AUTOPILOT DESIGN FOR THE ERICA TILT-ROTORCRAFT

Adolfo Sollazzo, a.sollazzo@cira.it, Luigi Federico, l.federico@cira.it, Mariana Poderico, m.poderico@cira.it
The Italian Aerospace Research Centre (CIRA), Capua (CE) Italy

Abstract
The paper discusses the design of a full Autopilot for the ERICA tiltrotor. The structure of the whole control system is implemented by means of classic control technique. The Autopilot envisages several automatic modes, such as the typical hold modes as well as a trajectory following control mode. Both the activation logics of the Autopilot and the automatic nacelle positioning system for the flight envelope protection are also described. The whole control system is implemented in the FLIGHTLAB software environment and it is tested by means of a proper test campaign, whose most significant test simulations results are reported.

1. ACRONYMS & SYMBOLS

A/C	Aircraft
A/P	autopilot
AFCS	Automatic Flight Control System
EAS	equivalent airspeed
ERICA	Enhanced Rotorcraft Innovative Achievement
FD	Flight Director
FSM	Finite State Machine
H/C	Helicopter
IAS	indicated airspeed
SCAS	Stability and Controllability Augmentation System
T/R	tilt-rotorcraft
V/S	vertical speed

2. FOREWORD

The activities of the European research project CleanSky, and in particular the JTI Green Rotorcraft “Environmentally Friendly Flight Paths”, have two main objectives: the reduction of noise and emissions through the optimisation of flight paths. These objectives directly lead to a reduction of CO_2, NO_X as well as fuel consumption for helicopter and tilt-rotor aircraft. Further, the development of new low-noise procedures to minimise the noise perceived on ground during the departure, low-level flight and approach of helicopters and tilt-rotor aircraft.

ERICA is an innovative second-generation T/R for passenger transport, whose key characteristics are the minimum rotor diameter, still compatible with hover performance, and the outboard portion of the wing able to tilt independently of the tilt-able nacelle. This configuration removes the loss of thrust due to the downwash of the rotor on the wing in helicopter mode, giving the opportunity to reduce the rotor diameter in such a way as to improve the cruise performance. Furthermore, the independent tilt freedom allows the outer wing to avoid stall and to supply the suitable amount of lift during the conversion phase. This improves the operational capability of the aircraft, that enjoys more flexibility thanks to a wider corridor, and exploits, for the STOL operations, the possibility of take-off and landing as a conventional airplane.

The comprehensive rotorcraft analysis code applied for the tilt-rotor flight mechanic analyses is FLIGHTLAB, which is a widely used commercial tool based of the flexible-multi-body approach. The features of FLIGHTLAB are fully described in [1], [2] and [3]. The choice of such a comprehensive tool allows to provide in a reasonable CPU time sufficiently accurate aeromechanic results for a large number of flight test simulations.

Figure 1. The ERICA novel concept tilt-rotor.

The dynamic model of ERICA was developed within the NICETRIP European research project. All the model details are included in [4]. The rotor-induced flow dynamics was evaluated by using a finite state wake model ([5], [6]) with 33 state variables producing 4 inflow harmonics. The same wake model was used to evaluate the rotor-on-wing influence only. No mutual interferences nor fuselage interactional effects can be taken into account. A structural dynamic module for a rigid blade with gimbal articulation was applied. The details of the blade and gimbal structural properties are fully documented in [4]. The full model of ERICA provided to CIRA also comprehends a complete AFCS system for the manual augmented piloting mode.
In this paper, both the design of the A/P system for a more automatic piloting mode and the trajectory following mode are presented in sections 3 to 7

Presented at 45th European Rotorcraft Forum, Warsaw, Poland, 17-20 September, 2019

3. AUTOPILOT FUNCTIONAL CONTEXT

The functional context of the ERICA T/R autopilot is reported in Figure 1. This paper is focused on the two main elements of the autopilot (Figure 2, in light blue), the managing logics and the control loops.

