PERFORMANCE CODE FOR TAKE-OFF AND LANDING TILT-ROTOR PROCEDURES STUDY

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Abstract

The present study investigates steady and unsteady performance of a generic tilt-rotor thanks to a simulation code. A pilot model integrated in the code allows to simulate take-off and landing procedures including engine failure and respecting safety criteria (safety heights and speeds). This work is based on the EUROPA code (EUropean ROtorcraft Performance Analysis) elaborated for helicopters within the European project RESPECT (Rotorcraft Efficient and Safe ProcEdures for Critical Trajectories) that ended in 2000 [1,2]. The paper first focuses on the tilt-rotor modeling used to adapt the EUROPA code, originally built for helicopters, to a tilt-rotor. The main characteristics of a tilt-rotor are taken into account (two contrarotative rotors that can be tilted, a wing with trailing edge flaps, interaction phenomena, controls and pilot model adapted to the different flight configurations : helicopter, airplane and conversion). Some performance results generated by the modified code are presented to enhance the role of the main tilt-rotor parameters on the flight behavior of the aircraft for every flight configuration. Conversion corridors are studied to elaborate conversion strategies and some take-off and landing procedures are simulated with and without engine failure.

Notation

C_D	drag coefficient
C_t	rotor thrust coefficient
DL	wing download, N
d_{nac}	nacelle tilt angle, ° (rad)
K	interaction coefficient
S	wing surface impacted by the rotor flow, m²
T	rotor thrust, N
V_{ac}	aircraft speed, m/s
V_i	rotor mean induced velocity, m/s
V_{TOSS}	Take-Off Safety Speed, kts
V_Y	speed of best rate of climb
α	wing incidence, ° (rad)
α_e	tailplane local incidence, ° (rad)
α_0	wing zero-lift angle, ° (rad)
Δ_e	tailplane setting, ° (rad)
δ_f	wing flap deflection angle, ° (rad)
ε	deflection angle, ° (rad)
η_l	pilot cyclic stick position
ρ	air density, kg/m^3
θ_s	rotor longitudinal cyclic pitch, ° (rad)
AEO	All Engine Operative
OEI	One Engine Inoperative

Introduction

The use of civil tilt-rotors has been envisaged as an interesting solution to decrease airports congestion and to improve the efficiency of short airlinks traffic. Tilt-rotors have two rotors mounted on nacelles able to tilt from 90° to 0° which provide them with the combined advantages of helicopters and turboprop airplanes. In airplane mode (nacelles tilted at 0°), tilt-rotors can reach cruise flight speeds comparable to turboprop airplanes and their Vertical and Short Take-Off and Landing (VSTOL) capabilities reduce take-off and landing time and distances. Tilt-rotors could therefore operate in smaller areas than classical runways or in confined spaces and replace part of the commuter aircrafts of low capacities [3,4].

Even though the benefit of integrating civil tilt-rotors into the airspace system has been demonstrated [5,6], until now, few studies have been carried out regarding take-off and landing procedures of tilt-rotors. The purpose of the present paper was to study steady and unsteady performance of a generic tilt-rotor thanks to the simulation code EUROPA modified for tilt-rotors. Coupled to a pilot model, the code is able to simulate take-off and landing procedures with and without engine failure. This work was based on the EUROPA code developed for helicopters within the scope of the European project RESPECT (Rotorcraft Efficient and Safe ProcEdures for Critical Trajectories) that ended in 2000.

The first part of the paper describes the modeling used to adapt the EUROPA code originally dedicated to helicopters for the case of a tilt-rotor. The main characteristics of a tilt-rotor were taken into account : a classical aircraft configuration with at wing tips two rotors which are mounted on nacelles able to tilt from 90° (helicopter mode) to 0° (airplane mode) including a conversion phase, strong aerodynamic interaction phenomena at low speeds between the rotors and the wing, controls and pilot model adapted for any flight configurations (helicopter, conversion and airplane). The models implemented in the EUROPA code are simple enough to allow fast calculations. A more detailed modeling description is given in the previous paper [7].

The second part presents some steady performance results generated by the modified code. The effect of some tilt-rotor parameters (such as wing flap deflection for example) on the performance of the aircraft is studied for every flight configuration. Conversion corridors are elaborated to determine the tilt-rotor flight boundaries during the nacelles tilting and to define some piloting strategies for conversion.

The last part focuses on the take-off and landing procedures simulation thanks to the pilot model integrated in the code. The main objectives are to study the influence of the nacelles tilting during the take-off maneuver and the flight behavior of the tilt-rotor in case of an engine failure.

The tilt-rotor considered in this study is a generic tilt-rotor (aircraft weight of 10 tons, two 3-bladed rotors with a rotor diameter of 5 meters).

Tilt-rotor modeling in EUROPA

The current modeling concerns a tilt-rotor in a symmetrical configuration restricted to a motion in the longitudinal plane.

Rotors modeling

The modeling of the two contrarotative rotors is similar to the one used to model the main rotor in the helicopter code. It is an analytic model which computes forces and moments, blade flapping, mean induced velocity and power of every rotor from collective and cyclic pitch controls and geometric parameters for the rotor and the blade [8].

Wing and fuselage aerodynamic modeling

In the present approach, the wing and the fuselage form only one aerodynamic model. The semi-empirical modeling uses aerodynamic coefficients, which can come from either wind tunnel tests data or estimations. They must include values for small and also large incidences corresponding to steep or vertical climb and descent. Trailing edge flaps are taken into account. They have a double function in the tilt-rotor case : flaps act as high-lift devices and they are also used to reduce the wing download (penalizing interaction between rotor wake and wing, described below) at low speeds.

Nacelles modeling

The two nacelles are located at wing tips and can tilt from 90° to 0° angle. The nacelles modeling is necessary because they increase significantly the aircraft global drag. The model is based on the same principle as the wing-fuselage one : aerodynamic forces and moments are computed from either wind tunnel tests data or estimations.

The rotors and nacelles tilting leads to several modifications both at geometrical and inertial levels. Actually, they can represent 5 to 10% of the aircraft weight and therefore modify the tilt-rotor center of gravity position in a significant way when nacelles and rotors tilt forward from 90° to 0° position.

Aerodynamic interactions

Wing download in hover and low speed flight In hover and low speed flight, the rotors wake impinges the wing located below creating a force opposed to the lift named download (Figure 1). The wing download can represent 10 to 15% of the total rotor thrust in hover and decreases with the tilt-rotor speed which sweeps back the rotor wake. The download depends on different factors such as the wing flap deflection, the nacelle tilt angle or the rotor-ground distance.

