LIFTING LINE APPROACH FOR THE MODELLING OF A TILT-ROTOR WING IN HOST: APPLICATION TO THE ERICA CONCEPT

Fabrice Cuzieux
Ph.D. Student
Fabrice.cuzieux@onera.fr

André Desopper
Research Scientist
desopper@onera.fr

ONERA - Centre de Salon de Provence
Base Aérienne 701 - Ecole de l'Air
13661 Salon Air - France

Abstract

This study first focuses on the implementation of a non-linear lifting line model (Ref 1) into the Eurocopter HOST* flight mechanics code for the modelling of the tilt-rotor's wing. It is shown that this model can even account for the behaviour of a wing with tiltable parts like the one of the ERICA's✈ concept (Ref 2). Comparisons are made with a previous model already implemented into the HOST and based on a set of 3D wing polar tables. For low speed conditions a model of the interaction between the rotor wake and the wing has been developed and results in helicopter mode with interaction are discussed.
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Notation

c	wing local chord, m
C_X	airfoil drag coefficient,
C_Z	airfoil lift coefficient,
C_M	airfoil momentum coefficient,
C_t	rotor thrust coefficient,
DDM	longitudinal cyclic pitch ,%
DDZ	collective pitch ,%
DL	wing download, N
D_{nac}	nacelle tilt angle, ° (rad)
D_{wing}	tilt wings angle, ° (rad)
Fx,Fz	wing drag and lift forces in the wing reference co-ordinate system, DaN
Mx,My,Mz	wing momentum in the wing reference co-ordinate system,M.DaN
T	rotor thrust, N
V_0	aircraft speed, m/s
V_i	wing induced velocity, m/s
V_{im}	rotor axial mean induced velocity,m/s
WNEC	Total power requirement, KW
α	wing local incidence, ° (rad)
α_i	induced wing local incidence, ° (rad)
α_{eff}	effective wing local incidence, ° (rad)
α_0	wing zero-lift angle, ° (rad)
ρ	air density, kg/m^3
Γ_0	initial circulation (elliptic wing)
Γ	local circulation,
θ	aircraft attitude, ° (rad)
-FWI	relative to the fixed wing,
-TWS	relative to the right tilt wing,
-TWP	relative to the left tilt wing,
-RD	relative to the right rotor,
-RG	relative to the left rotor,

* Helicopter Overall Simulation Tool.

✈ Enhanced Rotorcraft Innovative Concept Achievement.

Introduction

Among the solutions studied to decrease airport congestion due to air traffic increase, the use of civil tilt-rotors is an interesting solution. A tilt-rotor has the distinctive feature of being able to combine Vertical or Short Take-Off and Landing capabilities with cruise flight at speeds comparable to turboprop aeroplanes. Several studies carried out regarding tilt-rotors aerodynamic interactions have shown that the downwash of the rotors impacting the wings considerably affects such an aircraft in terms of a download force that occurs in hover and low speed flight (Ref 3,4,5,6). In order to reduce this download AGUSTA has proposed the ERICA concept (Ref 2). As shown in figure1 the wing parts located below the rotors can be tilted and adjusted to the rotor downwash direction in order to decrease the wing download. The best angle to set depends on the flight conditions.
The present work investigates steady performance of the ERICA tilt-rotor thanks to the Eurocopter HOST* code. In a first approach, a set of 3D wing polar tables is used to calculate the forces on the wing but this leads to some limitations when the wing is in a non uniform wind condition, when manoeuvring for example. More over the model of rotor/wing interaction presently in HOST is looking at the impact on the tilt wings supposing that the rotor wake always impacts only this part of the wing whatever the flight conditions are. For these different reasons it was decided to develop a wing model

based on a non-linear lifting line theory (Ref 1) and to implement it in the HOST code.
The paper first focuses on the lifting line model for the wing, which includes both the fixed and moveable parts with the use of the complete 2D-airfoil polar curves for the ERICA wing. Then the implementation of the model in HOST and some comparisons with the first approach (using the 3D wing polar tables) without rotor/wing interaction are presented for a velocity sweep in helicopter mode and airplane mode. With this lifting line approach it is possible to directly obtain the wing damping effect during roll (or yaw) motions for both the fixed and the moveable wing parts.
Wing download calculations performed in hover and in forward flight are also presented. In order to have the calculation of the wing loads in interaction with the rotor wakes, it is also needed to compute the intersection between the rotor wakes and the wing for all flight configurations including lateral flights.
The last part focuses on the calculation of the wing loads in airplane mode, taking into account the interaction with the rotor wakes through the swirl effect.

Wing lifting line modelling in HOST

The non-linear lifting line theory model (Ref 1) is based on the same statements as a conventional lifting line method except that the 2D-airfoil lift coefficient is not linearised. The non linear equation of the circulation is the following:

$$\Gamma(y) = \frac{1}{2} V_\infty \times c(y) \times \ldots$$

$$\ldots C_z\left(\alpha(y) + Arctan \frac{1}{4\pi V_\infty} \int_{y_0=-b/2}^{y_0=+b/2} \frac{d\Gamma}{dy}(y_0) \times \frac{1}{y_0 - y}\, dy_0\right)$$

Calculation under high angle conditions such as for a tilt-rotor wing in interaction with the rotor wake can then be performed.

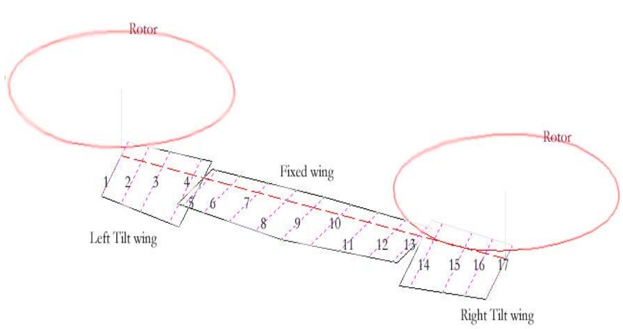
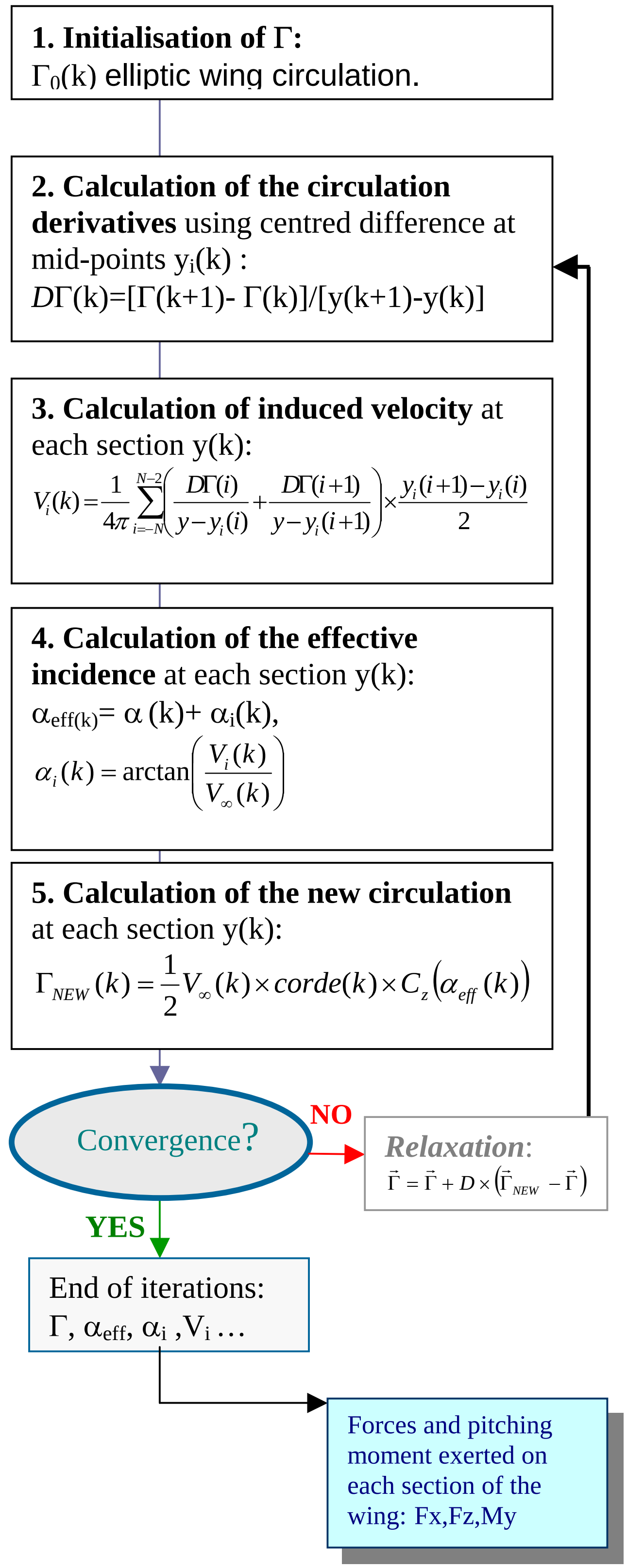


Figure 1. ERICA Wing segmentation for the lifting line model in HOST.

