

# INTERACTIONS MODELLING FOR A TILTROTOR IN HOST: APPLICATION TO THE ERICA CONCEPT

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**Abstract:** Among the solutions studied to decrease airport congestion due to air traffic increase, the use of civil tiltrotors is an interesting solution. A tiltrotor has the distinctive feature of being able to mix Vertical or Short Take-Off and Landing capabilities with cruise flight at speeds comparable to turboprop aeroplanes. With this configuration, two rotors at the tip of the wing, strong rotors wake/wing interaction occur in hover and low speed conditions producing a wing download force that affect the aircraft performance. In order to reduce this download the concept ERICA has been proposed by AGUSTA. In this concept the wing parts located below the rotors can be tilted in order to decrease the wing download. The best angle to set depends on the flight conditions. When close to the ground, strong ground effect occurs due to the rotors wake ground fountain effect that affects the wing, fuselage and tail loads. These two interaction phenomena have been studied for the ERICA concept with the Eurocopter HOST flight mechanics code.

For the modelling of the wing a non-linear lifting line theory has been developed and implemented in the code. This lifting line model includes both the fixed and moveable parts with the use of the complete 2D-airfoil polar curves of the ERICA wing.

This paper focuses on the rotors wake/wing interaction and ground effect. Download results are presented:

- In hover and forward flight with the influence of the tiltable-wing angle and the swirl effect,
- In lateral flight with the influence of the rotor wake geometry.

Ground effect results in hover focus on:

- The influence of ground proximity on rotors mean induced velocities which has a direct influence on the resultant download force,
- The influence of the ground fountain flow effect on the wing.

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## Notations:

c	wing local chord, m
D	jet thickness, m
DDM	longitudinal cyclic pitch, %

<sup>1</sup> Helicopter Overall Simulation Tool.

<sup>2</sup> Enhanced Rotorcraft Innovative Concept Achievement.

DDZ	collective pitch ,%
DL	wing download, N
$D_{NAC}$	nacelle tilt angle, ° (rad)
$D_{WING}$	tilt wings angle, ° (rad)
$F_x, F_z$	wing drag and lift forces in the wing reference co-ordinate system, daN
NLLL	non-linear lifting line
$M_x, M_y, M_z$	wing momentum in the wing reference co-ordinate system, m.daN
$P_o$	Atmospheric pressure, Pa
T	rotor thrust, N
r	blade radius location, m
R	rotor radius, m
$S'$	distance between jet impingement point on ground plane, m
$u_i$	rotor induced swirl at blade radius r, m/s
$V_0$	aircraft speed, m/s
$V_{im}$	rotor axial mean induced velocity, m/s
$v_i$	rotor induced axiale velocity at blade radius r, m/s
WNEC	Total power requirement, kW
$\Omega$	Rotational speed of the rotor, rad/s
$\rho$	air density, kg/m <sup>3</sup>
$\theta$	aircraft pitch attitude in deg, or Stagnation line slope in ground plane in deg
$\phi'$	computational polar angle measured in ground plane about a jet impingement point referenced to the line joining two jet impingement points, deg
$\kappa$	fountain sidewash inclination measured from the ground plane, deg
$\varpi$	fountain upwash inclination measured from the ground plane, deg
$\zeta$	distance from the ground stagnation line along the upwash direction, m
-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,
IGE	In Ground Effect,
OGE	Out of Ground Effect.

## 1 INTRODUCTION

Several studies carried out, regarding tilt-rotors aerodynamic interactions, have shown that the downwash of the rotors, impinging on the outboard portion of the wings, considerably affects such an aircraft with a download force that occurs in hover and low speed flight conditions (Ref. 1,2,3,4,5). In order to reduce this download the ERICA concept (proposed by AGUSTA Ref. 6) has the distinctive feature of being able to tilt the wing parts located below the rotors (figure 1).

Last year (Ref. 7) the non-linear lifting line model implemented in the HOST was presented as well as some results for this ERICA concept in different flight conditions.

The present paper first focuses on the research of the best wing tilt law for different flight conditions inside the ERICA's conversion corridor. The driving parameter used is the minimisation of the total power requirement. Some results will be presented in forward flight for different nacelle angles.

The behaviour of the ERICA tiltrotor in lateral flight has also been studied. Special attention has been given to the dissymmetric interaction causing a roll moment on the aircraft.

To complete the modelling of the rotor influence on the wing, the swirl velocity induced in the rotor wake has been taken into account. Its influence on the download in hover is analysed.

The last main topic of this paper concerns the implementation of a ground effect model, dedicated to the tiltrotor's configuration, in the HOST code. This model includes both the decrease of the rotors mean induced velocities and the ground fountain flow effect.