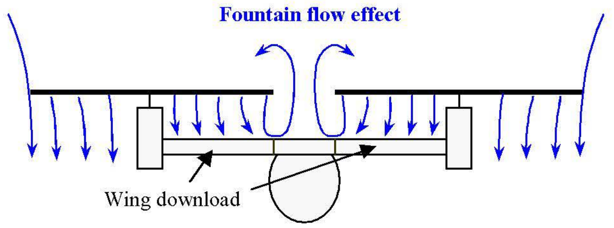


Figure 1. Wing download and fountain flow effect phenomena present on a tilt-rotor

The method uses a semi-empirical model based on interpolation of published or estimated data curves in hover and for 90° nacelle tilt angle [9,10]. The first curve provides the evolution of the download in hover normalized by the rotor thrust (DL/T) as a function of the rotor thrust coefficient. The second curve gives the download normalized by the download at 0° flap deflection versus flap setting (published data).

According to these two curves, the resulting download in hover takes into account the wing flap deflection and the rotor thrust coefficient as described on Figure 2.

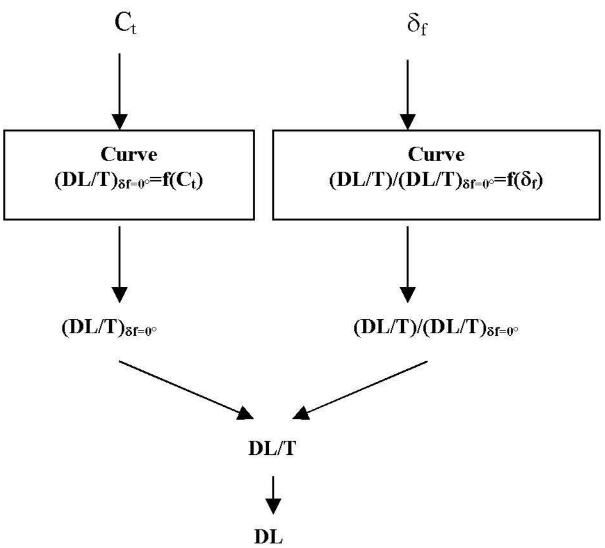


Figure 2. Download computation in hover

From the download value in hover, the model then computes the evolution of the download with both the nacelle tilt angle and the aircraft speed considering that the interaction disappears at a certain speed limit, V_{lim} (V_{lim}≈30m/s).

$$DL = DL_{hover}\left(1-\sin^2\left[\frac{\pi . V_{ac}}{2 . V_{\lim}}\right]\right)\sin d_{nac}$$

Figure 3 enhances the influence of wing flap deflection on download reduction. It can be optimized in order to minimize the download at low speeds and the needed total power for each flight case (refer to the following paragraph on steady performance).

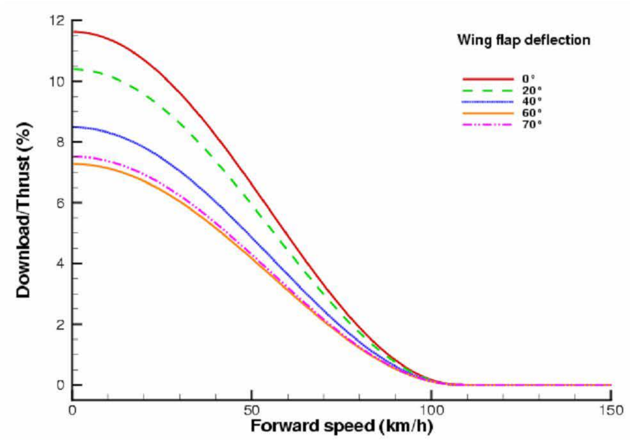


Figure 3. Download versus forward speed for different flap deflections (helicopter mode)

<u>Ground effect on wing download</u> When a tilt-rotor approaches the ground, the rotors wake impacts the ground with a “fountain flow effect” on the ground that lifts up the aircraft and therefore decreases the download (Figure 4).

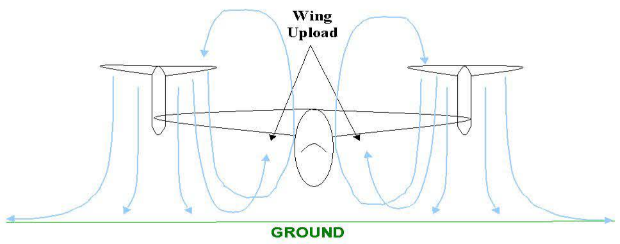


Figure 4. Ground effect on a tilt-rotor

This ground effect on the download is also implemented in the code using published data [10] on the evolution of the download with the rotor height above the ground. Typical results for helicopter mode in hover case are presented on Figure 5.

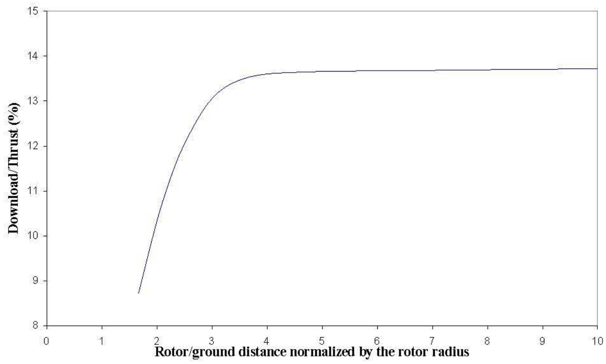


Figure 5. Ground effect on download in helicopter mode for hover case

<u>Wing deflection on tailplane</u> Downstream of the wing, the flow is deflected by the wing and its wake and then modifies the tailplane local incidence. This deflection angle ε has to be taken into account to compute the tailplane local incidence (Figure 6).

$$\alpha_e = \Delta_e + \alpha - \varepsilon$$

with, α_e the tailplane incidence
Δ_e the tailplane setting relatively to the wing
α the wing incidence

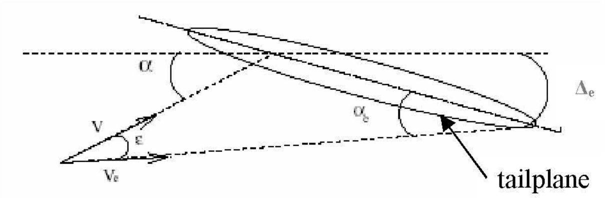


Figure 6. Scheme of the tailplane flow

The deflection angle ε can be computed using the classical Prandtl theory and is therefore function of the wing span, the wing lift coefficient, the aspect ratio of the wing and the wing-tailplane distance.