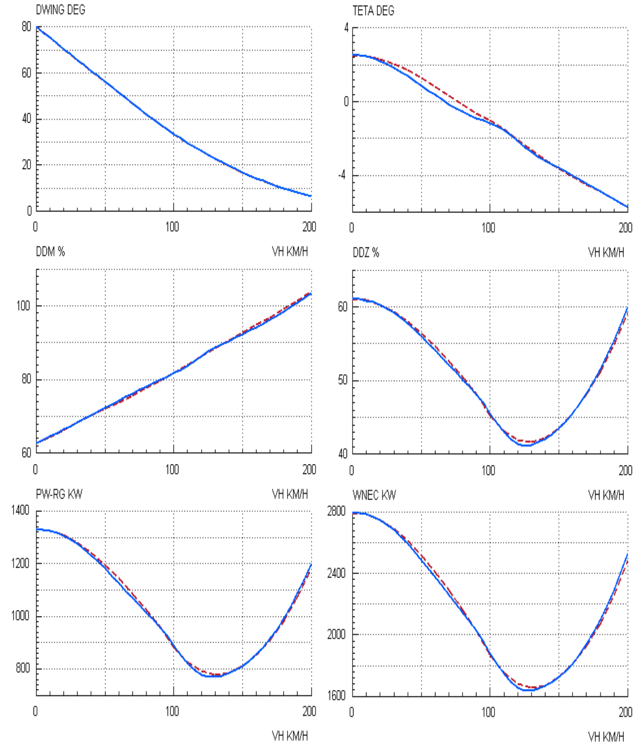
To solve this equation, the wing is split into wing segments where the local values of the setting angle, chord and airfoil can be specified by the user. In the present study, the wing includes 17 segments, 9 on the fixed wing (with one at the centre) and 4 on each tilt wing as illustrated on Fig 1. The numerical resolution is based on a fixed-point method, which is quite efficient in this case. The main steps of the algorithm are presented in the following graph:



Codes comparison with no rotor/wing interaction

Comparisons have been performed for the results of trim calculations in both helicopter and airplane modes obtained with this lifting line model and the previous model implemented in HOST which uses a set of 3D polar tables (Fig 2,3). In these conditions with no rotor/wing interaction, the speed is uniform along the wing, which is coherent with the 3D tables' approach.
In order to take into account the influence of the speed on the airfoil coefficients, multiple 2D airfoil coefficient tables are used depending on the Mach number.

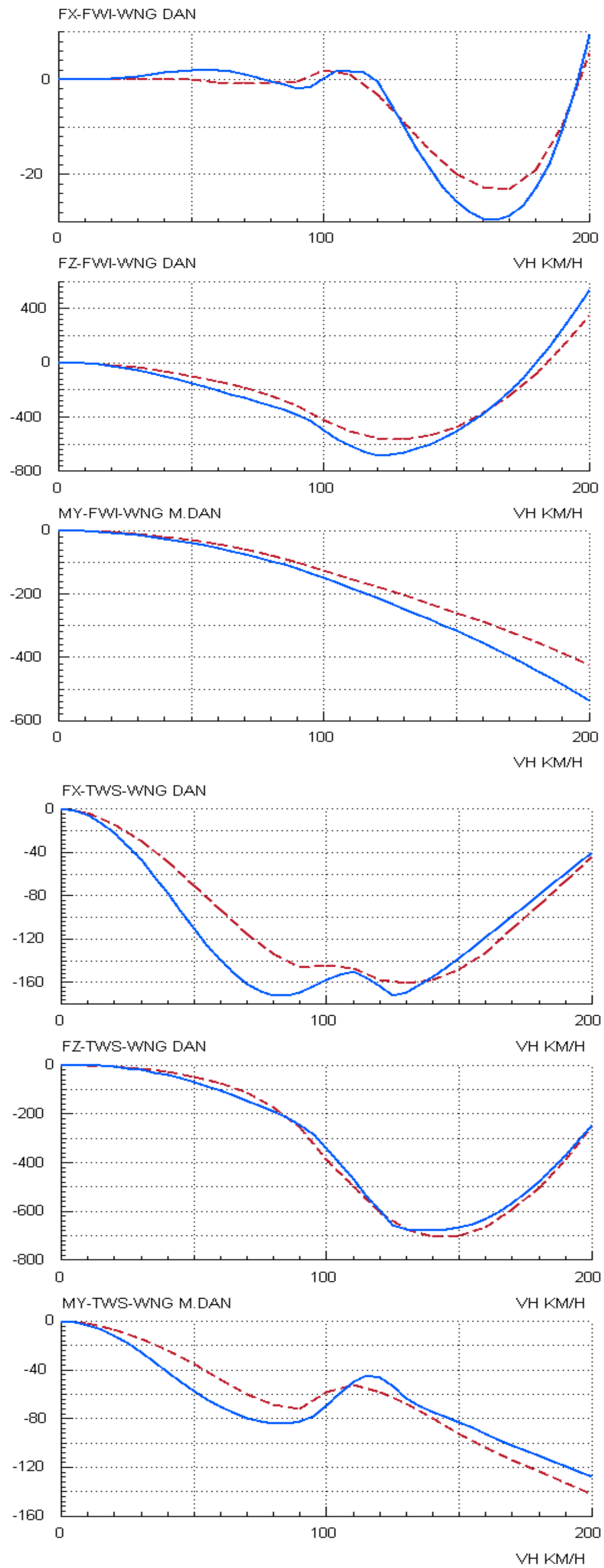
<u>Helicopter mode:</u> These calculations have been computed with 90° nacelles tilt angle and an altitude of 100m to avoid ground effect phenomenon. Using a wing tilt angle function of the speed (similar to the one used to decrease the required power Fig 10), one can see that the behaviour of the complete aircraft obtained with the two approaches has no relevant differences (Fig 2.a). Moreover the forces and pitching moment on the fixed wing and on the tilt wing are quite similar (Fig 2.b).



(2.a)

HOST with lifting line model

HOST with 3D wing tables model

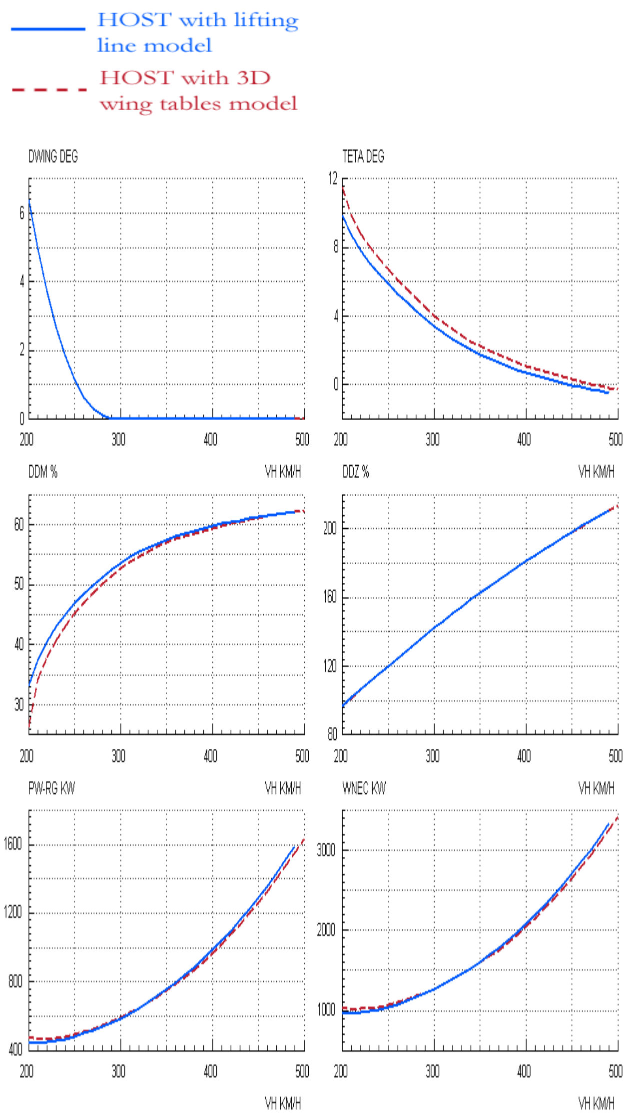


(2.b)

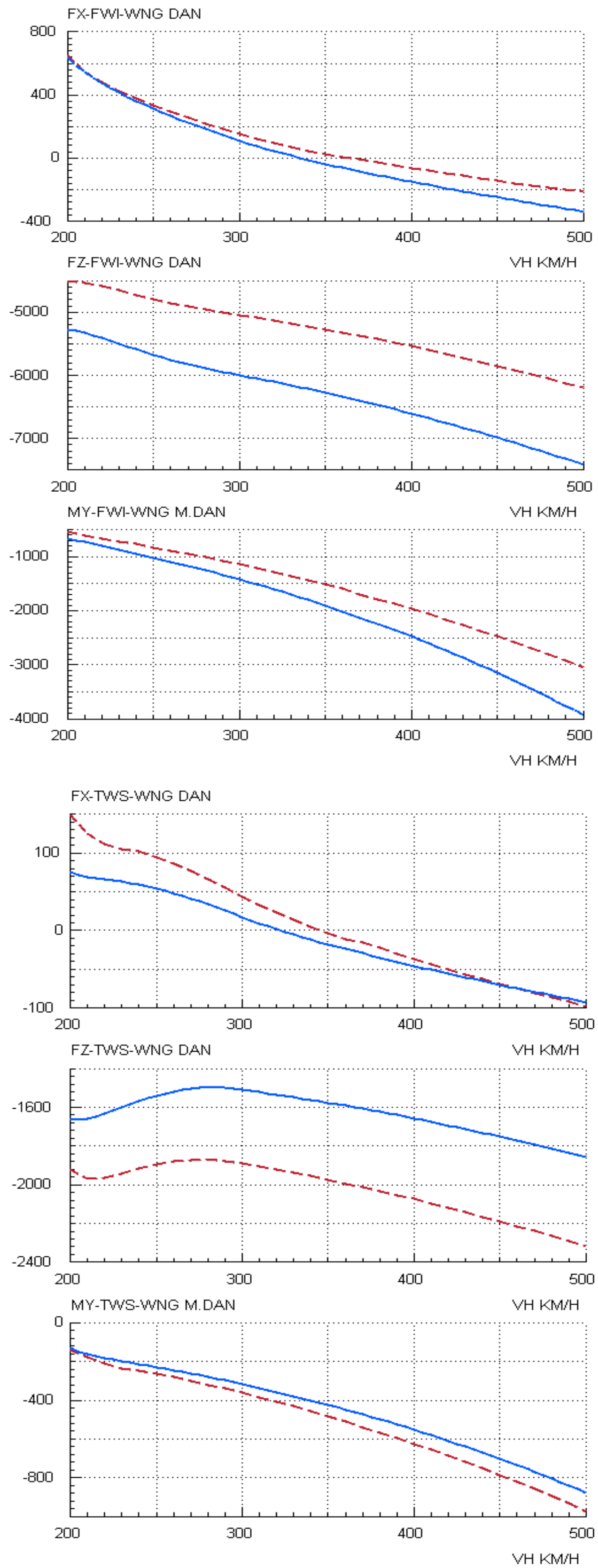
Figure 2. Comparison HOST+wing table models and HOST+lifting line model in helicopter mode with no rotor wake interaction.