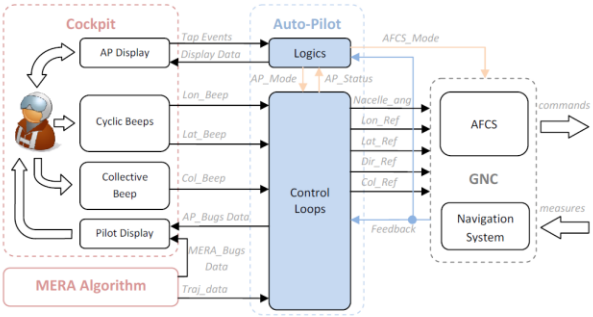

Figure 2. ERICA Autopilot and its functional context.

The pilot interacts with the AP touch-display by tapping the virtual buttons, and thus configuring the automatic behaviour of the vehicle. Moreover, by means of the cyclic and collective beeps, he can adjust the held references for the auto-pilot control loops. Thus, a proper module shall implement the logics of the auto-pilot, by receiving the display events and giving back the announcing data of the current AP configuration. The Logics shall activate the corresponding control loops, which will receive, and eventually use, the reference displacements represented by the cyclic and collective beeps, or in the proper mode by the MERA algorithm. The control loops shall provide the proper reference for the AFCS, whose mode will be activated properly by the A/P logics. Furthermore, the control loops shall provide the currently selected references, depending on the activated mode, to the Pilot display for the bugs driving. The A/P exploits the measurements data coming from the navigation system to allow its control loops work.

4. AUTOPILOT'S MODES AND FEATURES

The proposed A/P for the ERICA T/R relies on the pre-existing low-level attitude control loops, designed to augment and stabilize the T/R, while manually piloted. Thus, the designed A/P exploits the SCAS features to equip the vehicle with the desired automated flight modes, producing in output the four channels of the manual references along with the nacelle positioning command. As already told and evident in Figure 1, the developed modules of the whole system envisage the control loops, to implement each automated flight mode, and the management logic, to activate each possible combination of A/P modes.

The provided A/P has both basic hold modes, for pitch angle, roll angle, heading angle, IAS, V/S and altitude, and navigation modes, in terms of IAS, heading angle and altitude. These modes serve the trajectory following mode, called ECOLAND, whose reference trajectory is provided by a proper algorithm, called MERA, designed and implemented by NLR. Moreover, the provided A/P has also the automated management of engine nacelles positioning.

5. AUTOPILOT MAIN ARCHITECTURE

The main architecture of the proposed A/P for ERICA T/R is depicted in Figure 3.

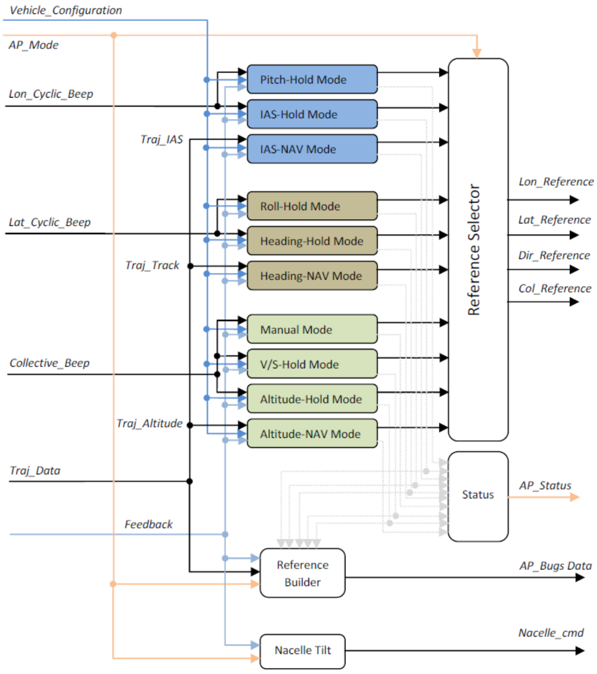

Figure 3. Control Loops main architecture.

Several elements are evident in the mentioned figure, In particular, the control modules, described in the following subsections, implement the specific automated flight modes of the A/P.