<u>Controls</u>

<u>Pilot controls</u> For the tilt-rotor, the motion in the longitudinal plane is operated by the fore/aft longitudinal stick and the collective lever. These two controls act on rotors or/and on aerodynamic control surfaces according to the flight configuration [11].

In helicopter mode, pitch moment and forward translation are accomplished by the fore/aft stick motion controlling both the rotor longitudinal cyclic pitch and the elevator. The elevator can be used to alleviate the rotors load. The vertical translation is operated by the collective lever acting on the rotor collective pitch to increase the thrust (Figure 7).

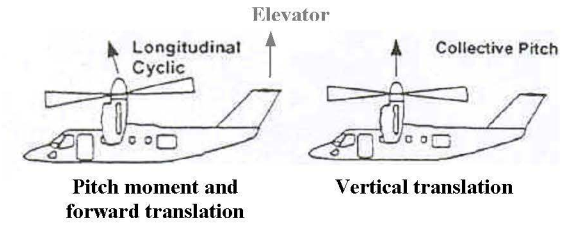


Figure 7. Longitudinal controls in helicopter mode

In airplane mode, the motion in pitch is totally induced by the elevator, as on conventional airplanes, operated by the fore/aft stick motion. Forward acceleration is made possible by an increase of horizontal thrust controlled by the collective lever (Figure 8).

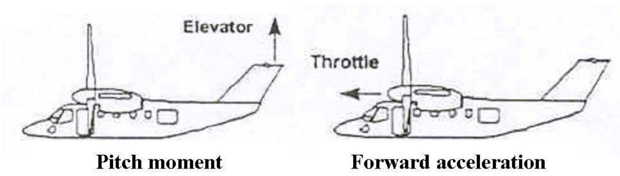


Figure 8. Longitudinal controls in airplane mode

During conversion from helicopter mode to airplane mode, the controls ensuring the motion in the longitudinal plane are a combination depending on nacelle tilt angle of the controls used for helicopter mode and for airplane mode. Predominant in helicopter mode, the rotor control decreases with nacelle tilt angle. In this study, a sine function has been used:

$$\theta_s = f(\eta_l)\sin d_{nac}$$

<u>Trim procedure</u> In order to trim the aircraft, tilt-rotor controls are adjusted to minimize the aircraft linear and angular accelerations. Trim procedures have to be adapted to the different flight configurations of the tilt-rotor.

In this way, the vertical acceleration is controlled by the collective lever in helicopter mode and by the aircraft attitude via the longitudinal stick for airplane mode. The longitudinal acceleration is controlled by the attitude via the longitudinal stick in helicopter mode and by the collective lever in airplane mode. As for the pilot model, trim controls are a combination depending on the nacelle tilt angle of controls for helicopter mode and airplane mode.

<u>Engine model</u>

The engine model used is fairly simple. It allows to maintain a constant rotor speed at 100% or at a target value after an engine failure with a feedback logic chosen to give expected realistic engine response.

Steady performance and conversion corridor computation

Steady performance

The modified EUROPA code provides steady performance results of the tilt-rotor in any flight configuration. The evolutions of pitch attitude and total power versus forward speed are plotted on Figures 9 and 10 at 0° of wing flaps deflection. The tilt-rotor performance are compared for different nacelles tilt angles from the helicopter mode (90°) to the airplane mode (0°) with intermediate nacelles positions during the conversion phase. The nacelles tilting capability allows the tilt-rotor to fly over a large range of speeds from the hover mode until more than 500 km/h in cruise flight.

Figure 11 shows the evolution of total power in helicopter mode for different wing flaps settings. A deflection of about 60° improves the tilt-rotor performance in helicopter mode in hover due to the decrease of the download as the wing flaps are deflected. In forward flight, for a speed above 50 km/h, a wing flaps deflection between 20° to 40° seems to be beneficial in terms of performance. In airplane mode, the best configuration is obtained at 0° or 10° of wing flaps deflection because the two curves offer very similar performance as shown on Figure 12. In this case, the evolution of pitch attitude (Figure 13) can give additional information about the wing flap to set in airplane mode : 10° of flap deflection allows the aircraft to fly at low speeds delaying the wing stall, 0° of flap deflection induces aircraft attitudes close to 0° preferable for passengers comfort. Such results enhance the influence of wing flaps deflection on the tilt-rotor performance and moreover the need to adapt the wing flaps deflection for every flight configuration. In this way, a wing flaps deflection law as a function of forward speed has been implemented in the code in order to optimize the tilt-rotor performance for every flight phases (Figure 14).

Conversion corridor

Conversion corridor is a particularity of a tilt-rotor. It defines the range of possible aircraft speeds for each nacelle tilting angle by taking into account some limits such as wing stall (or aircraft pitch attitude) for the lower limit, and power and flapping for the upper limit of the corridor. The purpose of such a corridor is to give an overview of aircraft flight boundaries and it must be as large as possible to provide a good and safe piloting strategy for conversion.

Figure 15 gives an example of conversion corridor obtained for 10° of wing flaps setting. The total power or the pitch attitude distributions within the corridor are important criteria used to define conversion strategies. For example, Figure 16 shows the iso-pitch line at 0° which can be followed to ensure a safe conversion in terms of respect of flight boundaries and also passengers comfort.

The wing flaps deflection has an important effect on the lower limit of the conversion corridor. By delaying the wing stall limit, wing flaps deflection allows the tilt-rotor to fly at lower speeds. This effect is illustrated by Figure 17. As the wing flaps deflection increases, the lower limit of the corridor moves to lower speeds making it wider until the optimum value of about 60° of flaps setting .