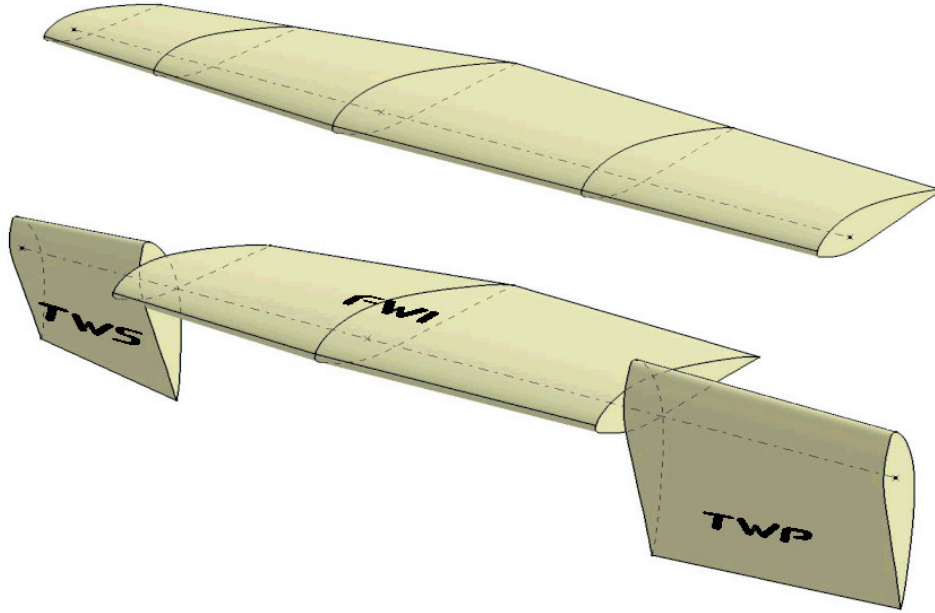


Figure 1: ERICA wing at 0 and 90° tilt wing angle.

## 2 ROTORS WAKE/WING INTERACTION

### 2.1 Wing non-linear lifting line (NLLL)

In order to model the ERICA wing, a non-linear lifting line model able to perform calculations under high angle of attack conditions, has been developed and implemented in the HOST code (See Ref. 7 for more details). This model is suitable for fully attached flow and up to stall region (Ref. 8) but for high angle of attack there are some three-dimensional effects that this type of relatively simple model can't catch. This is confirmed by the literature results on a flat plate perpendicular to the flow, where drag coefficient is lower than the one predicted by the lifting line. Nevertheless, in the ERICA tilt-rotor concept, thanks to its tiltable-wings, high angles of attack are supposed to be avoided. This model may over estimate a little the download force due to interaction between the rotor wake and the wing when high angles of attack are encountered but should be reliable for lower angles.

### 2.2 Rotors wake/Wing intersection

For the intersection between the wing and the rotor wake a quasi-steady cylindrical representation of the rotor wake is used. Taking into account the relative speed at each rotor centre, the mean induced velocities, the nacelles angle and geometric parameters of the tilt-rotor, the two cylinders equations are computed in the wing reference axes system. This model allows computing the percentage of wing chord intercepted by each rotor wake for each section of the lifting line as illustrated in figure 9. This percentage is used to balance the influence of the rotor-induced velocity on each section:

$$V_{im} = V_{imRG} \cdot \%c_{RG} + V_{imRD} \cdot \%c_{RD} \quad (1)$$

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.

### 2.3 Download and Tilt-wing angle law to minimise total power requirement

Thanks to the previous models, it has been possible to evaluate the influence of the tilt-wing angle on the download in hover conditions (figure 2). Figure 3 shows the benefits on the total power required when the tilt-wing angle is close to 85°. This result is coherent with a minimum drag condition on the tilt-wing part.

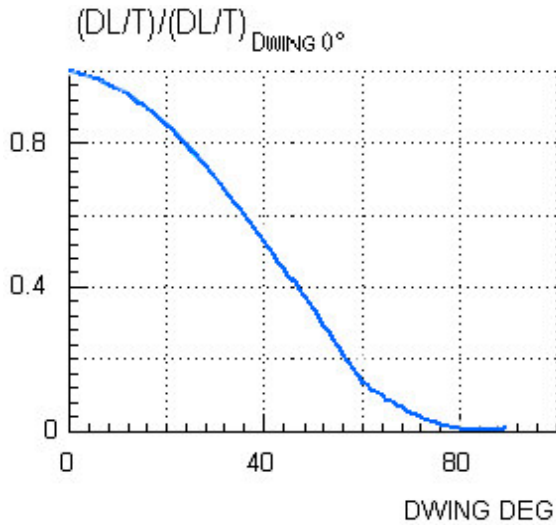


Figure 2: Wing download evolution with the tilt wing angle in hover

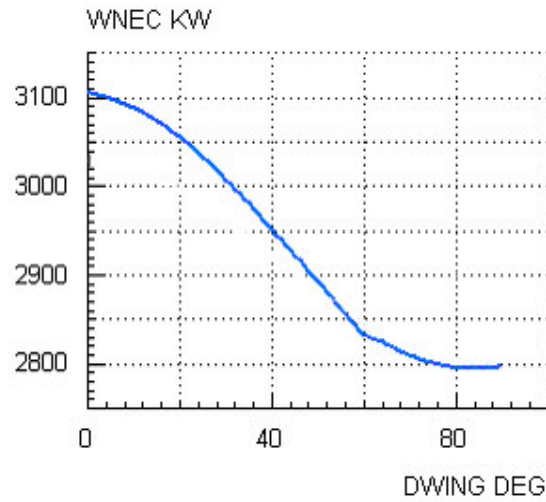


Figure 3: Total power evolution with the tilt wing angle in hover.