The reference selector is the module in chair to deal with references, produced by the control loops, to process them, depending on the current nacelle angle positioning, and to produce the proper references for the SCAS. Further, the module for the automatic nacelle positioning cares of engines nacelles command, depending on the current EAS value, and acts to keep the vehicle inside the safe flight envelope. Finally, the module for the A/P display feedback operates to represent the current A/P setting on the pilot's display. This last section of the A/P is out of the scope of this paper, being of less interest. In the next subsections, the main parts of the A/P are addressed and described in details.

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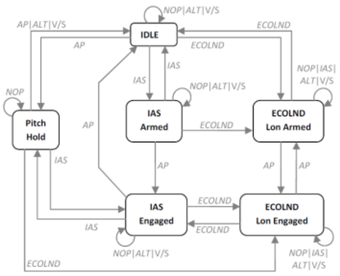
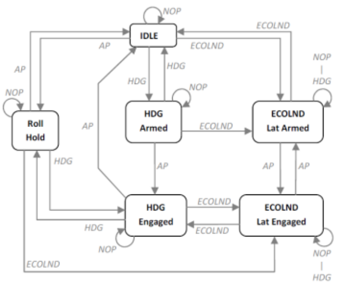
5.1. The Logics

The Logics is in charge to manage the A/P modes activations, as well as to animate the A/P display, by means of feed backing the status and data useful to understand the current behaviour of the T/R. The Logics is made of three sections, respectively named as Longitudinal Command Channel Logics (LoCC), Lateral Command Channel Logics (LaCC) and Collective Command Channel Logics (CCC).



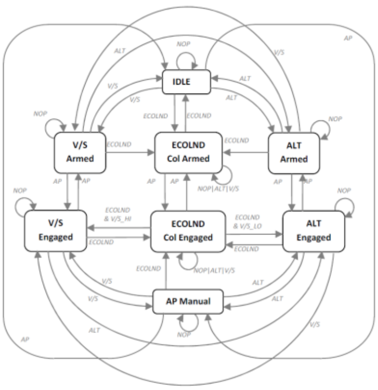
State	Meaning
IDLE	No auto-pilot mode is armed or engaged
Pitch-Hold	Default auto-pilot mode is engaged
IAS Armed	IAS-Hold mode is armed, but not engaged
IAS Engaged	IAS-Hold mode is engaged
ECOLND Lon Armed	ECOLND mode is armed, but not engaged, on the longitudinal channel
ECOLND Lon Engaged	ECOLND mode is engaged on the longitudinal channel
Event	Meaning
NOP	No tap event on the touch display
IAS	IAS virtual button has been tapped
ECOLND	ECOLND virtual button has been tapped
ALT	ALT virtual button has been tapped
V/S	V/S virtual button has been tapped
AP	AP virtual button has been tapped

Figure 4. Logics of Auto-Pilot longitudinal command channel.



State	Meaning
IDLE	No auto-pilot mode is armed or engaged
Roll-Hold	Default auto-pilot mode is engaged
HDG Armed	Heading-Hold mode is armed, but not engaged
HDG Engaged	Heading -Hold mode is engaged
ECOLND Lat Armed	ECOLND mode is armed, but not engaged, on the lateral channel
ECOLND Lat Engaged	ECOLND mode is engaged on the lateral channel
Event	Meaning
NOP	No tap event on the touch display
HDG	HDG virtual button has been tapped
ECOLND	ECOLND virtual button has been tapped
AP	AP virtual button has been tapped

Figure 5. Logics of Auto-Pilot lateral command channel.



State	Meaning
IDLE	No auto-pilot mode is armed or engaged
V/S Armed	Vertical speed hold is armed, but not engaged
V/S Engaged	Vertical speed hold is engaged
ALT Armed	Altitude hold is armed, but not engaged
ALT Engaged	Altitude hold is engaged
ECOLND Col Armed	ECOLND mode is armed, but not engaged, on the collective channel
ECOLND Col Engaged	ECOLND mode is engaged on the collective channel
Event	Meaning
NOP	No tap event on the touch display
V/S	V/S virtual button has been tapped
ECOLND	ECOLND virtual button has been tapped
AP	AP virtual button has been tapped
ALT	ALT virtual button has been tapped

Figure 6. Logics of Auto-Pilot collective command channel.

