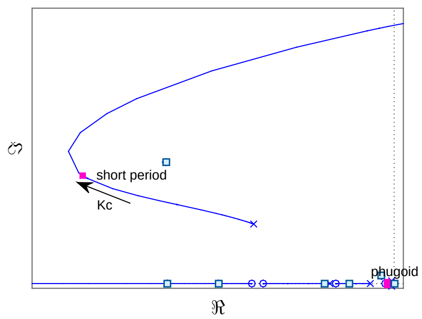
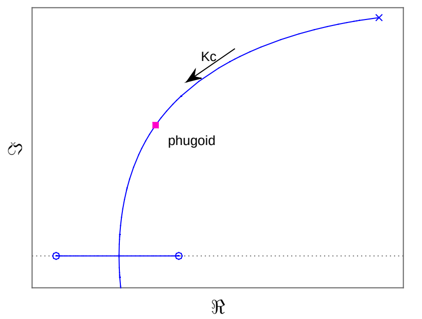


Figure 8: C* frequency response, from $\delta_{LON}(j\omega)$ to $Q(j\omega)$ and $\dot{\Gamma}(j\omega)$, compared to baseline rate command system.

(such as Gibson's time domain dropback[12]) can be also used to optimize the short period damping and the C* feedforward path. The frequency response of the C* system, from pilot's stick to pitch and climb angle rate, is compared to the original rate command system in Figure 8. The frequency responses shows that the short period mode and thus the high frequency roll-off is marginally impacted by the C* algorithm, as desired, whereas the control scheme introduces a significant boosting of low frequency gain instead of typical wash-out behaviour of conventional rate command system. This is a clear indicator of the long term flight path stabilisation capability of the C* control algorithm. The constraint on short period frequency comes generally from the handling quality indicator $\omega_{n,sp}^2/n_\alpha$[13], as the normal acceleration sensitivity to angle of attack (denoted briefly with n_α) can be assumed constant for a given aircraft configuration and flight condition. It must be also noted that the numer-



(a) short period mode.



(b) phugoid mode.

Figure 9: C* root locus (varying loop gain K_{cp}).

ical analysis confirmed the expected impact of the C* approach on phugoid mode, which becomes largely damped (almost real coincident poles), see Figure 9. An important limitation of standard C* controller is that it cannot assure null attitude deviation as effect of external disturbances, because it does not include an integral path fed by the flight path angle error. Therefore, without any automatic compensation the pilot would be periodically required to correct the flight path drift occurring. In the scope of the present work, the availability of the legacy pitch attitude hold system led us to improve the flight path hold performance of C* control scheme. A simplified schematics of the proposed flight path control architecture is shown in Figure 10. According to this control logic, the equivalent pitch command to aircraft longitudinal effectors (mainly elevator δ_e used in airplane mode) is switching between the previously described C* control, while the pilot is hands-on pitch axis, and the flight path angle hold logic. For sake of simplicity, the blocks have been depicted in parallel, although for implementation reason they share the same pitch integrator. During the hands-on phase, the flight path angle reference (γ_{REF}) is synchronized with the measured flight path angle. When the pitch axis of sidestick is released, the datum is frozen and the pilot can finely tune it by using standard beep switches. The LACSH (or SCSH) module shapes the pilot's throttle (left hand inceptor) input to produce a suitable airspeed reference, which is tracked by the auto-thrust feedback control. When the pilot is handling the throttle a provisional feedforward path can be used to quicken the coupled engine-thrust response. As previously anticipated, the use of a second short-pole sidearm controller in the left hand position instead of a large stroke throttle would make preferable the LACSH option, as the stick could be then displaced from center detent to command the desired acceleration and it would not require to be trimmed. In order to support this response type, and to prevent the auto-thrust integrator from quickly saturating, the acceleration limit applied to the pilot's command shall be continuously updated. A specific acceleration limit estimator has been thus implemented, which is based on a very simple albeit sufficiently accurate model of the aircraft power balance. The conservativeness of the estimator can be reduced, and hence the performance achievable by the acceleration command system improved, by processing the best estimate of the aircraft mass in place of the MTOW, and by incorporating in the algorithm a more accurate model of the engine available power. If we exclude the pitch hands-on logic, which

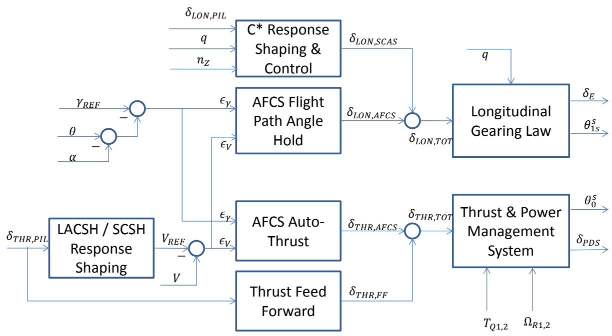


Figure 10: Tiltrotor flight path control in airplane mode.