Airplane mode: These calculations have been computed with 0° nacelles tilt angle and an altitude of 100m to avoid ground effect phenomenon. As for the helicopter mode, the behaviour of the aircraft

(Fig 3.a) does not have relevant differences except a slight one on the pitch attitude.
However, on Fig 3.b, some differences occur for the forces on the fixed and the tilt wing. If the lift force on the fixed wing is larger with the lifting line approach compared to the 3D tables one, the one on the tilt wing is smaller in such a way that the differences compensate each other.
There are also differences for the pitching moment predicted in a sense that is coherent with the differences observed for the pitch attitudes.



(3.a)



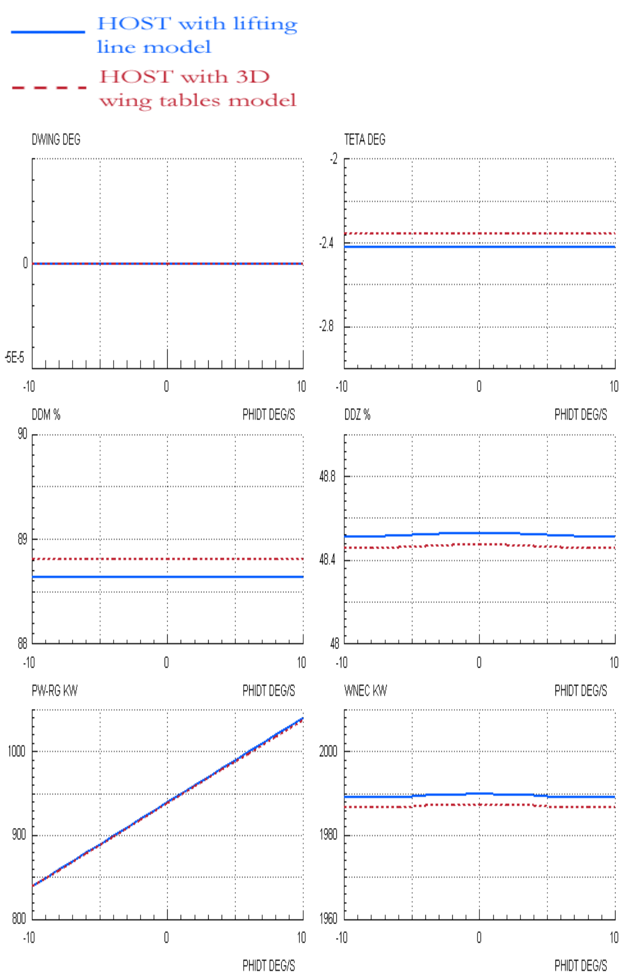
(3.b)

Figure 3. Comparison HOST+wing table models and HOST+lifting line model in airplane mode with no rotor wake interaction.

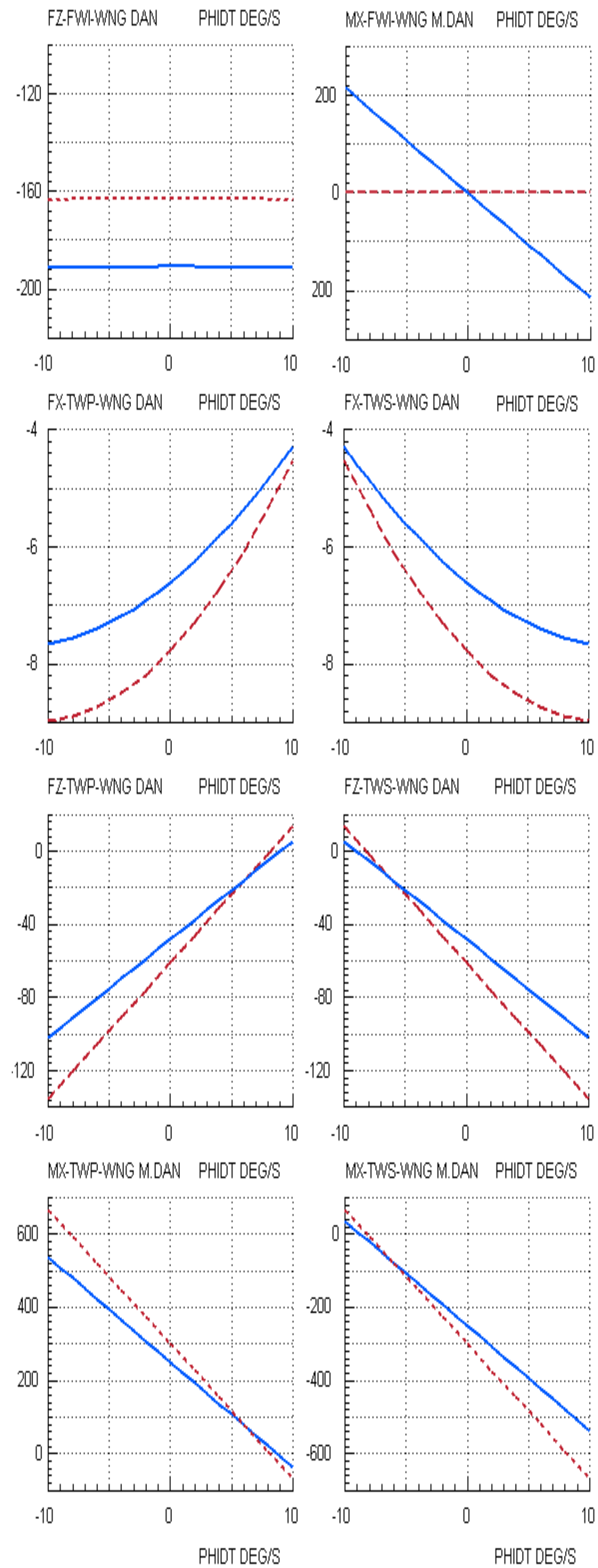
Wing damping effect.

These trim calculations have been computed in helicopter mode, at 0° tilt wing angle, a speed of VH=150km/H and an altitude of 100m to avoid ground effect phenomenon. Sweeps in roll and yaw rates have been performed.

Roll results: With the previous model (using the 3D polar tables), performing a calculation in such conditions with a non-zero roll rate has no effect for the fixed-wing as the relative speed is computed at the centre of the wing. For example the rolling-moment, calculated at the centre of the wing is then zero for the fixed wing (Fig 4.b). For the tilt wings, as the points where the relative speed is calculated is unique the resulting forces and moment are highly dependent of the position of this point. In the lifting line model, each section sees a different speed caused by the roll motion. As one can see, both the model and the results are more physically realistic.



(4.a)

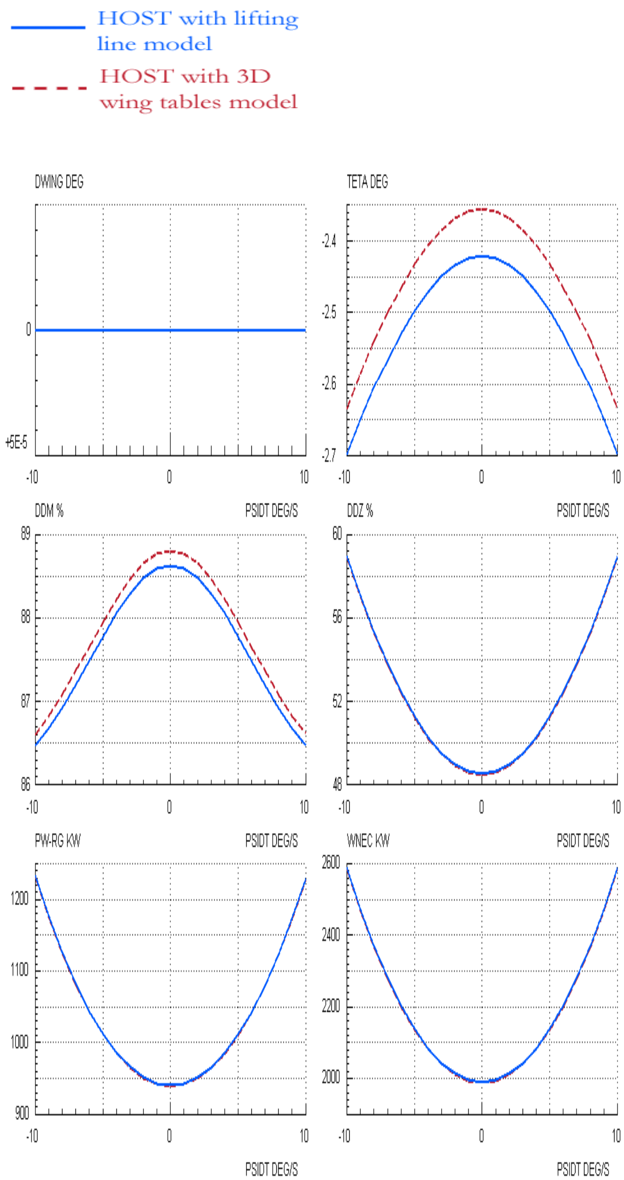


(4.b)