The charts of the FSMs of each of the control logics are reported respectively in Figure 4, Figure 5 and Figure 6. The three FSMs are based on the typical armed-activated concept, typically used in the autopilots to activate/deactivate each mode. Thus, by means of proper buttons, the corresponding modes are armed, and when the A/P is finally activated, by pressing the proper button, the armed mode gets engaged.

5.2. The Control Loops

The Control Loops modules (see Figure 3) is made of ten modules, implementing each one of the A/P modes, the full list is here reported:

- Hold: IAS, Pitch, Altitude, V/S, Roll, Heading;
- NAV: IAS, Heading, Altitude;
- Manual mode.

In the following, some details about the control structure and the gains of each control module are given.

5.2.1. Pitch Hold Mode

The pitch-hold mode has a proportional control structure [7] for the pitch angle. The gains are scheduled with the airspeed and nacelle angle and are reported below (Table 1).

*(m/s), °(%/deg)

IAS*	<20	40	80	>100
K90P°	-0.5	-0.5	-0.67	-1
IAS*	<50	80	110	>140
K0P°	-0.45	-0.5	-0.57	-0.67

Table 1. Pitch-hold mode gain scheduling.

5.2.2. IAS Hold Mode

The planar IAS-hold mode has a proportional and integral control structure [7] for the planar IAS. The gain scheduling is reported below (Table 2).

*(m/s), °(%/m*s-1)

IAS*	0	10	26	41	62	77	93	113	124
KP0°	8					5.6	4.8	3.2	2.8
KP30°	6					4	3.6	2.4	
KP40°	0								
KP75°	-0.4	-1.6	-3.2	-2	-1.2				
KP90°	-0.4	-2.4	-4	-3.2	-0.4				
KI0°	0.16								
KI40°	0								
KI90°	-0.6								

Table 2. IAS-hold mode gain scheduling.

5.2.3. IAS NAV Mode

The IAS NAV mode implements the planar speed control of the ECOLAND mode, its structure and gain scheduling is the same of the IAS Hold mode reported in Table 2.

5.2.4. Roll Hold Mode

The Roll-Hold mode has a Proportional control [7] structure for the roll angle regulation, thus providing the lateral reference and an always zero directional reference. The gain scheduling is reported below (Table 3).

*(m/s), °(%/deg)

IAS*	10	26	41	62	77	93	113	124
KP0°	1			6.5	6		5	4
KP90°	2.5	8	0.9	1				

Table 3. Roll-hold mode gain scheduling.

5.2.5. Heading Hold Mode

The Heading-Hold mode exhibits a control structure made of two nested loops. The inner one is a proportional [7] roll angle control loop, while the outer one is a heading angle proportional and integral control action [7]. The scheduling of all the control gains is reported below (Table 4).

*(m/s), °(%/deg)

IAS*	10	26	41	62	77	93	113	124
Roll angle Proportional Control Action								
KP0°	1			6.5	6		5	4
KP90°	2.5	8	0.9	1				
Heading angle Proportional and Integral Control Action								
KP0°	1			7				
KP90°	0.5	1.5	1.3	1				
KI0°	1			0.8				
KI90°	0.1	0.25	0.14	1				

Table 4. Heading-hold mode gain scheduling.

5.2.6. Heading NAV Mode

The Heading NAV mode, whose name is quite improper, being a lateral trajectory tracker, is made by three nested loops. The inner control loop is for the roll angle regulation, the middle one is for the ground-track angle regulation while the outer modifies the ground-track angle reference, provided by the MERA, by regulating to zero the cross track deviation. The scheduling of all the control gains is reported below (Figure 7 and Table 5).

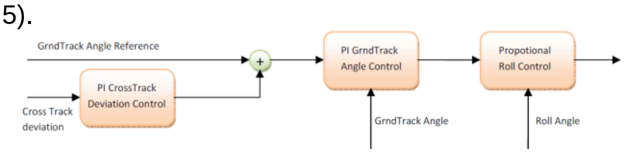


Figure 7. Heading NAV Mode control structure.