The influence of the tilt-wings angle has also been studied in forward flight for the helicopter mode ( $D_{NAC}=90^\circ$ ) and two conversion configurations ( $D_{NAC}=75^\circ$  and  $D_{NAC}=60^\circ$ ). Figures 5,6 and 7 show that the wing tilt angle is a very important parameter regarding the total power requirement.

To have the tilt-wing angle that minimises the total power requirement, at each speed, two strategies have been explored.

First, for each of the three nacelle angles tested ( $90^\circ$ ,  $75^\circ$  and  $60^\circ$ ) calculations have been performed to determine the optimum tilt-wing angle at different fixed forward velocities (figure 4), regarding the total power requirement. The tilt-wing angle laws function of the forward speed can be then determined for each nacelle angle value as it has been done in the helicopter mode (Ref. 7).

The second strategy is based on the assumption that if the tilt-wings are set in the slipstream direction, both the download force and the power required should be minimised. Figures 5,6 and 7 show that it is almost the case for the three nacelle angles considered and all the velocities. The resulting evolution of the tilt-wing angle are also presented on figure 4 in comparison with the "optima" values previously computed.

This strategy of setting the tilt-wings in the slipstream direction is the one that should be adopted because it will work also in conditions different from level flight such as climb or descent.

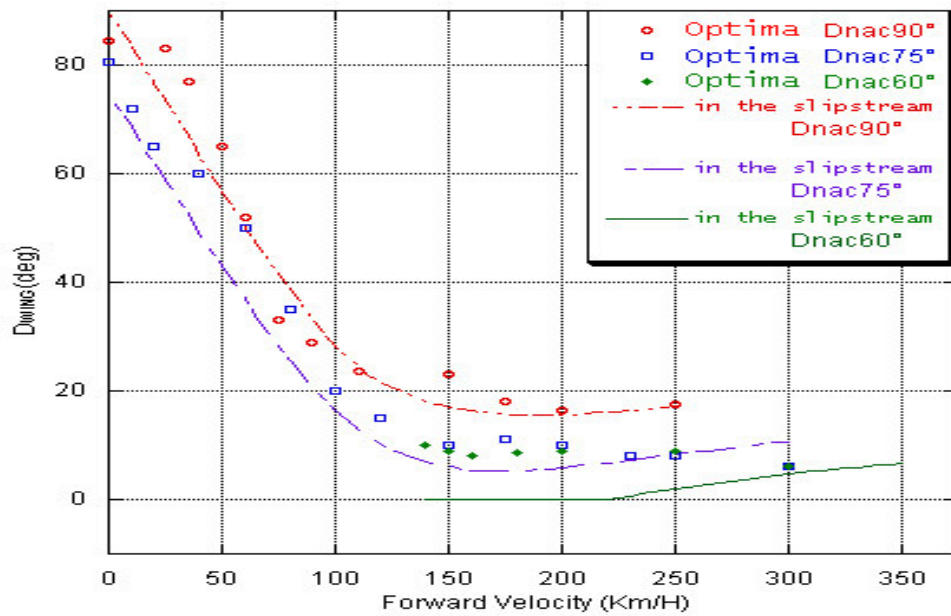


Figure 4: Optimum value of the tilt-wing angle for minimisation of total power requirement compared to the slipstream Tilt-wing angle law