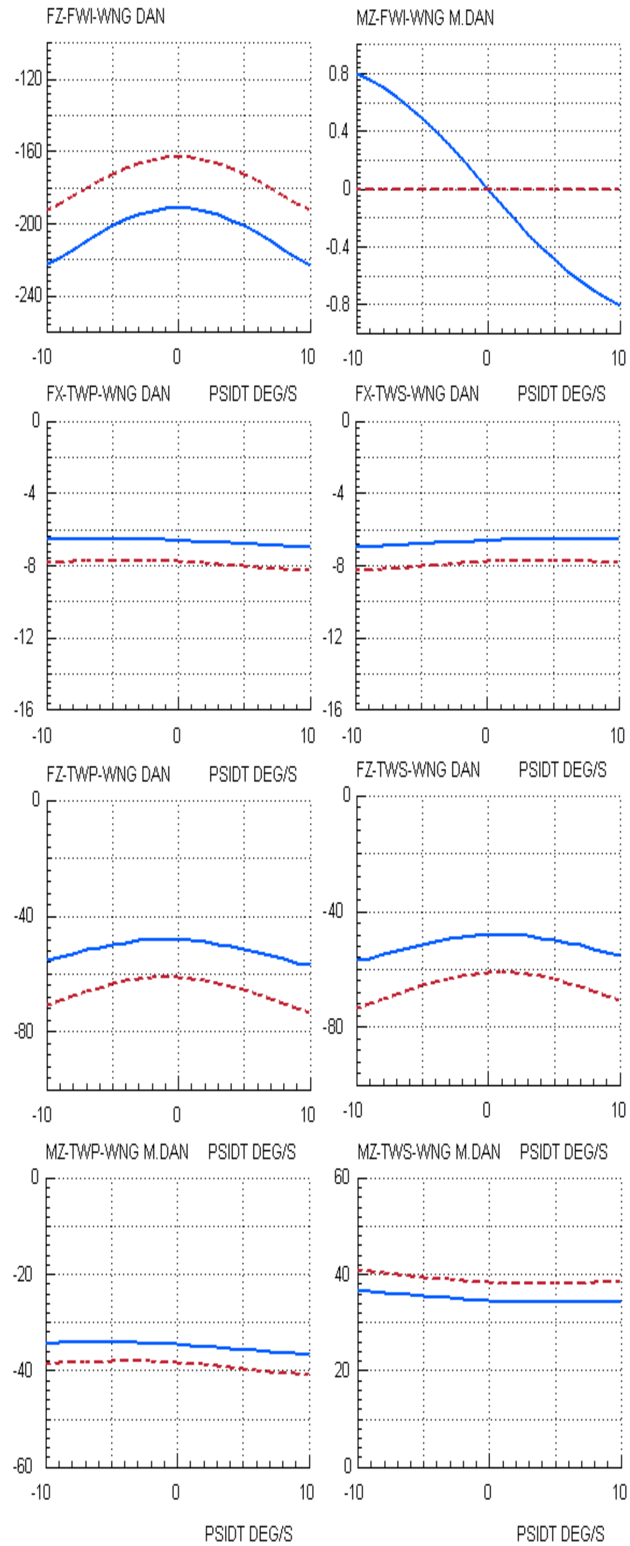
Figure 4. Comparison HOST+wing table models and HOST+lifting line model in helicopter mode with no rotor wake interaction for a sweep in roll rate at VH=150Km/h.

The figure shows that the lifting line model gives a damping effect for both the fixed and the tilt wings.

Yaw results: The same conclusion can be driven for non-zero yaw rate, but then it is the yawing-moment which is expected to be non-zero and opposite to the motion. As the wing incidence is not far from zero the drag force is not so high, but it is possible to see that the yawing-moment behaves in the opposite way to the yaw motion for both the fixed and the tilt wings.



(5.a)



(5.b)

Figure 5. Comparison HOST+wing table models and HOST+lifting line model in helicopter mode with no rotor wake interaction for a sweep in yaw rate at VH=150Km/h.

Rotor wake/Wing intersection

The model used to evaluate the interaction between the rotor wake and the wing is based on a quasi-steady representation of the wake. The wake is assimilated to a cylinder whose equation depends on the geometry of the tilt-rotor, the angle of the nacelles, the relative air speed at the rotor centre (including effect of roll, pitch and yaw motion) and the mean velocity induced by the rotor.
This model allows computing the percentage of wing chord intercepted by the rotor wake for each section of the lifting line as illustrated on Fig 6. This percentage will be used to balance the influence of the rotor-induced velocity on each section of the lifting line:

$$V_{im} = V_{imRG}.\%_{cRG} + V_{imRD}.\%_{cRD}$$

capacities of a tilt-rotor. For example, it can reach 10 to 15% of the rotor thrust (Ref 6).

With the model developed here, it is possible to evaluate the evolution of the download with the tilt wing angle for both hover and forward speed conditions.

Download in Hover: When in hover, the main interest of the tiltable wings is that they can be put in the local slipstream. Doing so, the drag force generated by the rotor wake impact should be drastically reduced. One difficulty is the modelling of the induced velocity at the wing level. Different studies have shown that various parameters can influence the download force such as the rotor thrust, the distance between rotor and wing, the sense of

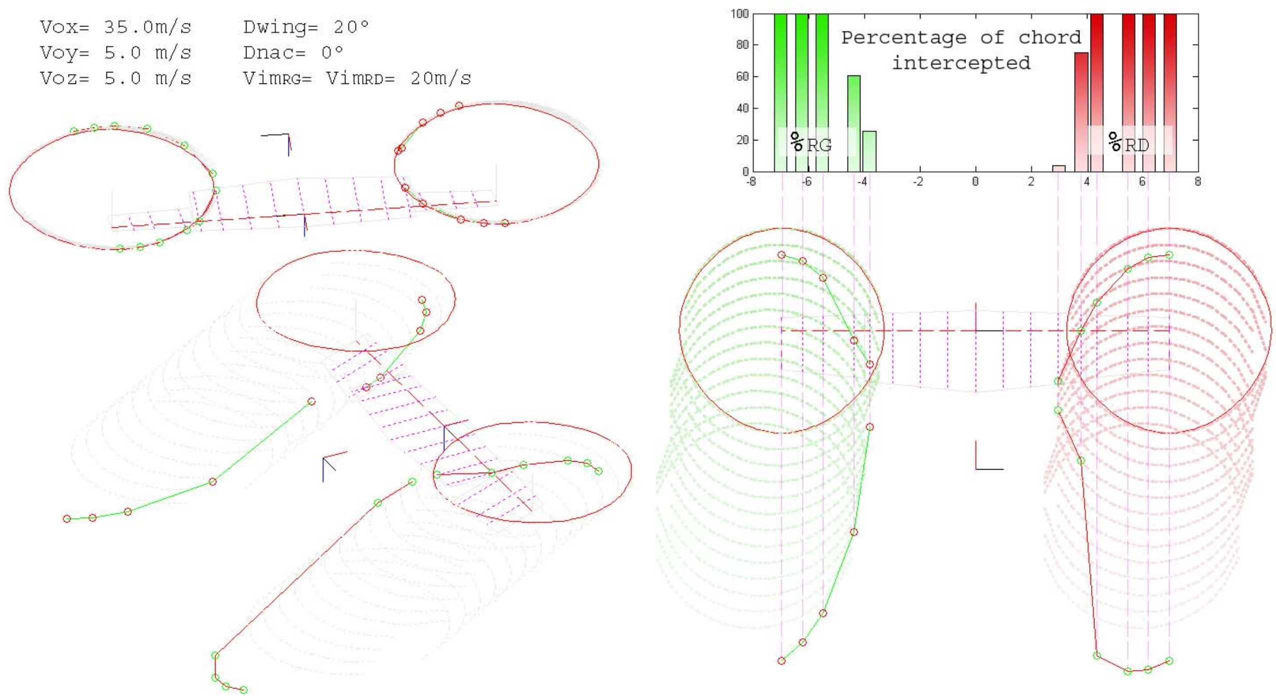


Figure 6. 3D representation of the cylindrical wake model and its intersection with the wing

The main advantage of such a model is to give the effect of even small variations in the surface intercepted by the wake as when around hover conditions and to prevent from step results behaviour when a section is getting out of the rotor wake.

Wing download calculation in hover and in forward flight

Download due to the interaction between the rotor wake and the wing considerably affects the global

In the present simplified model, only the mean rotor induced velocity is considered with a geometric contraction of 0.8 for the rotor wake; this implies that in hover conditions, only the tilt wing is concerned by the interaction. It is assumed that a more complete model of the induced velocities will not modify the general behaviour. The present model also considers no direct effect of the wing on the rotor-induced velocity (except by the mean of a reduction

of the download force that means also a lower value of the rotors thrust).
The results presented on Fig.7 and Fig.8 show the benefits of tilting the wing parts located below the rotors. The comparison with the previous model shows also no relevant differences in the general behaviour. Nevertheless, if Fig.8 shows that both models predict a lower required power when tilting the wings, a different value is obtained for low tilt angles (which corresponds to high angle of attack for the tilt wings).

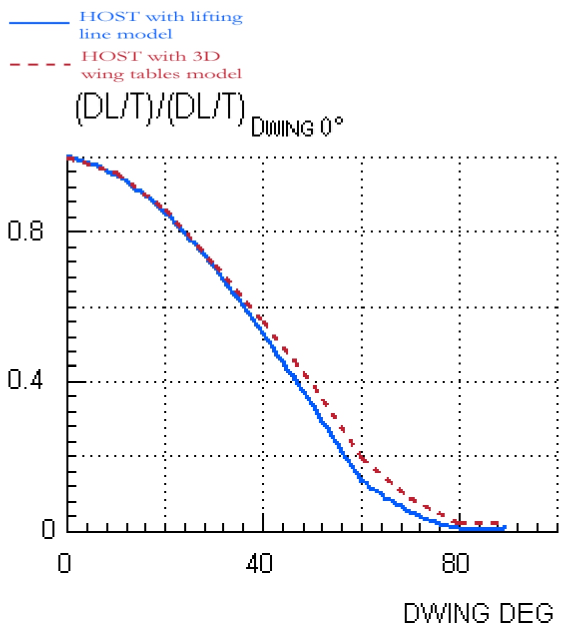


Figure 7. Wing download evolution with the tilt wing angle in hover.