*(m/s), °(%/deg), ^(%/NM)

IAS*	10	26	41	62	77	93	113	124
Roll angle Proportional Control Action								
KP0°	1			6.5	6		5	4
KP90°	2.5	8	0.9	1				
Heading angle Proportional and Integral Control Action								
KP0°	1			7				
KP90°	0.5	1.5	1.3	1				
KI0°	1			0.8				
KI90°	0.1	0.25	0.14	1				
Cross Track deviation PI Control Action								
KP^	-70							
KI^	-0.15							

Table 5. Heading-NAV mode gain scheduling.

5.2.7. Manual Mode

The manual mode implements a manual collective command, thus no control loops are present in this module.

5.2.8. Vertical Speed Hold

The vertical speed hold mode implements a proportional control structure [7] for the rate of climb. The gains scheduling is reported below (Table 6).

*(m/s), °(%/m*s-1)

IAS*	0	10	26	41	62	77	93	113	124
Vertical Speed Proportional Control Action									
KP0°	6					2.5	2	0.9	
KP30°	8					3.5	3		
KP50	10					5	4		
KP75	12								
KP90	16								

Table 6. Vertical Speed-hold mode gain scheduling.

5.2.9. Altitude Hold Mode

The altitude hold mode is made of two nested control loops. The inner is a proportional [7] action for climb rate, while the outer is a proportional and integral control action [7] for the altitude. The scheduling of control gains is reported below (Table 7).

*(m/s), °(%/m*s-1), ^(%/m)

IAS*	0	10	26	41	62	77	93	113	124
Vertical Speed Proportional Control Action									
KP0°	6					2.5	2	0.9	
KP30°	8					3.5	3		
Kp50°	10					5	4		
Kp75°	12								
Kp90°	16								
Altitude Proportional and Integral Control Action									
KP0°	0.8								
KP90°	2								
KI^	0.16								

Table 7. Altitude-hold mode gain scheduling.

5.2.10. Altitude NAV Mode

The altitude NAV mode has the same control structure of the corresponding hold mode as well as the same gain scheduling. This mode is the altitude component of the ECOLND mode for trajectory tracking.

5.3. Reference Selector

The reference mixing module has the goal of harmonizing the commands of the T/R, despite the change of the configuration due to the nacelles rotation, thus allowing the automatic control by means of the same control loops for all the configurations of the vehicle. This is only necessary for the longitudinal commands, not for the lateral and directional ones. Indeed, due to the action of the basic-gearing module, the collective command of the two rotors moves from affecting mainly the speed in A/C configuration, to affect the vertical speed and the vertical position, in H/C

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configuration. Similarly, the longitudinal cyclic command of the two rotors is mainly assigned to the longitudinal attitude in both A/C and H/C configuration, thus affecting the vertical speed and position, when in A/C mode, and the planar speed in H/C mode. It is evident the necessity to mix the outputs of longitudinal control loops (ROC and Altitude) along with the speed command to produce both the equivalent longitudinal manual commands. The only exception is the pitch-hold output, which is linked to the longitudinal cyclic command, coherently to the aforementioned command allocation. The used mixing functions are square of sine and cosine, due to their sum equals one and their derivability properties.

(1) $x_b = \delta_e \cdot cos^2\alpha + \delta_t \cdot sin^2\alpha + \hat{x}_b;$

(2) $x_c = \delta_e \cdot sin^2\alpha + \delta_t \cdot cos^2\alpha;$

where α is the nacelle positioning angle (0 deg is A/C configuration and 90 deg is H/C configuration), δ_e is the command results of any altitude mode or V/S control and δ_t is command coming from any IAS control mode. Moreover, $\hat{x}_b$ is the result of the pitch hold control, x_b is the equivalent longitudinal cyclic command for the two rotors, and x_c is the equivalent collective command for the two rotors.

5.4. The Nacelle Control

The nacelle control module provides the automatic nacelle positioning feature in a very basic manner. This system allows a careless positioning of the nacelle, thus making the pilot free from the necessity to care about the nacelle operation, or enabling the A/P to properly work without the assistance of a human pilot. Here a detailed description of the system is reported.