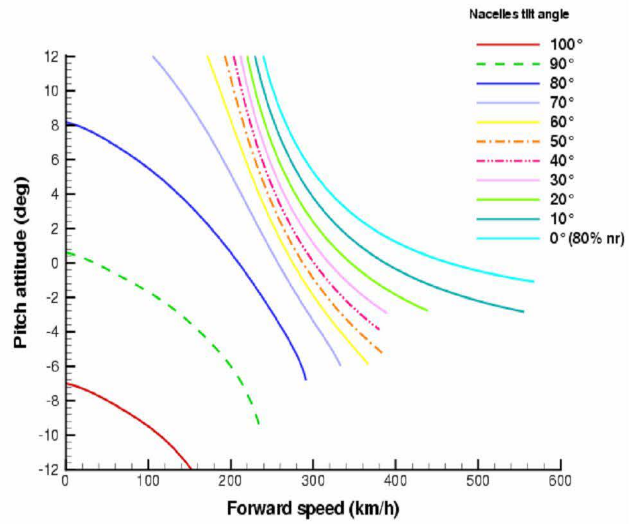


Figure 9. Pitch attitude evolutions versus forward speed for different nacelles tilt angles

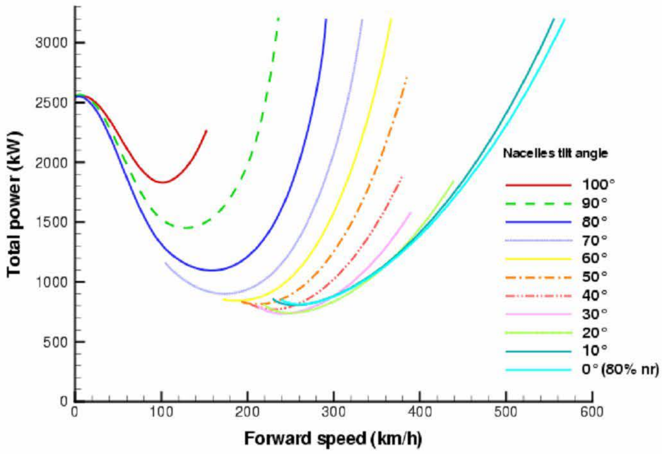


Figure 10. Total power evolutions versus forward speed for different nacelles tilt angles