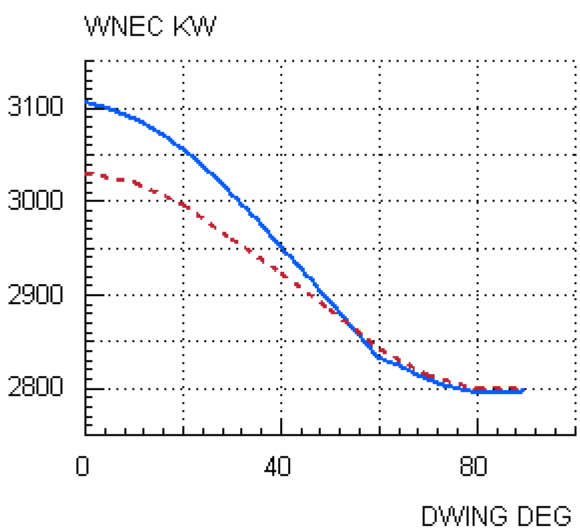


Figure 8. Total power evolution with the tilt wing angle in hover.

<u>Download in forward flight:</u> In forward flight the interaction effect decreases progressively as the speed increases with the rotor wake gradually leaving the wing area. Thus trim calculations with interaction should progressively be closer to those without interaction as the speed of the aircraft increases.
Two configurations have been tested. In the first one, the tilt wing angle is set to 0° and in the second to 40°. As one can see on Fig. 11 and Fig.12 in both cases the results with interaction progressively get closer to those without interaction. For speed conditions from 0 up to 120km/h it is clear that interaction between the rotor wake and the wing induces a higher power required. Thanks to a reduction of the download with 40° of tilt wing angle at low speed conditions, the results show a decrease of the power required relative to the one with 0° tilt angle.
Calculations with different tilt angle values have been performed in order to obtain the wing tilt angle law function of the speed that minimised the total power required (Fig. 13 and Fig.14). Figures 15 to 18 show the effect on the pitch attitude and the tilt wings' loads.

<u>The swirl effect in airplane mode</u>
Usually models of interaction between rotor and wing just use the axial velocity induced by the rotor. In real conditions a tangential velocity called swirl is also present in the rotor wake. This velocity induces a variation in the angle of the flow behind the rotor. Thus when interacting with the wing behind the rotor, the local incidence on the wing is modified in such a way that explain observations made upon the dependence of the download with the sense of rotation of the rotor (Ref 3,6 in helicopter mode and 3,7,8 in airplane mode).
Some results are presented here for the interaction in airplane mode. As the direction of rotation is commonly set to be up inboard we can easily understand thanks to Fig 8 that the swirl will induced an additional lift component on the wing.

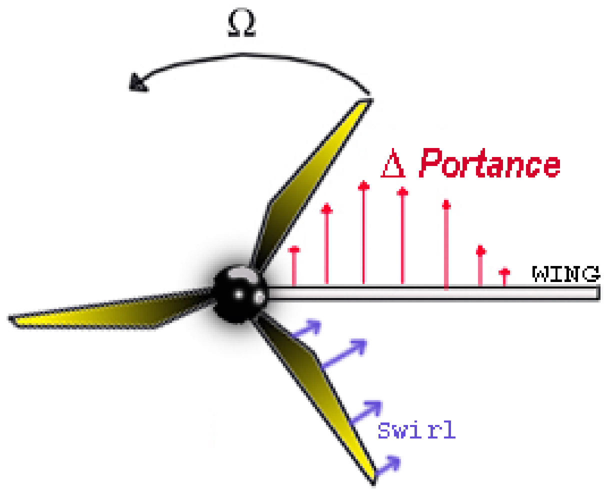


Figure 9. Illustration of the swirl effect on the wing in airplane mode.

As one can see on Fig 19, both directions of rotation have been tested for a sweep in aircraft velocity. As M.A.McVeigh, W.K.Grauer, and D.J.Paisley (Ref. 3) have obtained and illustrated on Fig 10, we notice that when the direction of rotation is up inboard there is an increased drag force but also an increased lift force on the tilt wings.

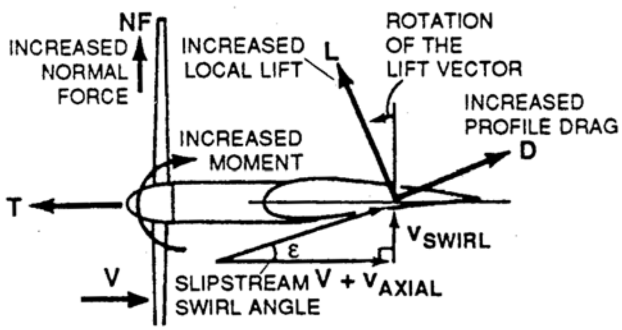


Figure 10. Increased Forces on the wing due to swirl effect in airplane mode (Ref.3)

It is exactly the opposite when the direction of rotation is down inboard (Fig19). As a result of this modification of the lift force the total power required is slightly decreased when the direction of rotation is up inboard and slightly increased when down inboard (Fig 19).
On Fig 20, the repartition of the normal force along the wing is illustrated for a speed of 350km/h showing that the swirl effect increases the lift on the tilt wings and slightly decreases it on the fixed wing part.

Conclusion

A non-linear lifting line model for the modeling of a tilt rotor wing has been developed. A brief description of the model, its implementation into the Eurocopter HOST flight mechanics code and results for the Erica's tilt-rotor concept are presented.
A rotor wake/wing interaction model has been developed for the calculation of the wing download in hover and low speed conditions. Thanks to this model, it has been possible to define a tilt wing angle law function of the speed that minimizes the power required.
In airplane mode, the swirl effect has also been added to the interaction model in order to show the influence of the rotor's direction of rotation.
In the future, wing flaps and ailerons will be taken into account. Improvement of the rotor induced velocities at the level of the wing, swirl effect in helicopter mode and ground effect in low speed conditions will also be considered.

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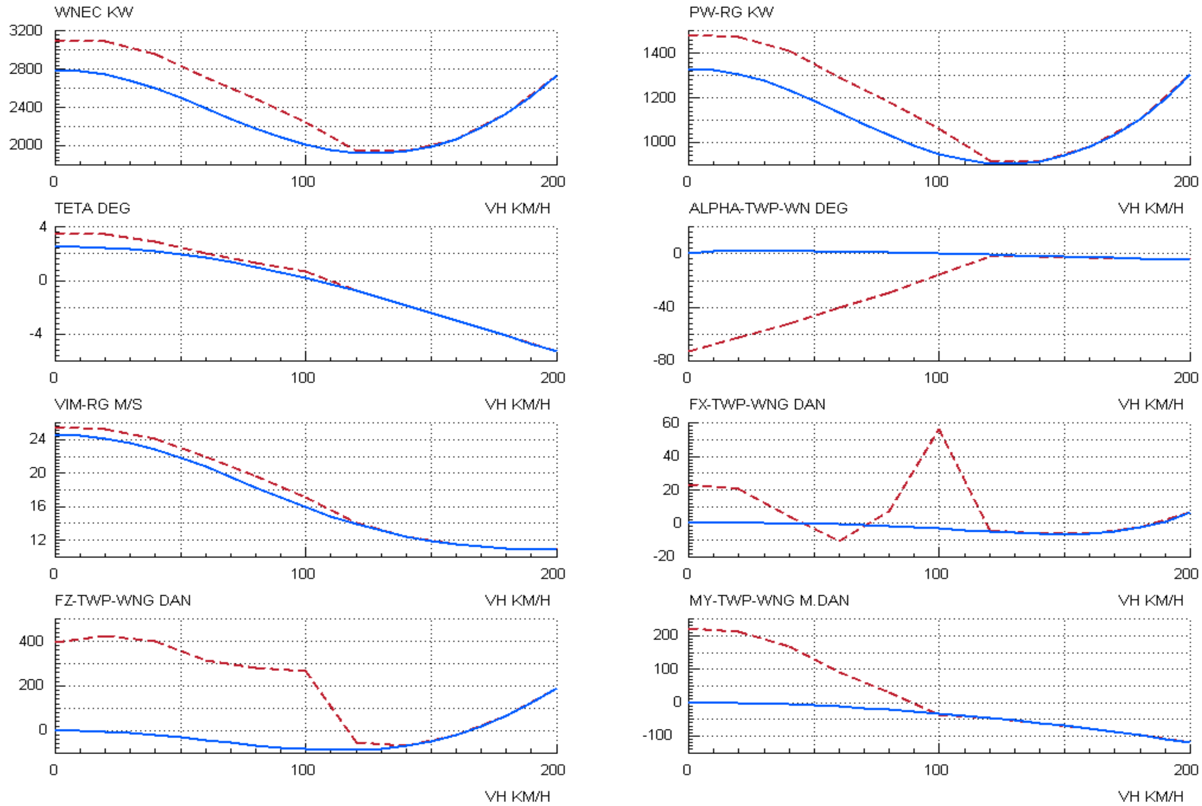

Figure 11. Code comparison with and without interaction with tilt wing angle at 0°