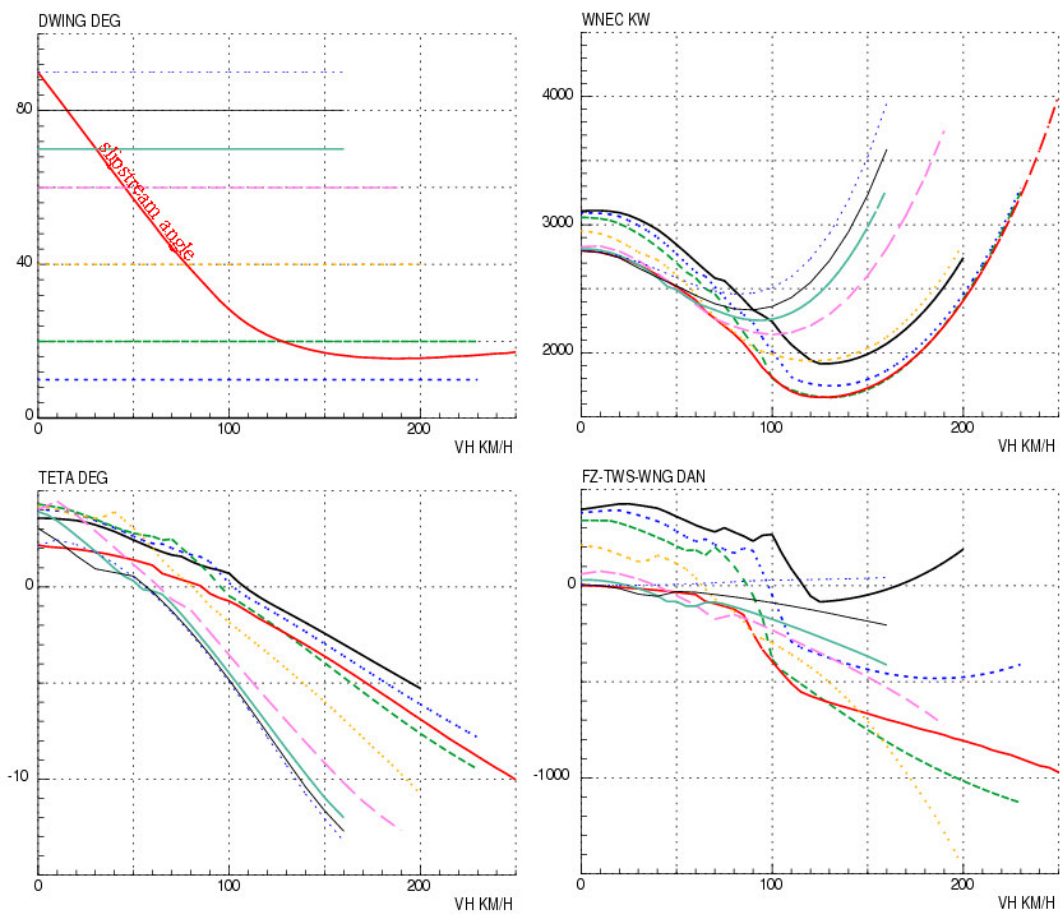


Figure 5: Influence of forward speed and tilt-wing angle on total power requirement ( $D_{NAC}=90^\circ$ )

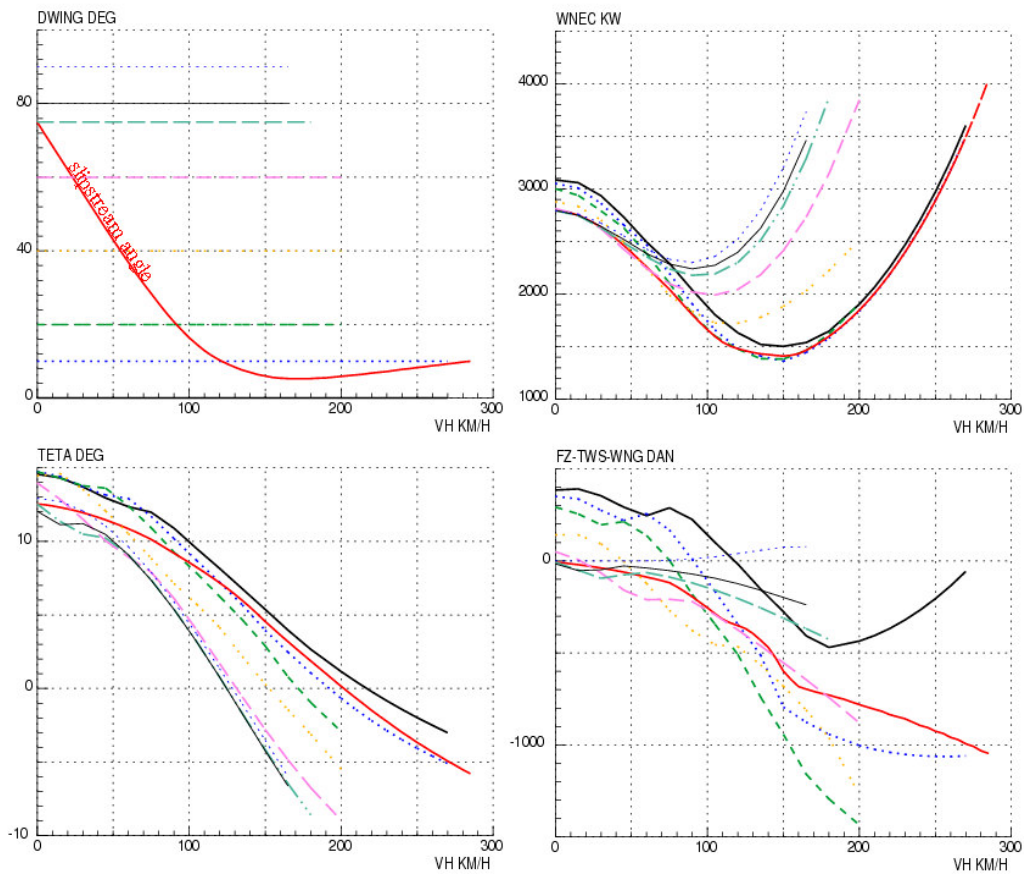


Figure 6: Influence of forward speed and tilt-wing angle on total power requirement ( $D_{NAC}=75^\circ$ )