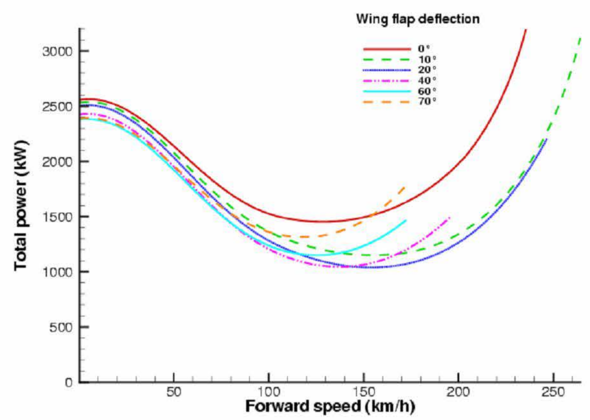


Figure 11. Total power versus forward speed in helicopter mode

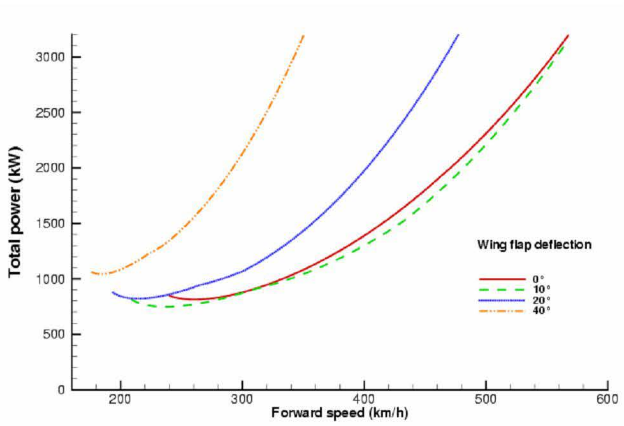


Figure 12. Total power versus forward speed in airplane mode

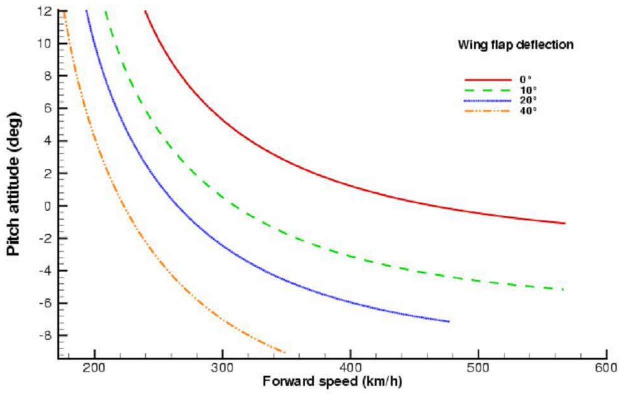


Figure 13. Pitch attitude versus forward speed in airplane mode

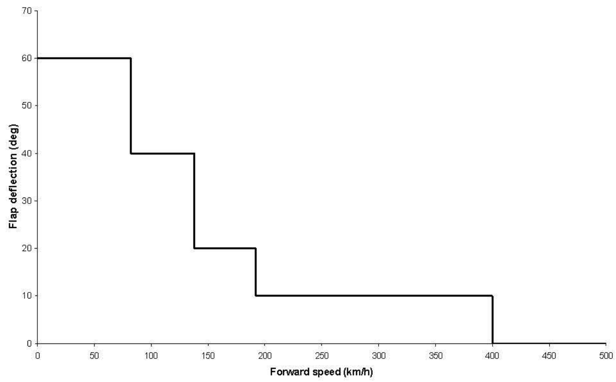


Figure 14. Flap deflection law

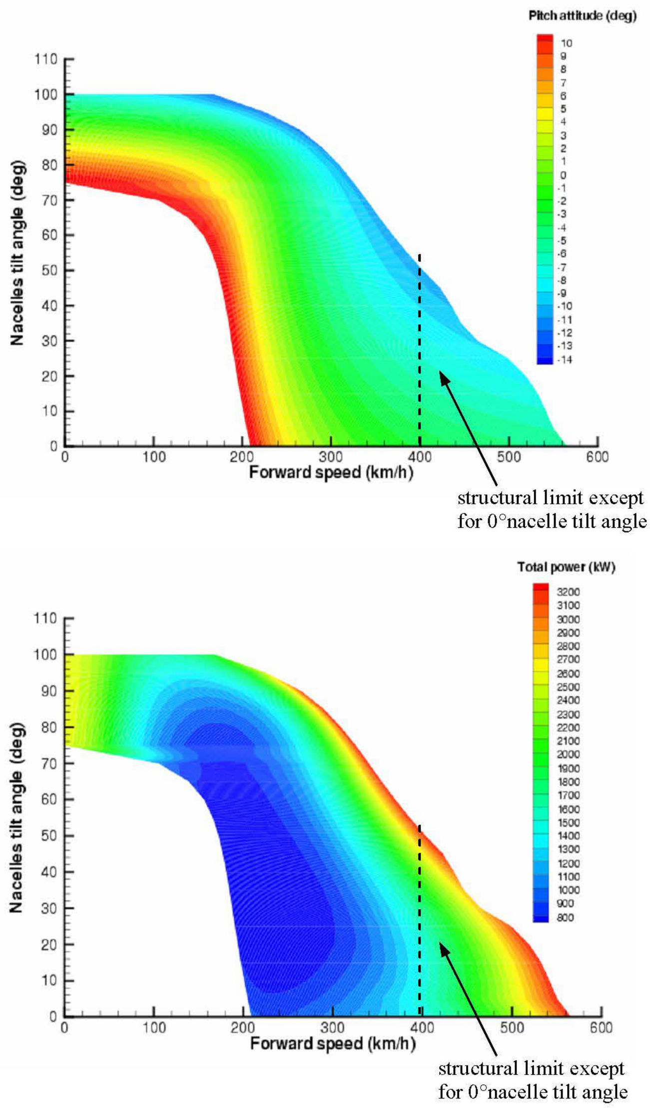


Figure 15. Conversion corridors at 10° wing flap deflection

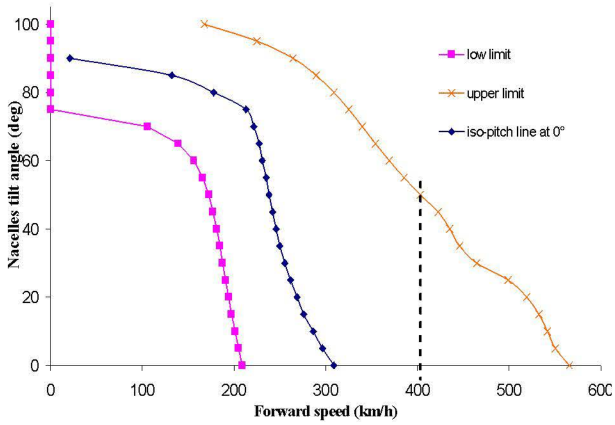


Figure 16. Conversion corridor limits for 10° of wing flaps setting and 0° iso-pitch line

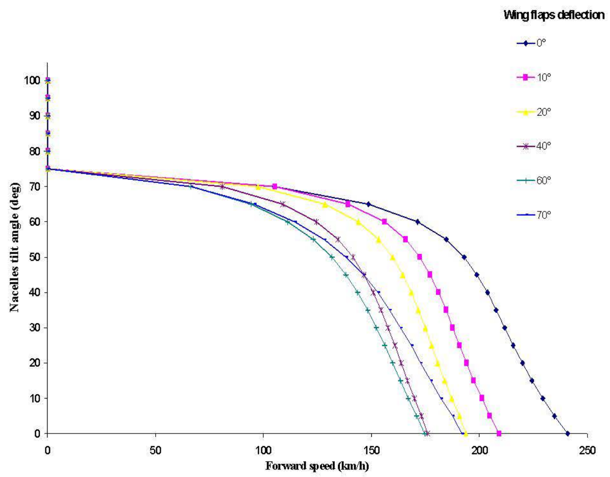


Figure 17. Effect of the wing flaps setting on the low limit of the conversion corridor

Pilot model, take-off and landing procedures and complete conversion

A pilot model integrated in the code allows the simulation of any maneuvers including take-off and landing procedures with or without engine failure by reproducing the main activities of a human pilot. The structure of the pilot model consists in decomposing a specific maneuver in different phases as shown on Figure 18. For each phase, the pilot controls are adapted to achieve specific piloting goals such as target speed, altitude or rotor speed.

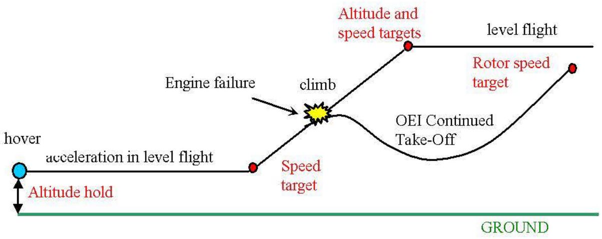


Figure 18. Example of take-off maneuver decomposed in flight phases

As, currently, no regulation has been completely established regarding tilt-rotors terminal procedures [12,13], the first procedures simulations performed are thus based on procedures elaborated for helicopters. In this paper, only procedures in clear areas are treated.

Take-off procedure simulation

The following AEO take-off procedure has been simulated (Figure 19).

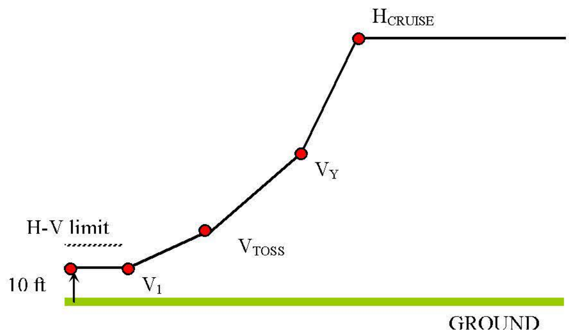


Figure 19. AEO take-off procedure for tilt-rotor

The take-off begins with a hover at 10 ft above the ground followed by an acceleration in level flight until reaching the speed V_1 of 25 kts. The tilt-rotor then starts to climb in three stages with different rates of climb :

- the first one is performed at 150 ft/min rate until attaining V_{TOSS};
- the second one at 500 ft/min until attaining V_Y;
- the third one at 1000 ft/min until reaching the cruise altitude of 5000 ft at which the nacelles will be tilted forward to convert into airplane mode.

The speed V_{TOSS} has been estimated at 40 kts using the power curves evolution. In the same way, the speed V_Y has been estimated at 80 kts at 90° of nacelles angle and 86 kts for a nacelles tilting at 75°. In these conditions, it is expected that the complete maneuver will stay within the limits imposed by the Height-Velocity diagram. For the tilt-rotor considered in this study, the lower limit has been estimated at 20 ft.