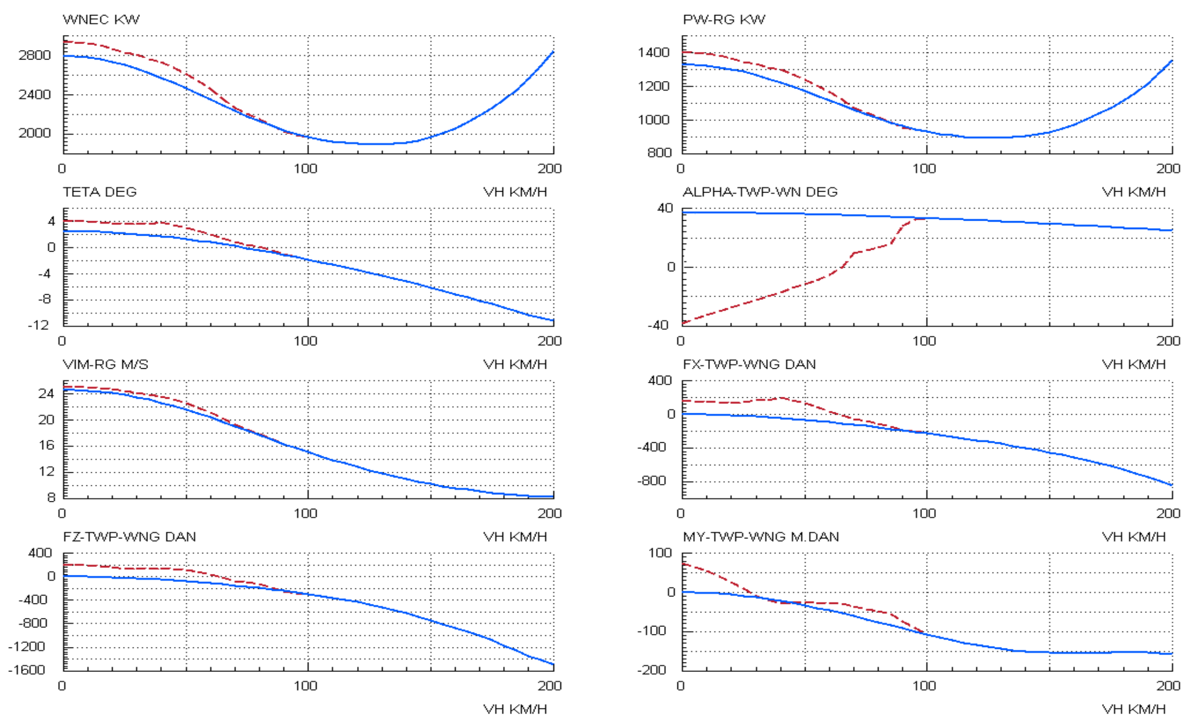

Figure 12. Code comparison with and without interaction with tilt wing angle at 40°.

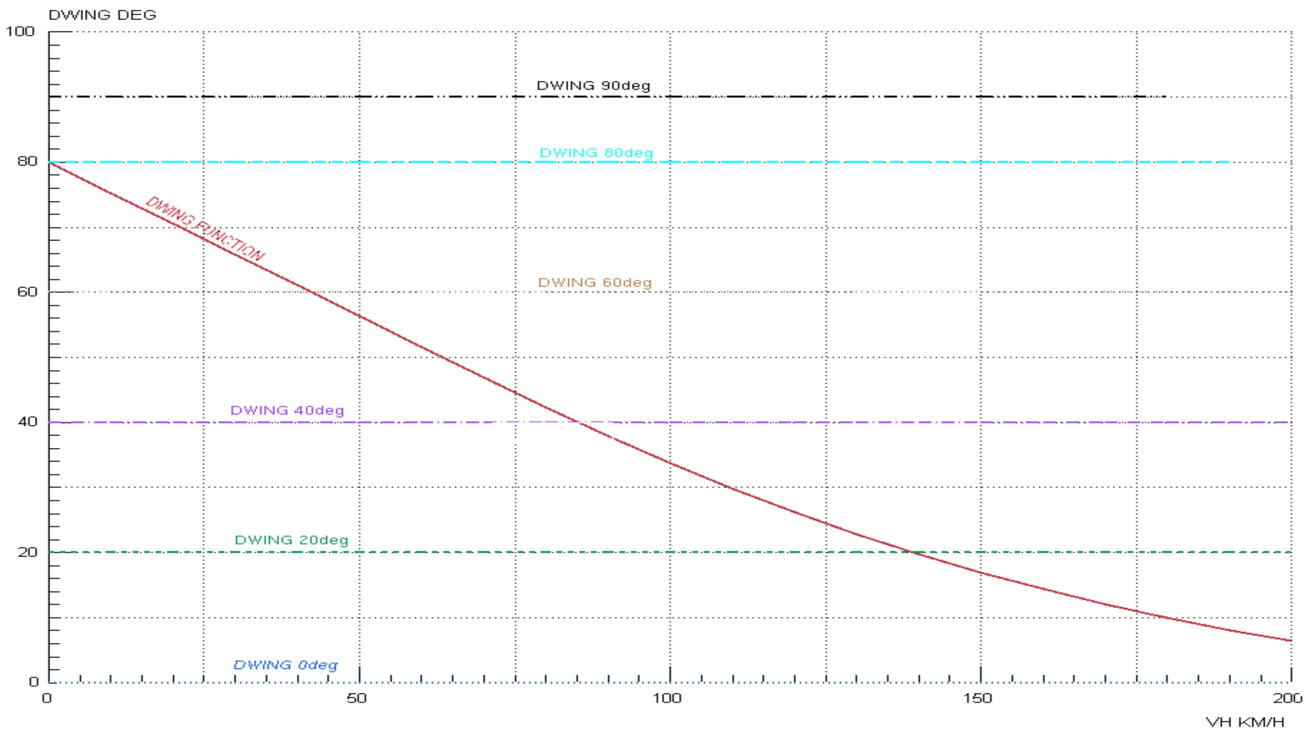

Figure 13. Tilt wing angle law function of the speed and different fixed values used in helicopter mode.

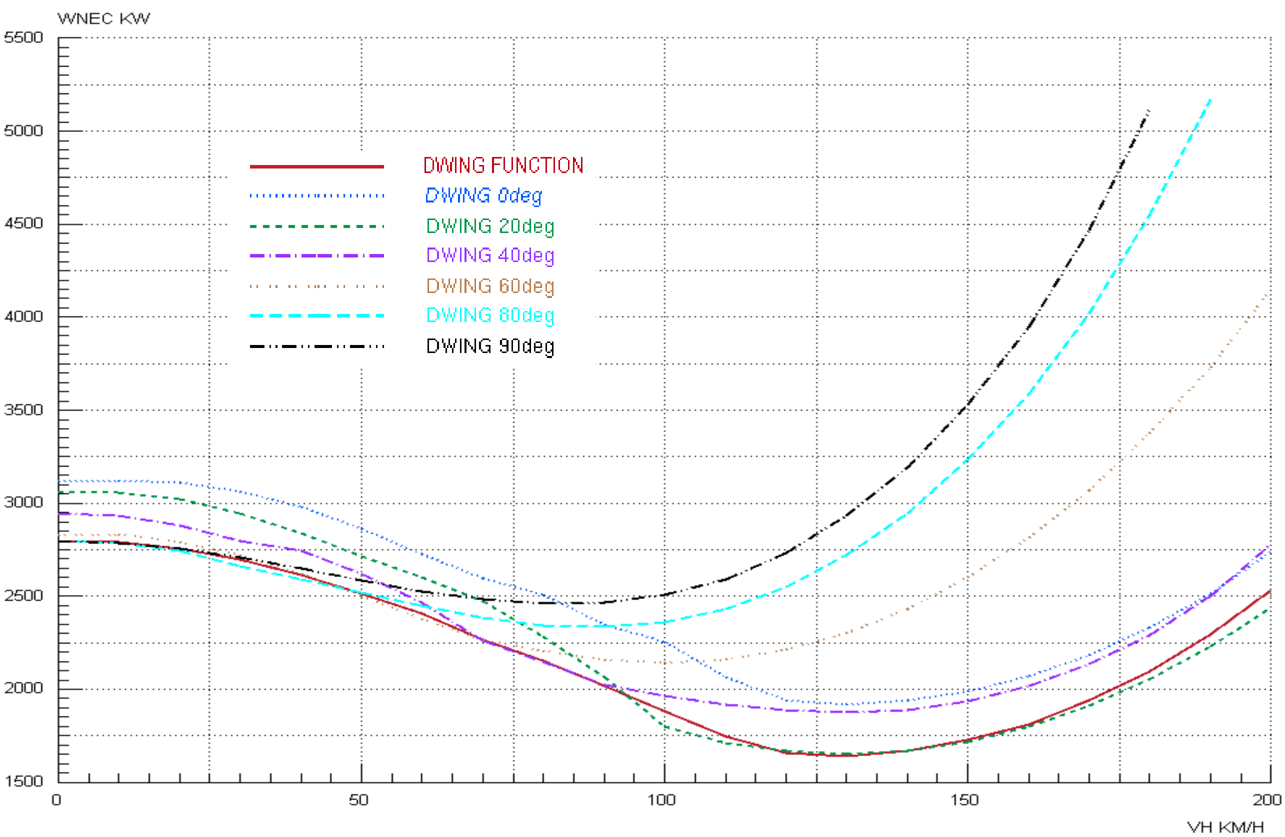

Figure 14. Total power requirement minimisation with the tilt wing angle law compared with different fixed values in helicopter mode.