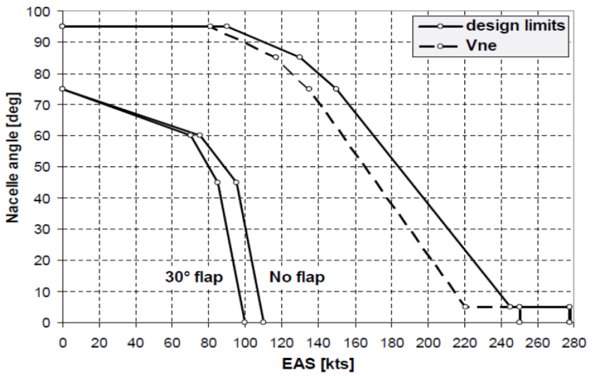

Figure 8. Safe flight envelope in terms of EAS vs Nacelle angle.

Regardless to flap, tilt-able wings and any other secondary commands, the system preserves the vehicle from EAS limits violations, reported in Figure 8. Thus, an upper and a lower limit is set in terms of EAS with reference to any possible nacelle positioning. When the lower or upper limit is violated a move up or down request is generated and the corresponding command is held high up to the next detent position is reached. It has preferred to adopt the logic to ignore any further request arising, while conversion is already on the way, so the EAS ranges for each nacelle positioning (0°, 75°, 90°, 95°) are properly overlapped to provide more safety. In Figure 9, it is depicted the reference generation for the nacelle positioning, which uses a hysteresis control scheme to generate the two logical commands *aft* and *fwd* for the nacelle operations. Following a brief description is reported. The elements, in the lower left section of the figure, allow the system to recognize the initial nacelle position. The first two inputs in the upper left corner of figure represent the logical signals of lower and upper EAS limit violation events, which produce the pulse signals of move aft and move forward. The third input signal is the current positioning error, used to produce the detent acquired signal, which enables the move aft or forward signals. Finally, a memory element, initialized as aforementioned, stores the current detent level (one of [1, 2, 3, 4] corresponding to [95°, 90°, 75°, 0°]) and is modified by the move aft or forward signal.

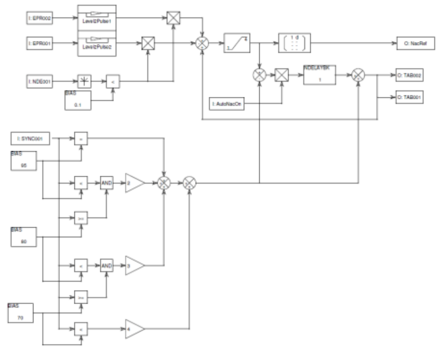

Figure 9. Reference generator for nacelle positioning.

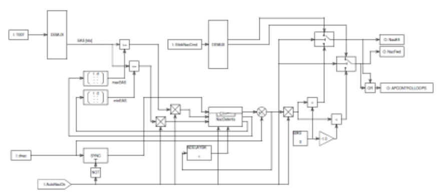

Figure 10. First level architecture of nacelle control system.

This positioning logic is used in the full automatic nacelle positioning system, which recognizes the high-EAS and low-EAS events, samples the current nacelle positioning and uses this data for the nacelle repositioning.

5.5. Remarks

The ERICA model is implemented in FlightLab. It is an extremely complete as well as complex model

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able to reproduce well the dynamics of a T/R. Even though the software environment allows to linearize the implemented models, some of the elements added in times by several contributors made this task really hard. Thus, not to lose any of the vehicle dynamics, it was preferred a trial and error technique to adjust each of the control gains. This manner, the design of the whole A/P did not followed the typical design process, getting extremely time consuming. Moreover, the final design does not guarantee the typically required robustness characteristic as well as very good performance levels. Nonetheless, the final result is a complete A/P and quite good in terms of performances. Regarding the robustness capability further test campaign shall demonstrate the real ability of the design.

6. DESIGN VERIFICATION

During the design the A/P has been fully tested to evaluate performances of each implemented mode as well as the activation logics and the automatic nacelle positioning for the flight envelope protection. In this section, some significant results of a test campaign are reported to validate the A/P and to show its performance capabilities.