Results of the AEO take-off procedure are shown in Figure 20. Two cases of nacelles tilting during the procedure are compared to the take-off in pure helicopter mode. In the two cases with the nacelles tilt at 85° at the end of the hover phase, the tilt-rotor accelerates easily and stays within reasonable limits of pitch attitudes ($|\theta| \leq 5°$). Nacelles are then tilted forward to 75° either after V_{TOSS} or after V_Y. The best configuration is obtained with the tilting after V_{TOSS}. The tilt-rotor climbs faster and needs less power to continue the take-off and the pitch attitude stays reasonable.

Landing procedure simulation

Only the last part of the landing procedure has been simulated which means that the descent starts at a low altitude and is executed in pure helicopter mode. Figure 21 presents the different phases of the landing procedure simulated for the tilt-rotor.

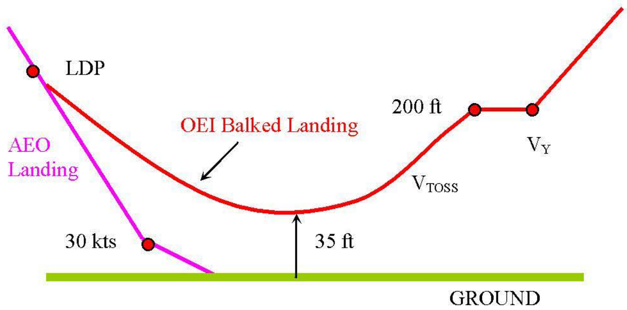


Figure 21. AEO Landing and OEI Balked Landing procedures for tilt-rotor

For the AEO landing, the tilt-rotor decreases its speed in order to reach 30 kts at the altitude of 15 ft while the vertical speed is maintained at about 500 ft/min. The landing ends when both vertical and longitudinal speeds are reduced to zero. If an engine failure occurs before the LDP (Landing Decision Point), the tilt-rotor can abort its landing and climb on one engine respecting the 35 ft clearance. During the OEI Balked Landing, the tilt-rotor must attain and hold V_{TOSS} on one engine at the rotor speed of 93% until the altitude of 200 ft at which it accelerates to V_Y before continuing to climb.

On Figure 22, results from AEO landing procedure for a 6° glide slope are compared to results from OEI Balked landing for different initial glide slopes (about 3°, 6° and 9°). The engine failure occurs after 15s and in the case of the 9° glide slope approach, the aircraft does not descend below the altitude of 35 ft.

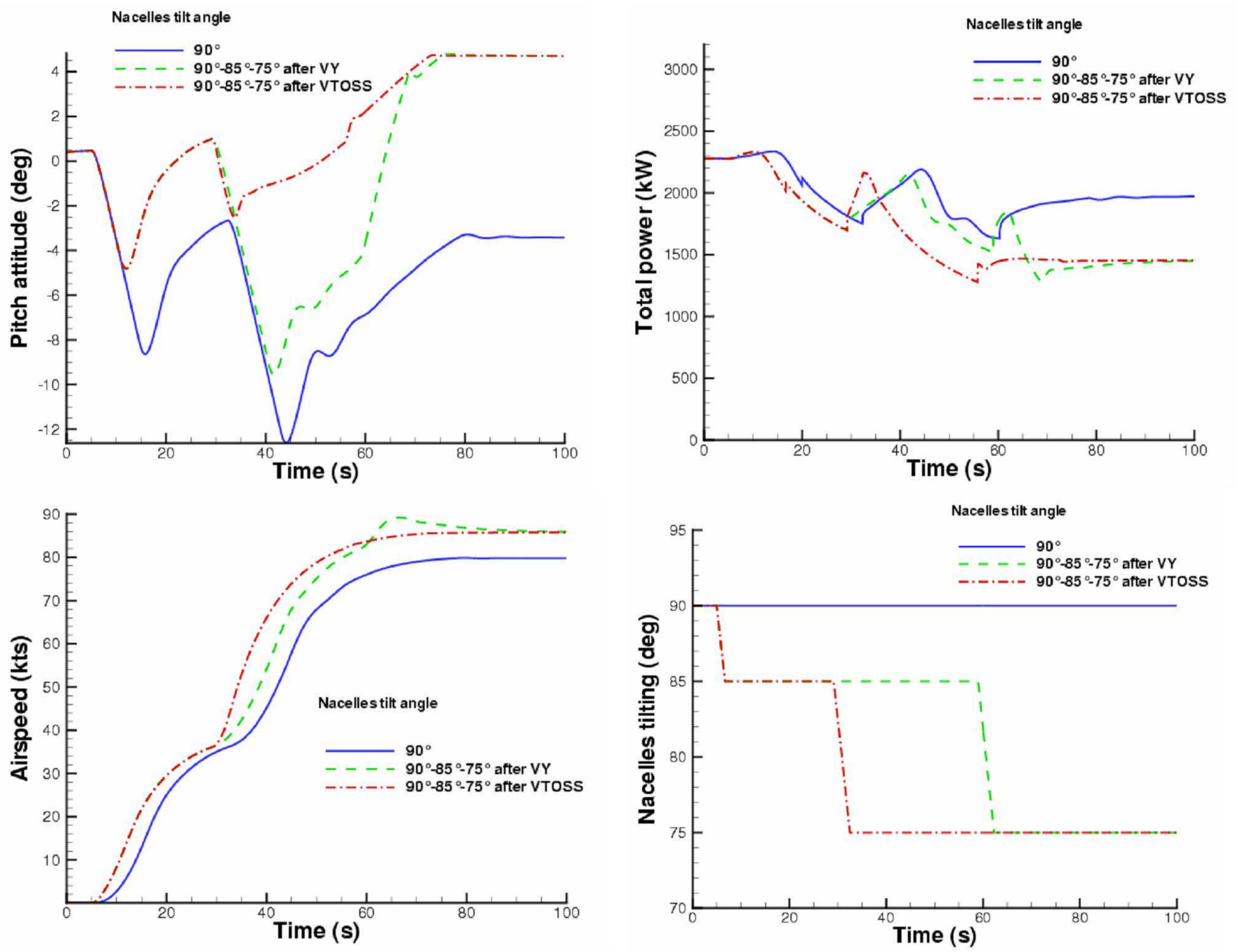
Such calculations can be used to determine the LDP and the results of Figure 22 show that the altitude of the LDP will certainly have to be increased when the approach slope increases.