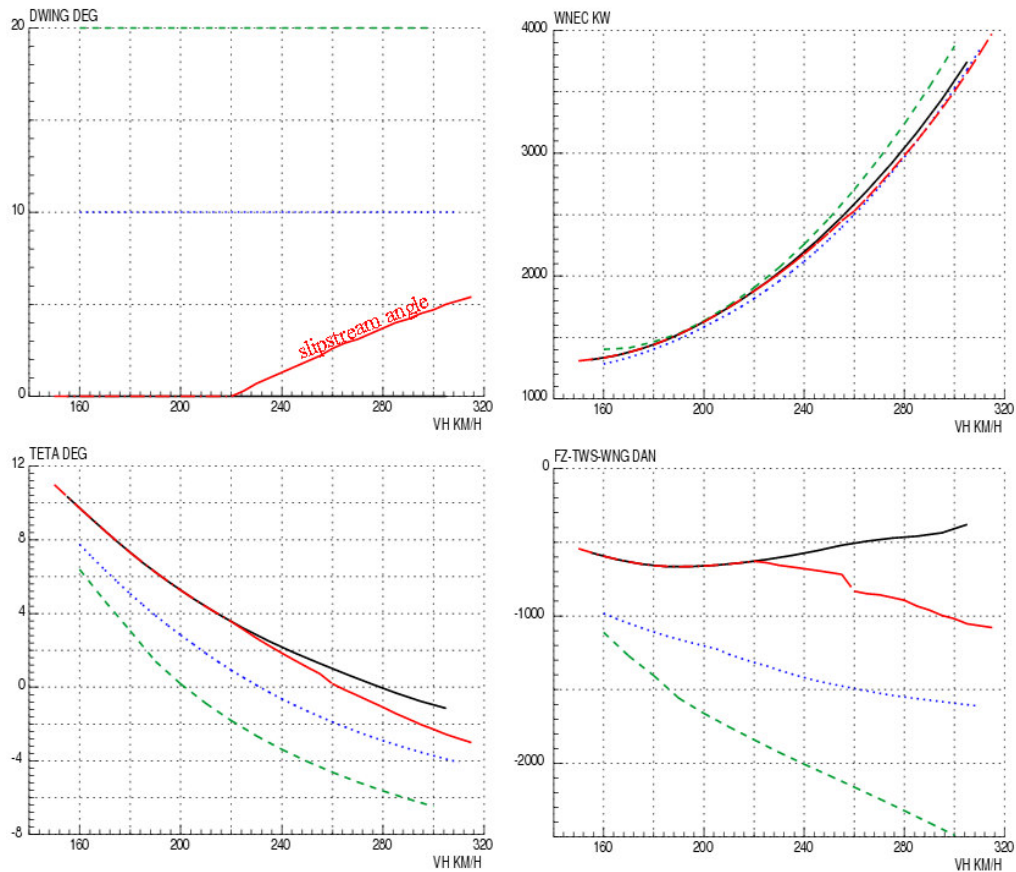


Figure 7: Influence of forward speed and tilt-wing angle on total power requirement ( $D_{NAC}=60^\circ$ )

The models implemented in the HOST (NLLL, Rotors Wake/Wing intersection and interaction) have been also designed for time marching simulations. Figure 8 shows the HOST code results of a time simulation for a slow longitudinal acceleration in helicopter mode with the tilt-wings put in the slipstream direction.

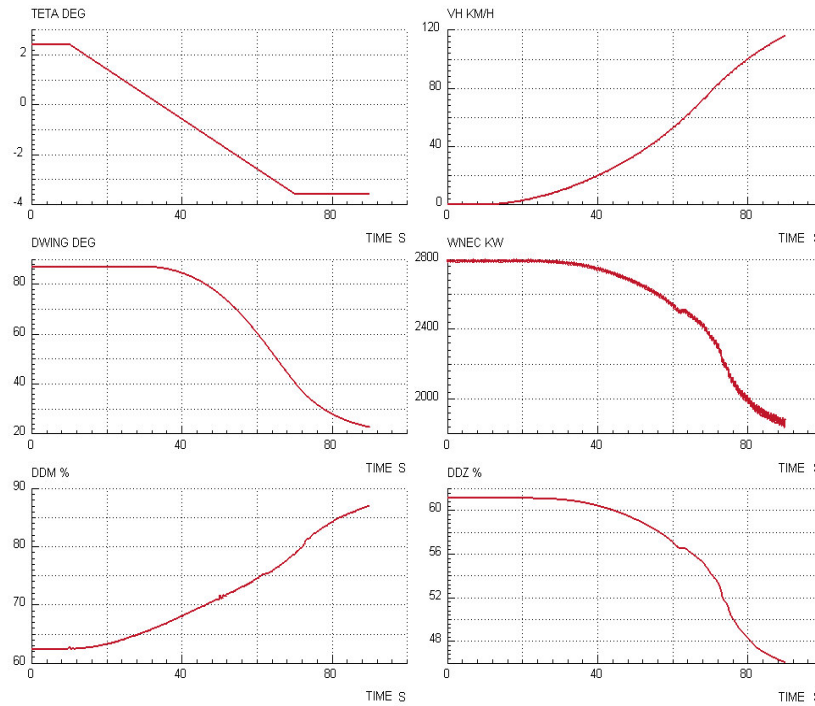


Figure 8: Time simulation results including rotor/wing interaction, for an acceleration from hover up to 120km/h at a constant altitude in helicopter mode