6.1. Test Cases

The chosen test cases, to evidence the performance of the A/P, are described in details below (Table 8 and Table 9). The two cases have been selected for the completeness of maneuver they represent and the amplitude of the flight envelope investigated.

Test Case 1: Large speed variation	
T/R initial mode	A/C Mode, Nacelle angle 0 deg
Trim condition	IAS = 200 kts; Altitude = 5000 ft;
Description of maneuver	IAS reference to track: decrease of 160 Knots with a negative slope of -1knots/s, followed by a ramp with a positive slope of +1Knots/s for an overall increase of 180 Knots

Table 8. Detailed description of test case 1.

Test Case 2: Large speed variation	
T/R initial mode	H/C Mode, Nacelle angle 90 deg
Trim condition	IAS = 60 kts; Altitude = 750 ft;
Description of maneuver	IAS reference to track: increase of 40 Knots with positive slope of 1 knots/s, followed by a ramp with a negative slope of -1 knots/s for a decrease of 80 Knots.

Table 9. Detailed description of test case 2.

6.2. Numerical Simulations

Test case 1, described in Table 8, represents a comprehensive test for the A/P, due to the fact it investigates a wide portion of the flight envelope, testing the capability of the activated control loops as well as the automatic nacelle positioning system. In this test case, the ECOLAND mode is activated, that is to say the NAV modes. Thus, the T/R shall follow the IAS, altitude and heading angle profile. While no variation is demanded for altitude and heading angle, Figure 11 reports the IAS demand profile along with the actual profile. The performances are quite good along all the IAS demand profile, but two extremely evident points. The former, while reducing speed, the vehicle needs to change configuration from A/C to H/C, thus this phase represent a strong disturbance not properly managed by control loops but anyway acceptable. The same happens while increasing, and the vehicle needs to convert from H/C to A/C. All this is evident in Figure 12, where the whole maneuver is depicted along with the limits of the safe flight envelope. As it is evident in Figure 13, altitude variation is not significant during the maneuver, the same is true for the heading angle, thus it is not represented for the sake of brevity.

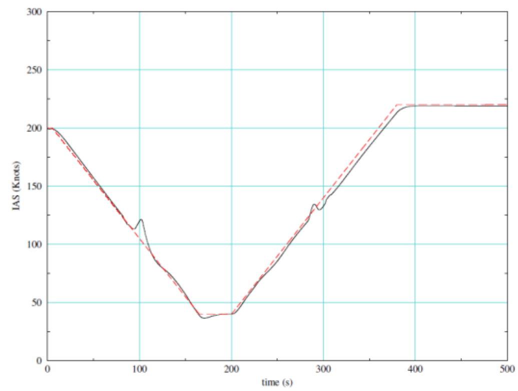

Figure 11. IAS demand profile (red dashed line) and actual T/R IAS time-history (black solid line).

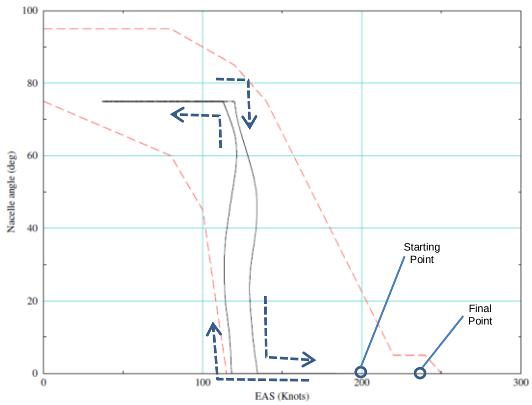

Figure 12. Maneuver (black solid line) represented in the safe flight envelope (limits in red dashed lines).

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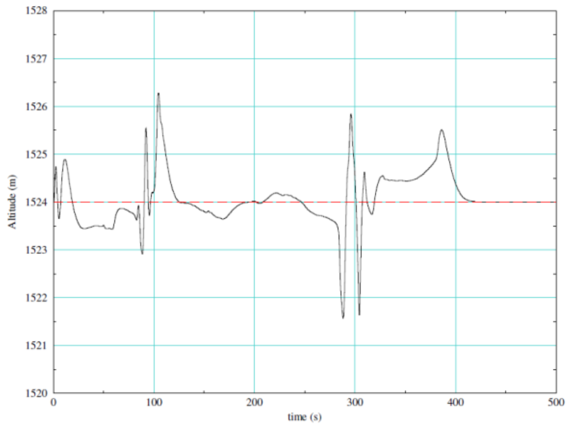

Figure 13. Altitude reference (red dashed line) and actual time-history (black solid line).