Complete conversion simulation

The take-off procedure presented on Figure 19 has been completed in order to make the tilt-rotor convert until the airplane mode. As soon as the aircraft attains the altitude H_{CRUISE} of 5000 ft, the nacelles tilt forward progressively with intermediate stages : 75°, 60°, 30° and 0° with a tilting speed of 3°/s.

Figure 23 shows the evolution of the simulation parameters for the complete conversion including the take-off maneuver and the climb until the cruise altitude.

The conversion strategy has been elaborated in order to stay within the limits of the conversion corridor. The tilt-rotor has a reasonable pitch attitude evolution ($|\theta| \leq 4°$). The nacelles tilting schedule chosen is plotted on the conversion corridor (Figure 24). The simulated conversion is compared to the "optimal" conversion strategy elaborated to minimize the pitch attitude and the power required, and to the iso-pitch line of 0°.



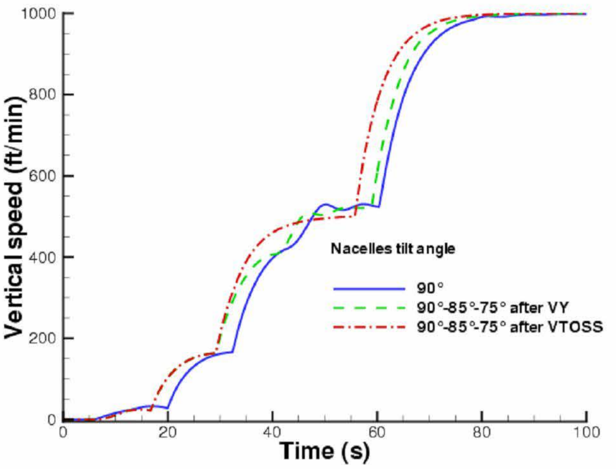


Figure 20. Simulation parameters for AEO take-off

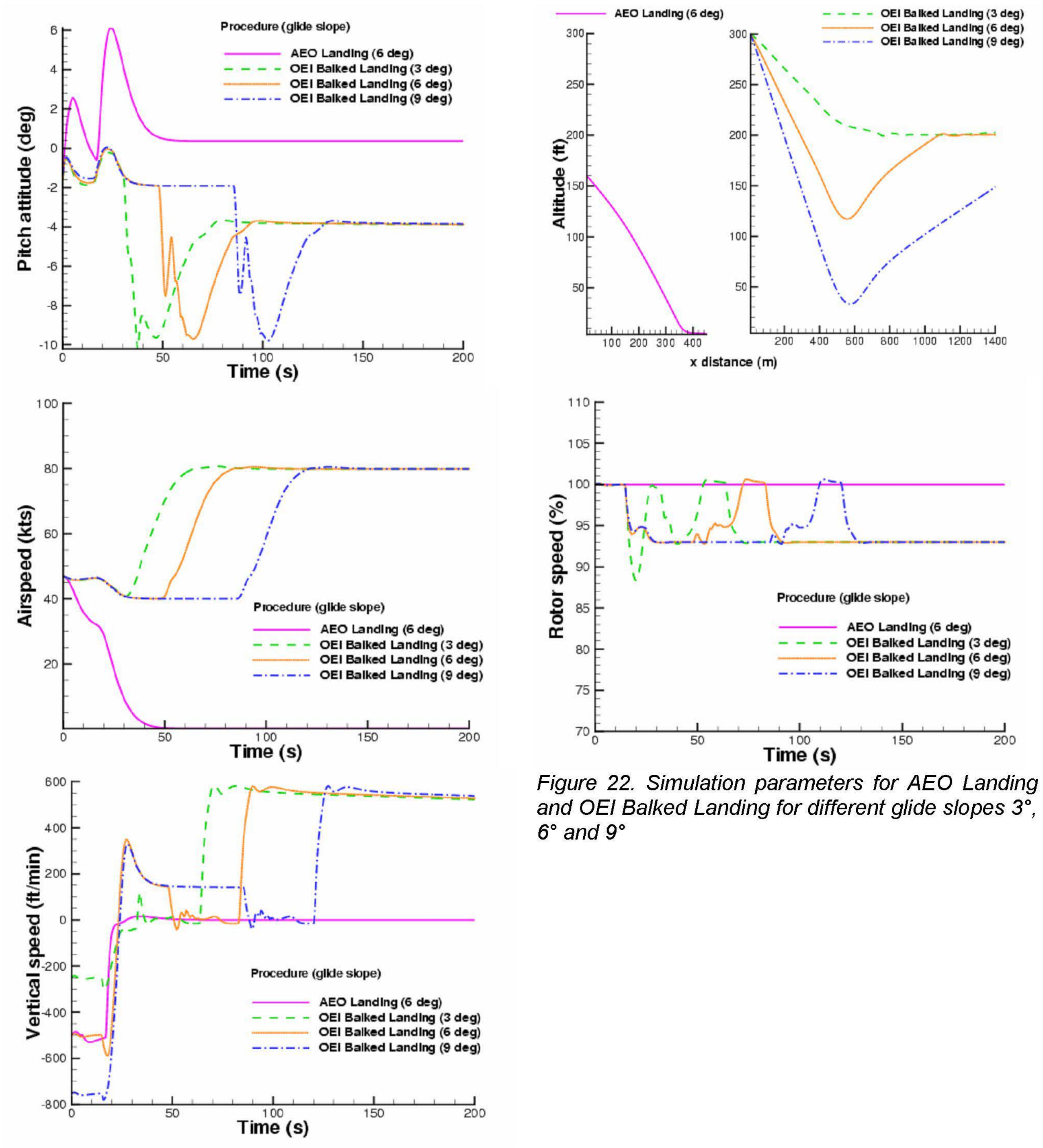
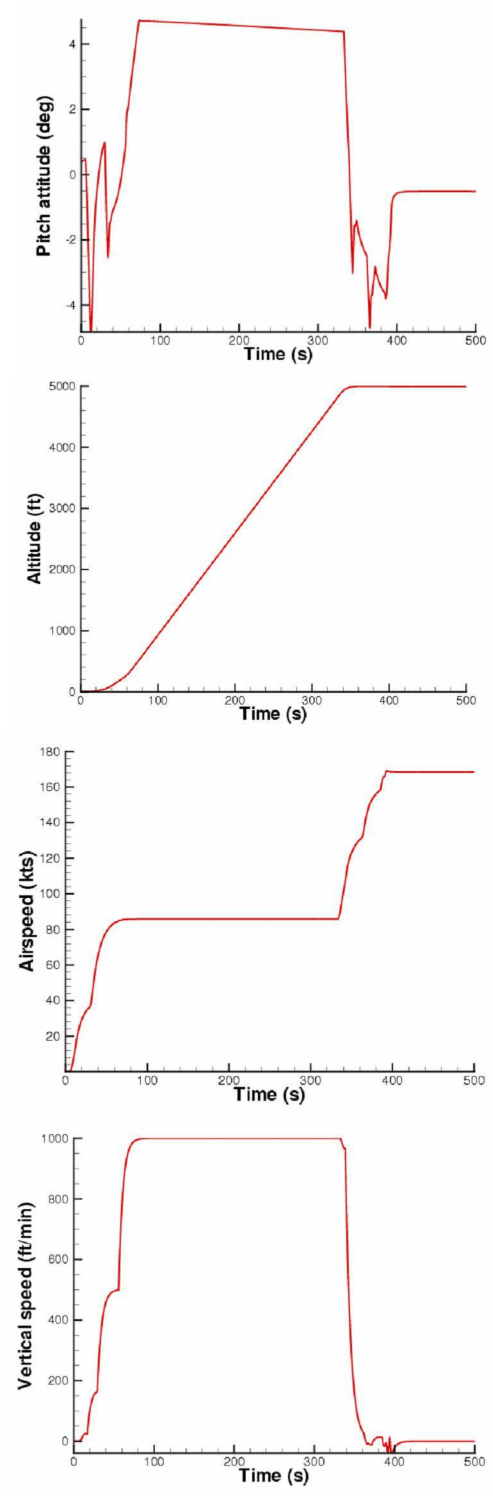