can take advantage from the natural frequency separation between the aircraft pitch (short period) and the closed-loop thrust-airspeed response (lagged by the aircraft inertia and the engine dynamics), the overall controller governing and decoupling flight path angle and airspeed response is generally multivariable. Specifically, the control problem to be addressed is square (2×2), and it has been thoroughly analysed in different fixed-wing applications. One way to deal with such a problem has been proposed by Boeing with TECS (Total Energy Control System[14]), which is based on energy principle: the thrust command can be used to vary the total energy of the aircraft (kinetic and potential), whereas the elevator command would be needed to distribute the available energy between flight path angle and airspeed. However the TECS scheme is meant to be used primarily for automatic guidance and control purposes, and in fact it requires to be interfaced with an existing pitch tracking loop plus it assumes a precise thrust demand system. A structurally similar though more flexible linear compensation network has been adopted for EnFCS, which offers a greater tuning flexibility and is not subject to the TECS constraints. This controller comprises proportional and integral command paths towards the equivalent pitch and thrust stick control signals ($\delta_{\text{LON,TOT}}$, $\delta_{\text{THR,TOT}}$). The preliminary tuning of this multivariable controller has been carried out by using a structured H_∞ optimization technique[15,16], which allows to take into account as mathematical constraints the various requirements applicable to the control system design. Among these, the control problem addressed in the present work entailed on-axis tracking performance requirements (*i.e.* adherence to a prescribed dynamic model and therefore desired complementary sensitivity), off-axis disturbance rejection (*i.e.* off-diagonal terms of the complementary sensitivity matrix), control moderation (control sensitivity) and MIMO stability margins according to disk criterion (*i.e.* relying on balanced sensitivity function[17]). The numerical optimization is carried out by considering the real structure of the controller, differently from classical H_∞ synthesis methods. This approach is very powerful as it allows to evaluate the performance achievable with different controller structures, *i.e.* by disabling or activating the various controller paths. The gains are numerically optimized after each structural modification to the control loop. For instance, the analyses carried out so far have highlighted that in airplane mode the combined use of elevator and throttle to track the commanded acceleration (or airspeed) provides some benefits with respect to the classical auto-throttle design relying just on thrust demand. These benefits should be traded off against the increased control complexity, although it must be remarked that the full MIMO longitudinal controller would be anyway needed to manage the conversion phase. Moreover, the full-time inclusion of this loop would modify the low-frequency hands-on response characteristics of the C* controller transforming it into an equivalent C*U control scheme[11]. On the other hand, the thrust contribution (from flight path angle error to auto-thrust module) is used to improve the long period flight path hold tracking performance.
Figure 11, 12 and 13 report off-line simulation results extracted from the FLIGHTLAB non-linear model of the Tiltrotor flying in airplane mode at 4000 feet. The first test entails the flight path angle response at 200 knots following 5% stick input. As it can be seen from Figure 11, during the hands-on phase the aircraft responds with approximately constant climb angle rate (*i.e.* normal load factor). The speed perturbation occurring through the pitch maneuver is minimized by the auto-thrust loop. Once the stick is released, the integrated flight path and airspeed hold logic comes into play by capturing the syncronized attitude and airspeed reference signals. The aircraft is then stabilized on a climb trajectory simply by pulling back the stick for few seconds. In the second test (Figure 12) the Tiltrotor is flying straight and level at a lower speeds (120 knots) but still in airplane mode, and the EnFCS is commanded to accelerate the air-

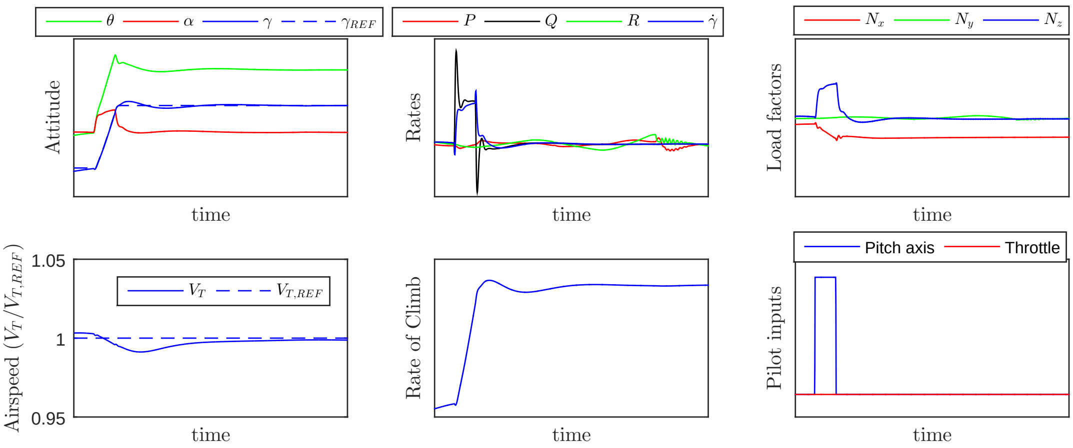


Figure 11: Pitch response in airplane mode.