## 2.4 Interaction in lateral flight

When flying to the left as illustrated on figure 9, the rotor wake of the right rotor is swept out of the wing while the left rotor wake is progressively redirected toward the centre of the wing. Thanks to the lifting line model in conjunction with the rotors wake/wing intersection modelling it is possible to analyse the influence of lateral velocity magnitude on the forces and moments produced. Even if this representation doesn't take into account the influence of the fountain flow resulting in such conditions it can be admitted that its influence on the behaviour of the aircraft is secondary to the forces produced by the direct impact of the rotor wakes on the wing. Moreover for a high value of lateral velocity, as one rotor wake is progressively swept out of the wing while the other one is redirected toward the centre of the wing as illustrated on figure 9, the fountain flow will decrease rapidly.

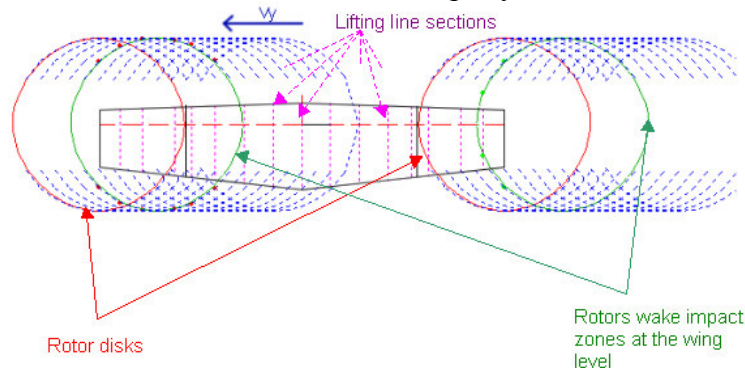


Figure 9: Schematic representation of the rotors wake and its impact on the wing in helicopter mode for a lateral flight

Figure 10 shows that the HOST code is now able to render the corresponding decrease of the download force on the right tiltable wing and the increase on the fixed wing as the left lateral velocity increases. As well the resulting roll moment due to the right tilt-wing is decreased while the one due to the fixed and left tilt-wing is increased. The resulting roll moment participates to the roll motion to the left.