Figure 22. Simulation parameters for AEO Landing and OEI Balked Landing for different glide slopes 3°, 6° and 9°



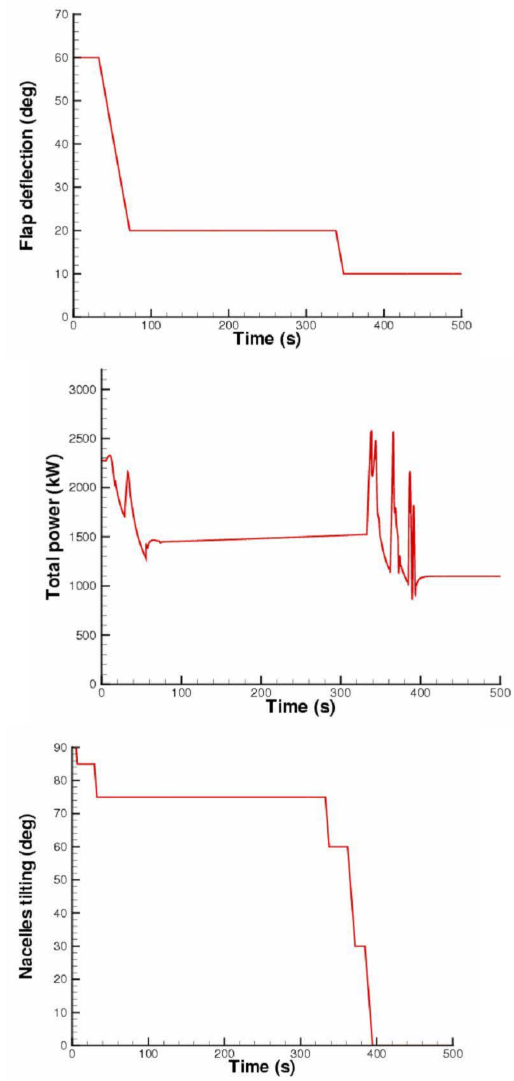


Figure 23. Simulation parameters for complete conversion

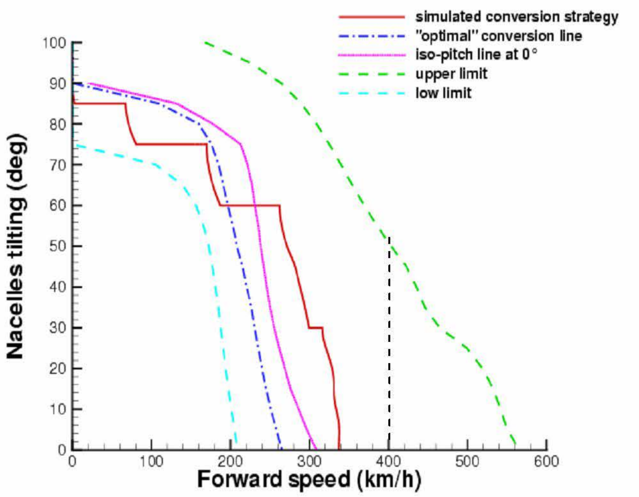


Figure 24. Nacelles tilting schedules and conversion corridor boundaries

Conclusion

Thanks to the performance code developed for tilt-rotors, the flight behavior of a generic tilt-rotor has been simulated for every configuration of the aircraft for a motion in the longitudinal plane.

The main characteristics of a tilt-rotor were modeled and implemented in the code. They concern the geometrical characteristics of the tilt-rotor such as two contrarotative rotors mounted on nacelles able to tilt forward from 90° to 0° position, a wing with trailing edge flaps and the most significant aerodynamic interactions in terms of performance :

- the download generated by the rotors wake impinging the wing;
- the ground effect on the download;
- the wing deflection on the tailplane.

The models chosen are simple enough to allow fast calculations. Controls and pilot model were also adapted to the different flight configurations (helicopter, airplane and conversion).

The code was then used to study the steady performance of the tilt-rotor. Performance charts enhance its capability to fly in different configurations by tilting the nacelles. After having highlighted the influence of flap deflection on tilt-rotor performance, a flap deflection law depending on nacelles tilt angle and forward speed was defined and implemented in the code.

The conversion corridors provide an overview of the tilt-rotor flight limits. Analyzing the power and pitch attitude distributions within the conversion corridor made it possible to define some conversion strategies.

The code has been used to perform some take-off and landing procedures by using a pilot model approach. The maneuvers simulated are inspired by the conditions of altitudes and speeds required by the category A helicopters regulations. Simulations have shown :

- the importance of the nacelles tilting during a take-off;
- the aptitude of the tilt-rotor to execute a successful Balked Landing after an engine failure.

The code allows to achieve a complete conversion from a take-off maneuver until the airplane mode in cruise altitude.

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