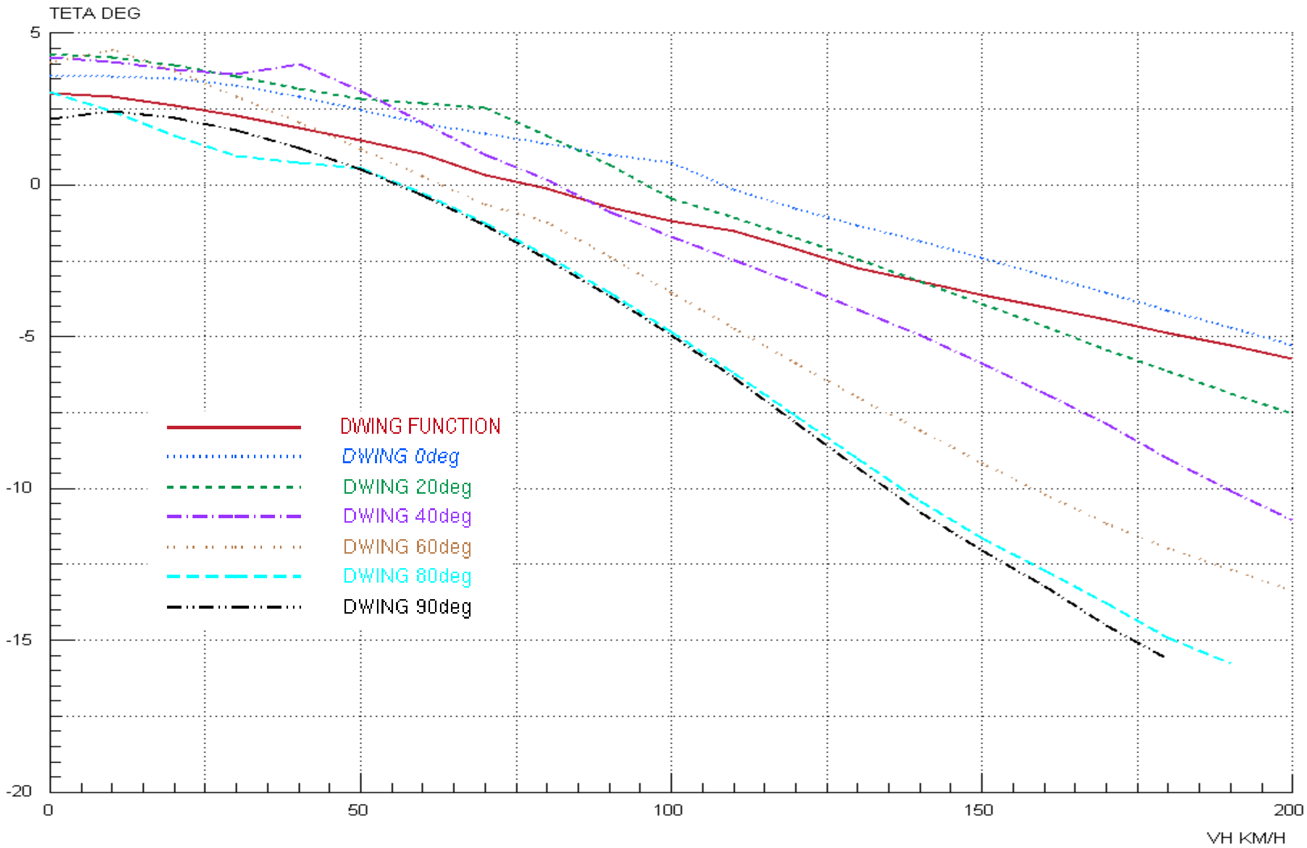

Figure 15. Influence of the wing tilt angle on pitch attitude in helicopter mode.

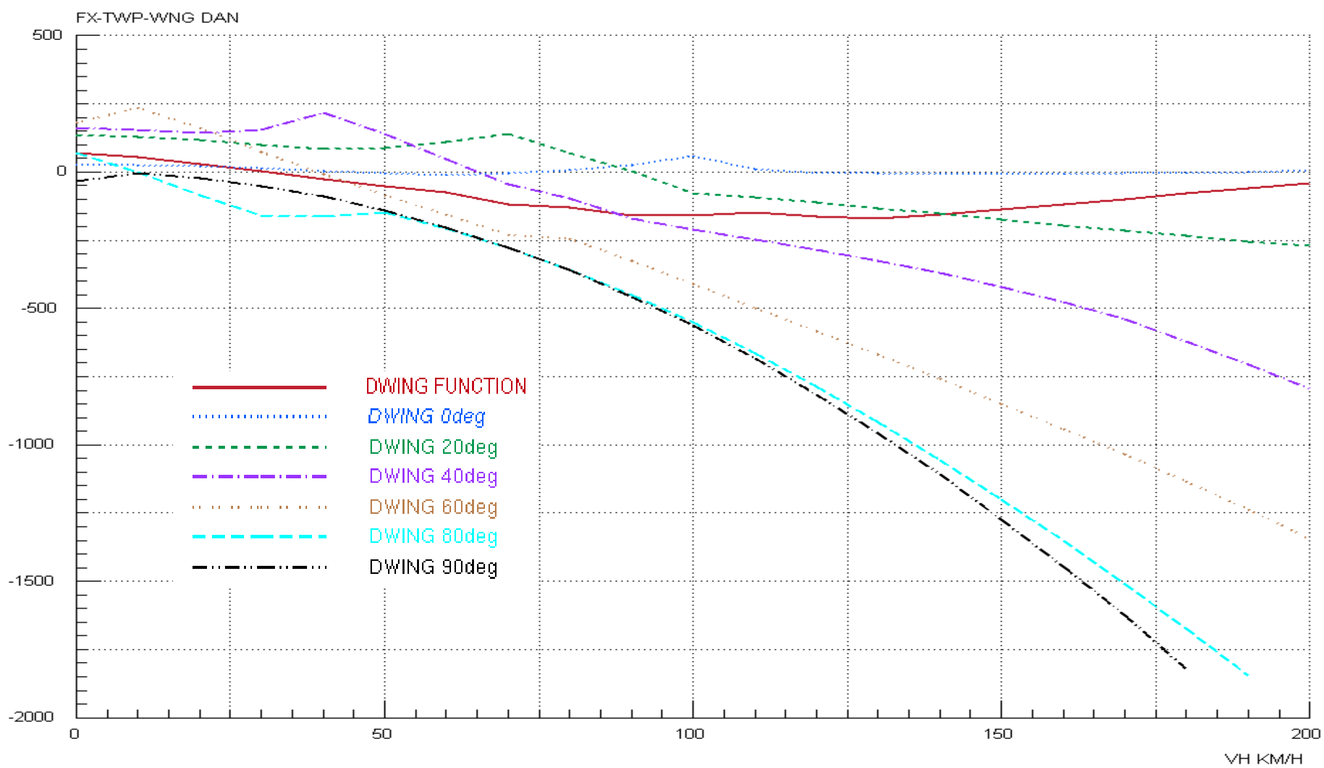

Figure 16. Influence of the wing tilt angle on the drag force exerted on the tilt wing in helicopter mode.

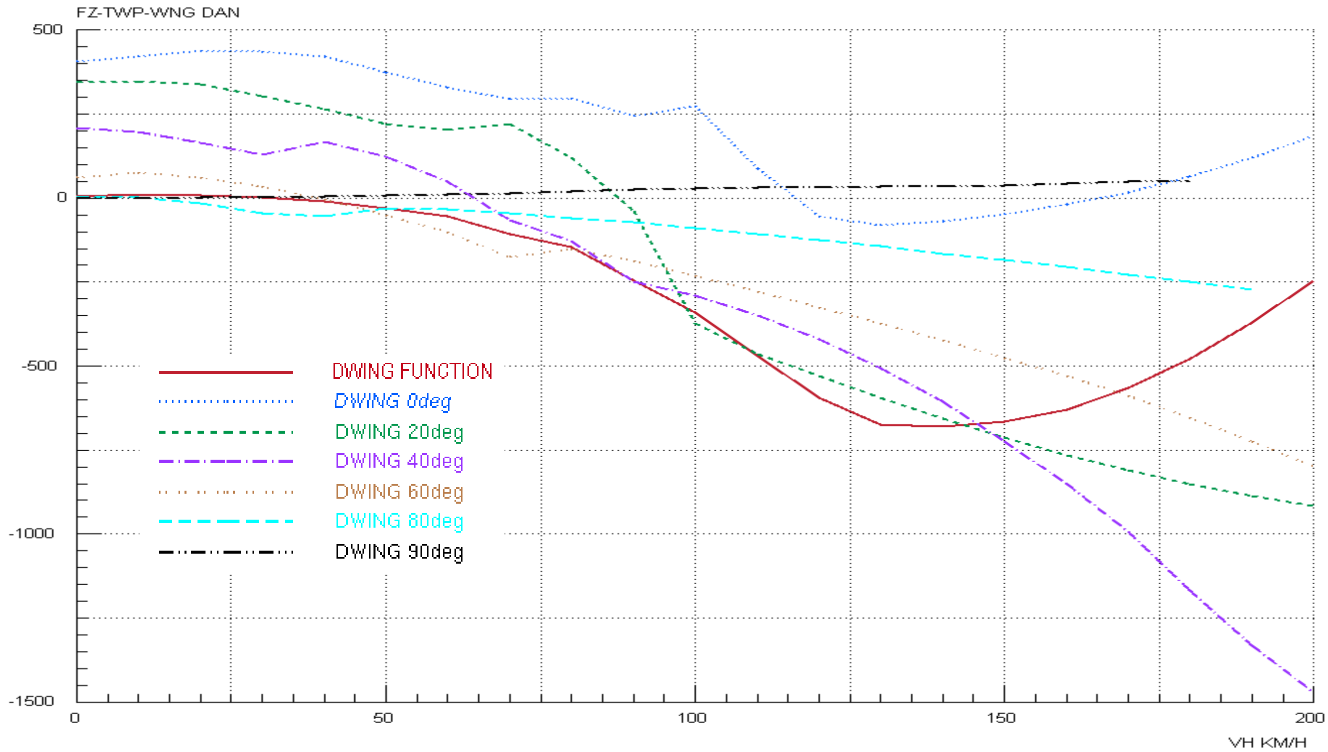

Figure 17. Influence of the wing tilt angle on the lift force exerted on the tilt wing in helicopter mode.