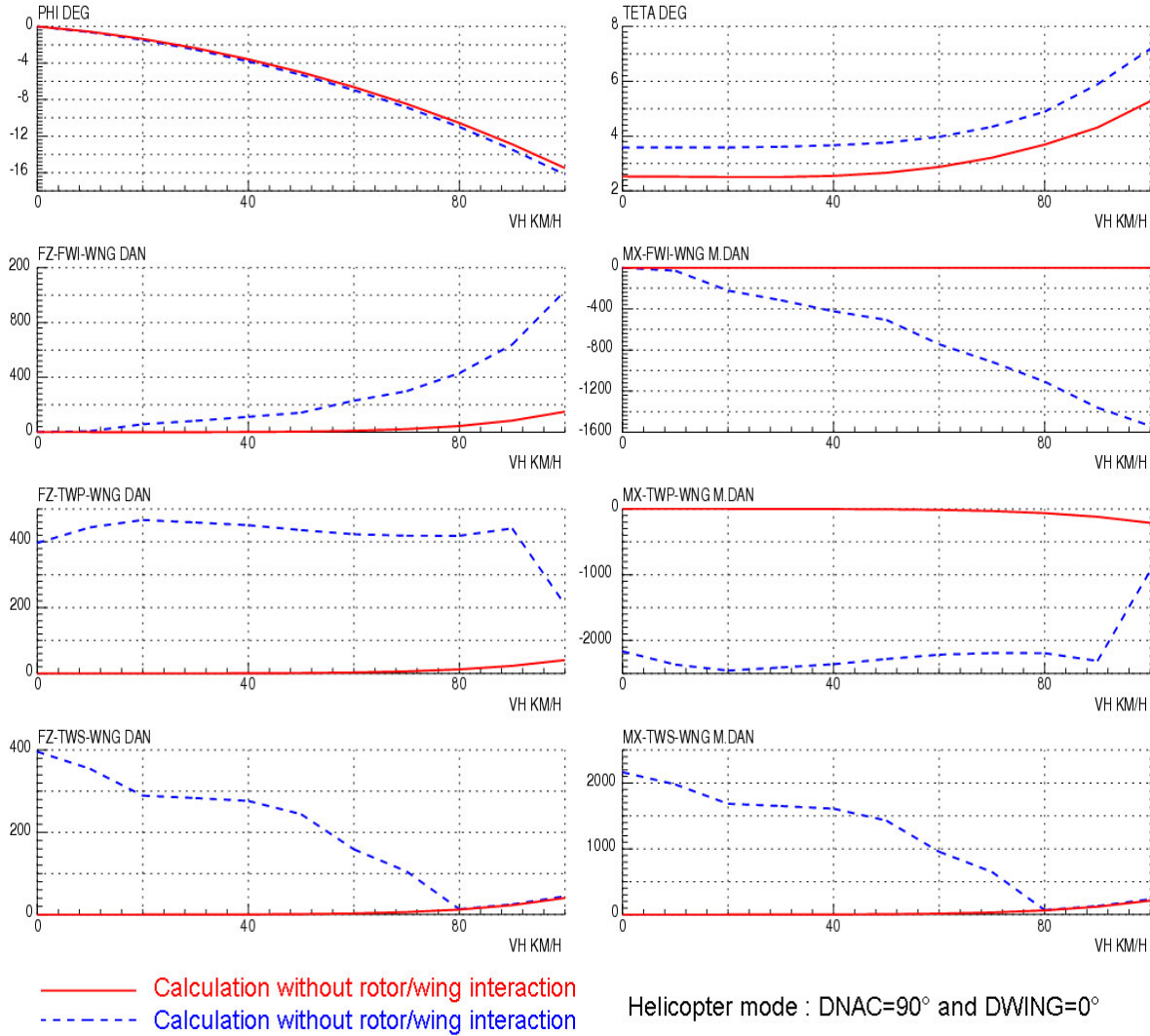


Figure 10: Influence of rotor wing interaction in helicopter mode for a sweep in lateral velocity  
(Roll moments are referenced to the centre line of the wing)

## 2.5 Swirl induced by the rotor wake

It is widely admitted that the rotor direction of rotation in helicopter mode has an effect on the download force (Ref 2,3,4). This is due to the swirl induced in the rotor wake (figure 11) that influences the local incidence on the wing. M.A.McVeigh et al. (Ref 1) have also highlighted the influence of the swirl component of the induced velocity in airplane mode which was demonstrated last year (Ref 7) with the non-linear lifting line code.

- Swirl around hover conditions

A model to compute the swirl velocity in helicopter mode is now presented. It is based on the 'Extended momentum theory' presented in Wayne Johnson's book (Ref. 9) and which yield to a relation (Equation 2) between the induced swirl velocity " $u_i$ " and the induced axial velocity " $v_i$ " at each radius " $r$ " along the blade.



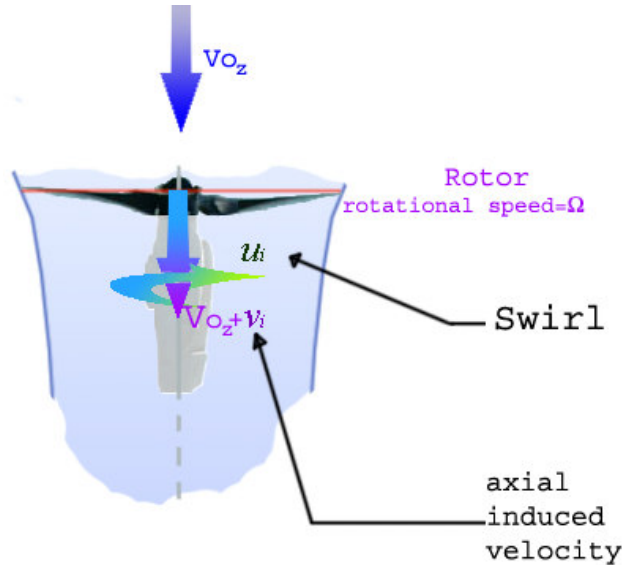


Figure 11: Swirl Induced in the rotor wake

This formulation can be used near hover conditions:

$$2(V_{Oz} + v_i)v_i = u_i \left( \Omega r - \frac{u_i}{2} \right) \quad (2)$$

With  $u_i$  and  $v_i$  functions of  $r$  and  $V_{Oz}$  the axial velocity

Solving this equation for the swirl velocity  $u_i$  gives only one physical solution:

$$u_i = \Omega r - \sqrt{\Omega^2 r^2 - 4V_{Oz}v_i - 4v_i^2} \quad (3)$$

If the axial induced velocity is known from experimental measurements or from calculations, the swirl velocity and the resulting angle induced in the slipstream can be computed. To validate this approach, especially around hover conditions, comparisons have been made between the measurements performed by D.W. Boatwright (Ref 15) and the swirl velocity computed with equation (3) using the mean axial induced velocity measured as an input (figures 12,13).

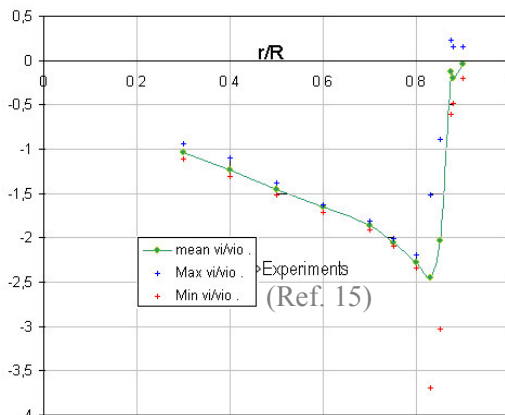


Figure 12: Axial induced velocity at a location 0.1 R below rotor.