Test case 2 results are here discussed. In this case, again, ECOLAND is activated and only a speed variation is requested. Figure 14 reports the IAS demand profile and the actual speed behavior. Again, a quite good performance is evidenced, except for the conversion phase. Indeed, comparing the IAS behavior with the actual nacelle angle positioning (see Figure 15), it is evident how the speed control performances deteriorate during the transient of nacelle repositioning.

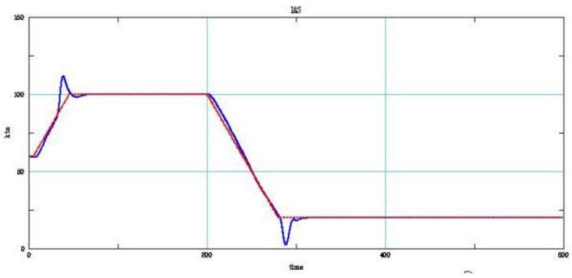

Figure 14. IAS demand profile (red dotted line) and actual IAS time-history (blue solid line).

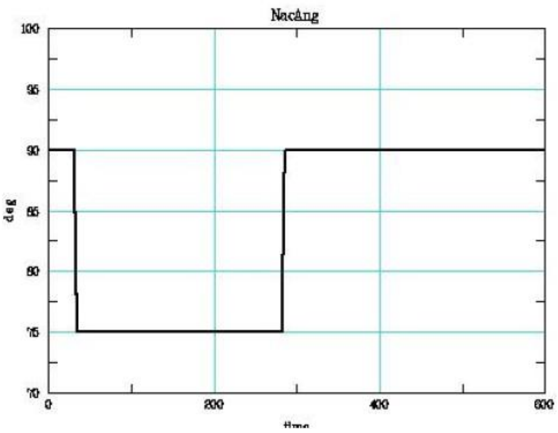

Figure 15. Actual nacelle angle time-history.

In the following Figure 16, it is reported the heading angle whose variation is negligible and enough to keep the cross-track deviation null.

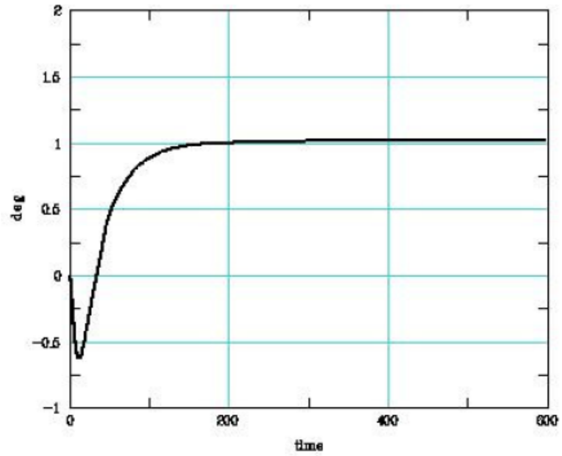

Figure 16. Actual heading angle time-history.

7. CONCLUSIONS

The proposed design of a full A/P for the ERICA T/R has been presented and discussed. The structure of the whole control system is implemented by means of classic control technique, while the control gains have been scheduled by means of the trial and error method due to several problem, arose and addressed in the paper. The Autopilot envisages several automatic modes, such as the typical hold modes, as well as a trajectory following control mode. Both the activation logics of the Autopilot and the automatic nacelle positioning system for the flight envelope protection have been described. The whole system has been developed in the FLIGHTLAB software environment and it has been tested by means of a proper test campaign. The most significant test simulations results, reported and fully discussed, demonstrate the good performance of the proposed A/P.

8. REFERENCES

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Presented at 45th European Rotorcraft Forum, Warsaw, Poland, 17-20 September, 2019