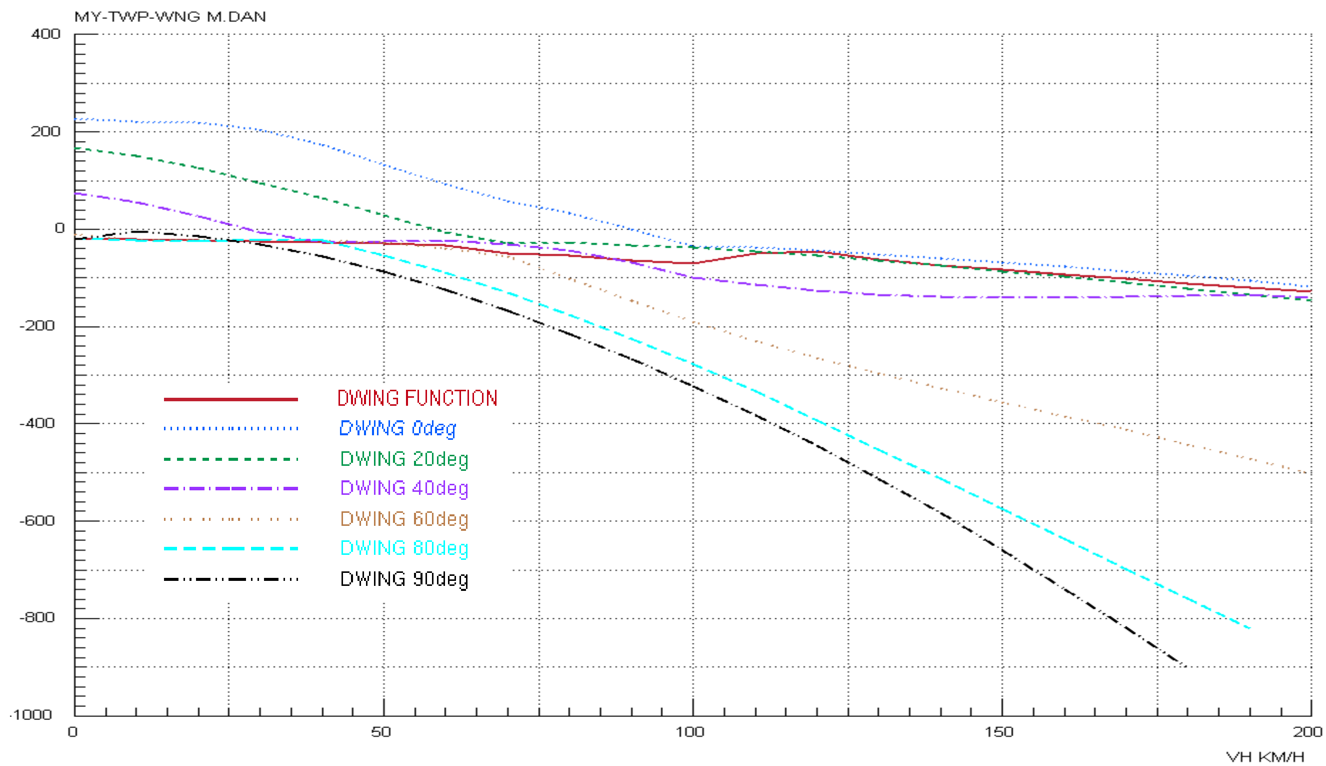

Figure 18. Influence of the wing tilt angle on the pitch momentum exerted on the tilt wing in helicopter mode.

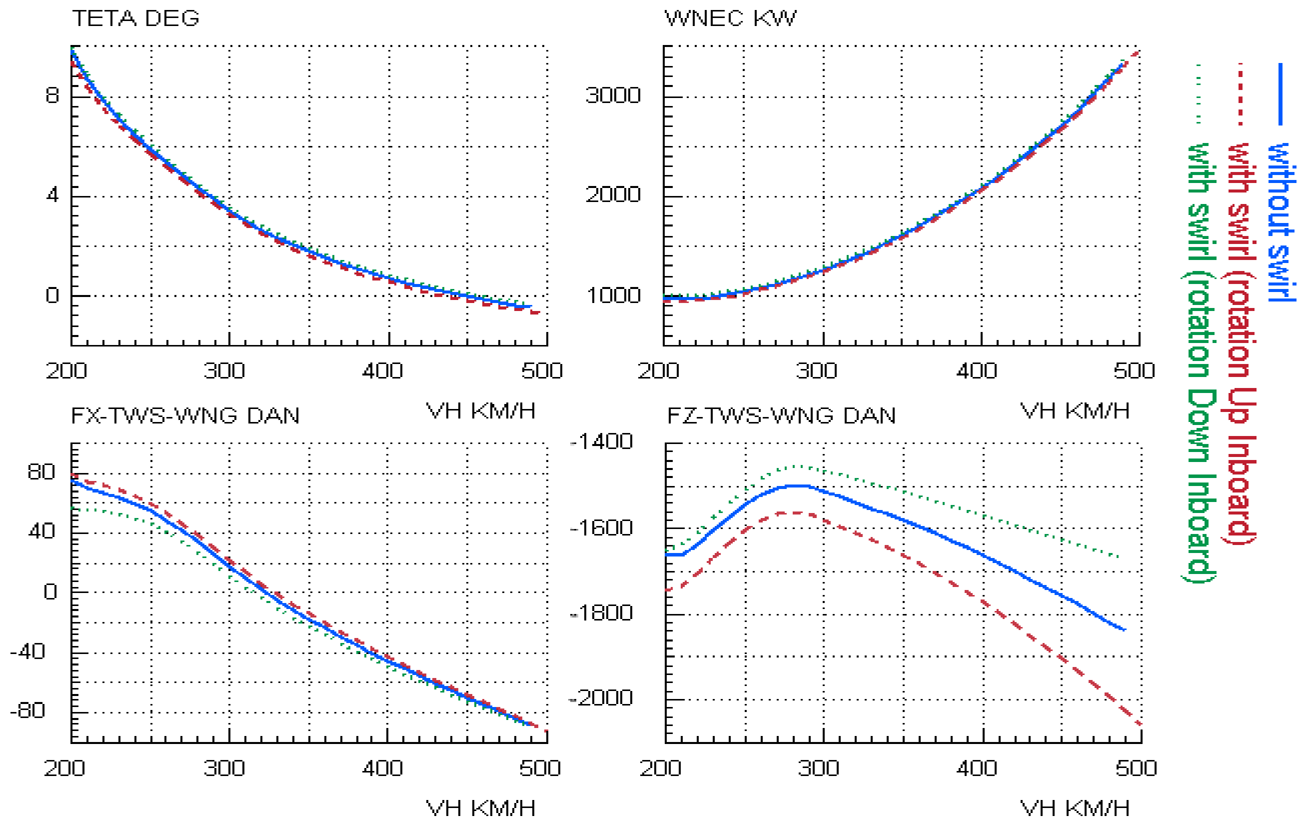

Figure 19. Influence of the swirl effect on the tilt wing in airplane mode.

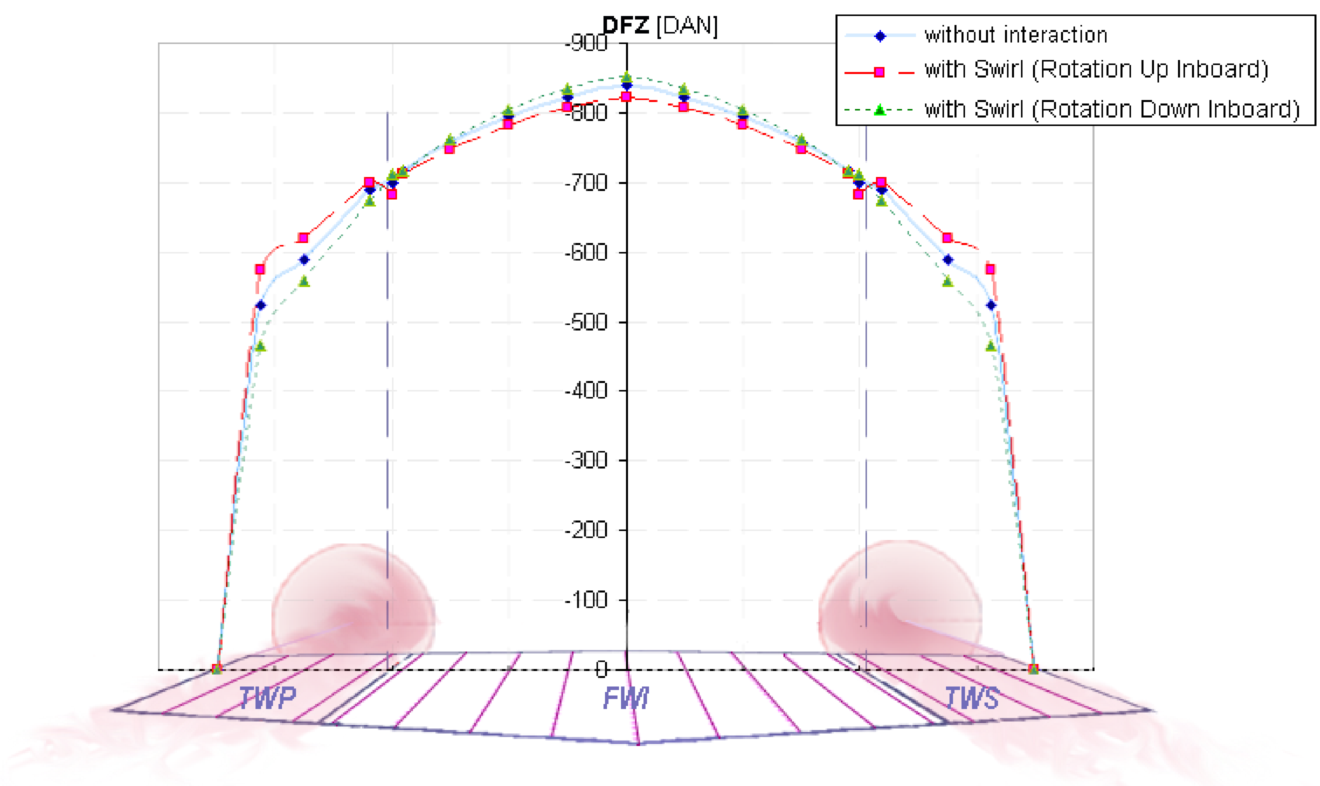

Figure 20. Repartition of the normal force on the wing in airplane mode at 350km/H with and without swirl effect.