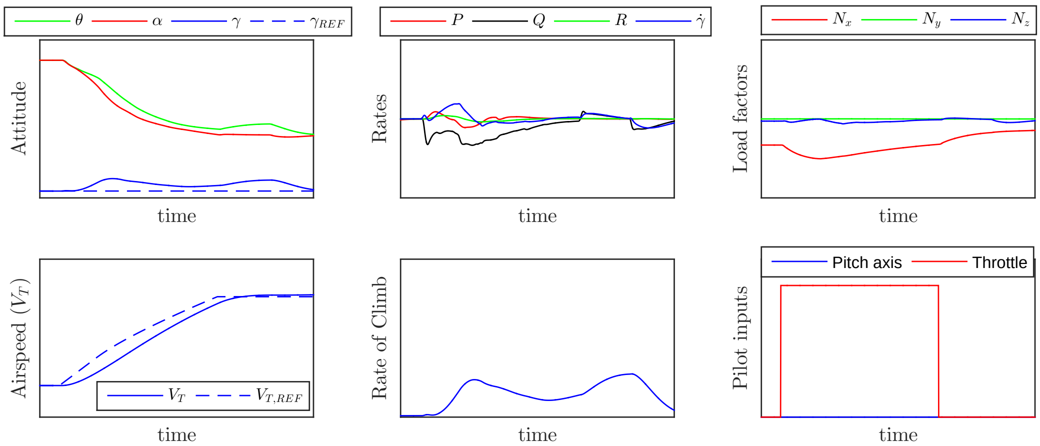


Figure 12: Throttle response in airplane mode.

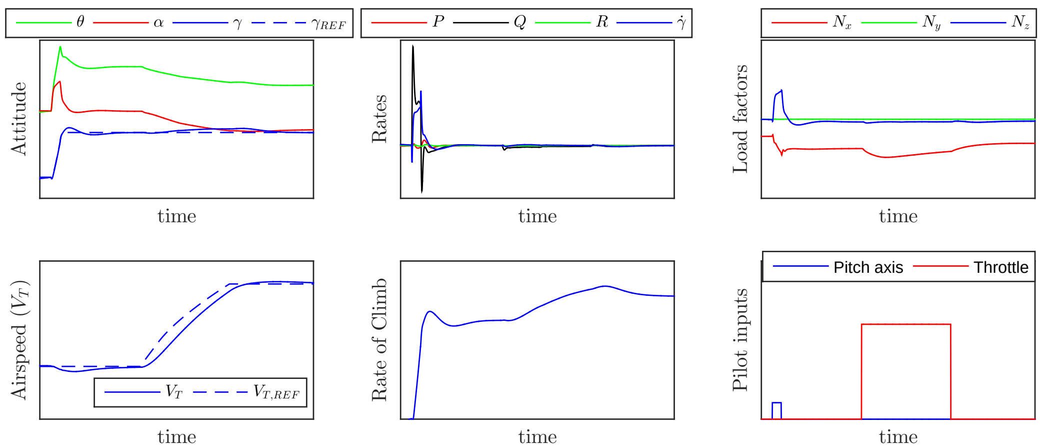


Figure 13: Pitch and throttle response in airplane mode.

craft through a 50% throttle displacement. The flight control system drives the Tiltrotor aircraft acceleration phase, by compensating for the natural tendency of the aircraft to climb, and by smoothly reducing the angle of attack consistently with airspeed increase. It must be remarked that the aircraft acceleration during the transient is modulated by the airspeed rate limit estimator previously mentioned. Finally, the third test (Figure 13) involves an accelerated climb, produced by first commanding a positive flight path angle variation and then a throttle command. During the acceleration phase, the rate of climb is obviously growing almost linearly as effect of the linear acceleration command.

As far as the force feedback aspects are concerned, in airplane mode it is envisaged to program the active inceptors force-feel characteristics to implement a basic gradient force plus appropriate non-linear tactile cues. By assuming that the control laws are enforcing a RCAH response type on climb angle, as previously described, the sidestick pitch axis stiffness should be made proportional to airspeed: since the stick displacement would command a certain rate of climb angle $\dot{\gamma}$, for higher airspeed the normal acceleration would be proportionally greater and this cue would be hence worth to be provided to the pilot. Furthermore, should a LACSH response type be adopted for throttle input, also this inceptor should be made spring centered. Active stick features would be then used to implement straightforward envelope protection functions without requiring complex solutions at control law algorithm level, as generally made necessary by passive stick technology. The following basic protection functions would be then implemented:

- The margin existing with respect to safe AoA boundaries (as function of weight and configuration) will be monitored and, if exceeded, would trigger specific cues (*e.g.*. stick pusher or shaker). Alternatively, the software hard-stop capability on the pitch axis could be used to prevent the pilot from exceeding the stall AoA in any condition. As additional envelope protection feature, the longitudinal control law would not permit to trim the aircraft above a specific AoA limit.

- Low and high speed cues should be activated on the throttle inceptor. In airplane mode, the stall protection acting on pitch axis is already advising the pilot of incipient stall and hence minimum airspeed. If the pilot is handling the throttle, and the aircraft airspeed is close to the minimum operating value (for airplane configuration), the pilot should feel a soft-stop in the backward direction indicating the boundary of conversion maneuver. Conversely, a movable hard-stop (consistently with airspeed variation) could indicate either the V_{MO} or V_{NE} limit.

- Assuming the requirement to protect flight path angle instead of the conventional pitch attitude, suitable γ limits should be defined for the trimmability of the aircraft, and the pilot should be made aware of the proximity of these limits, *e.g.*. through movable soft-stops. Namely, upper limit should correspond to null acceleration margin along the positive flight path, whereas the negative limit should coincide with minimum thrust command (below this value the aircraft cannot be trimmed during descend).

- Although normal load factor limitation would be already provided "passively" by the C* control algorithm, as previously discussed, this feature would not prevent from implementing also dedicated feel warning as a variable hard-stop on pitch axis, which would help to improve pilot's situational awareness.

It must be noted that command priority issues can arise when the aircraft is operated on one edge of the climb angle vs. airspeed envelope, if the pilot is acting on both throttle and sidestick. In these circumstances, a suitable priority logic should discriminate the resulting command based on the forces applied by the pilot. For instance, if the Tiltrotor is flown on the envelope edge relevant to available engine power, the pilot can increase the airspeed by pushing the throttle provided that climb angle decreases (*i.e.* the sidestick pitch axis is back-driven forward). Similarly, the pilot could prioritize the climb maneuver by sacrificing the airspeed, and therefore the throttle would be back-driven rearward.

4. CONCLUDING REMARKS

The research project introduced in the present work represents an opportunity for investigating innovative control strategies that can be applied to future Leonardo Tiltrotor products. The problem to be addressed is twofold: on one side it is required to select and consolidate a viable cockpit control allocation strategy that helps to reduce the potentially high workload which can arise in some critical flight phases of a Tiltrotor vehicle such as depart, conversion, approach and landing. The selected strategy should imply a certain set of response types to be associated to each cockpit control axis during each flight phase. From a control law perspective, the goal of enforcing decoupled control responses about the aircraft axes without relying on continuous pilot's corrections appears very challenging due to the significant non-linearities associated to the aircraft configuration changes. On the other side, the designed control strategy must be complemented by a set of ergonomically efficient though kinematically simple cockpit flight controls. The most promising solution identified so far makes use of active side-arm sticks allocated according to an "airplane-style" control strategy. This solution appears suitable for a typical Tiltrotor mission, and it allows to improve system safety by providing prompt tactile warnings. The preliminary control laws design activity carried out in the Phase 1 of EnFCS development highlighted that:

- At hover and low speed, automatic feedforward nacelle command represents a valid option for minimizing the response lag that characterizes longitudinal TRC response if pitch attitude limitation is taken into account. This solution does not require a continuous toggling of pylon conversion actuators rates. Lateral acceleration software limits shall be carefully tuned to prevent the aircraft from reaching undesired bank attitudes, unless the Tiltoror is fitted with lateral cyclic actuators.

- C* control scheme appears as a promising solution for replacing conventional control augmentation system on Tiltrotor aircraft when flying in airplane mode and in the last portion of the conversion corridor. This well known command logic can be augmented by a full-time auto-thrust function to achieve a dual objective: restore an artificial speed stability (C*U) and implement a speed (or acceleration) command response type. A multivariable controller allows to harmonize auto-thrust and flight path angle hold functions.

Future EnFCS design tasks will entail the design of lateral-directional modes and the adaptation of longitudinal airplane mode to conversion corridor. The EnFCS algorithms and the proposed cockpit concept will be evaluated through extensive piloted assessments at the Leonardo Tiltrotor engineering flight simulator facility in Cascina Costa (Italy).

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