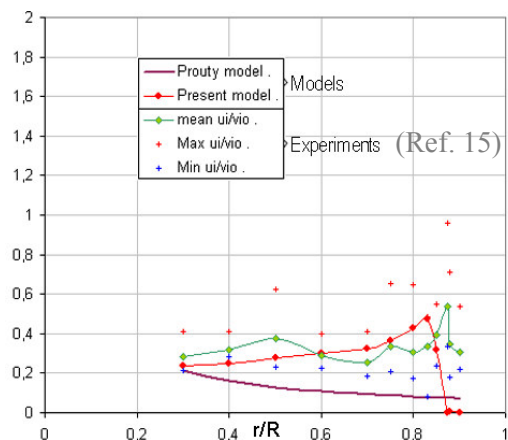


Figure 13: Swirl induced velocity at a location 0.1 R below rotor.

On the figure 13 is also reported the results obtained with a formulation given in R.W.Prouty's book (Ref. 10). Fair comparisons are obtained between our results and the experimental re-

sults. Note that the swirl velocity is imaginary for  $r^2 < (4v_i V_0 + 4v_i^2)/\Omega$  and is therefore not considered.

The swirl velocity has been incorporated in the modelling of the interaction between the rotor wake and the wing. Figure 14 shows the influence of the swirl on the download in hover conditions for a sweep in tilting angle and for the two directions of rotation of the rotors. These download results show that the "up inboard" direction is better than the down inboard as already observed for conventional tiltrotors (Ref. 1, 4).

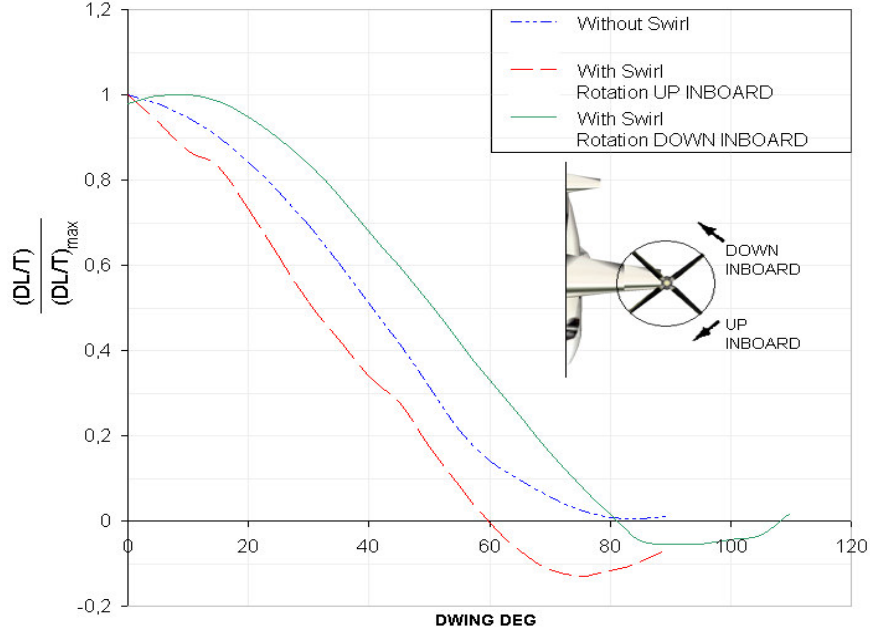


Figure 14: Influence of the swirl and the direction of rotation on the wing download in hover.

- Forward flight extension

It is possible to extend the previous model to forward flight conditions with the H.Glauert (Ref. 11) resultant velocity at the rotor disk in forward flight:  $U^2 = (V_0 \cos \alpha)^2 + (V_0 \sin \alpha + v_i)^2$  as illustrated on figure 15:

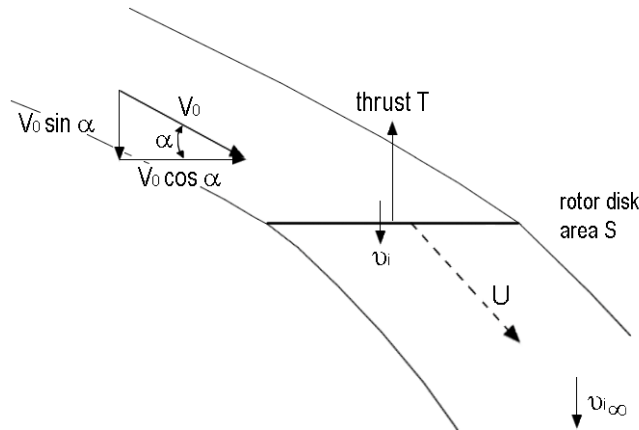


Figure 15: Flow model for momentum theory analysis of a rotor in forward flight.

The rotor traction on a circular element  $dS$  located at  $r$  is given by:

$$dT = 2\rho v_i \sqrt{V_0^2 + 2V_0 v_i \sin \alpha + v_i^2} dS \quad (4)$$

Thus, the 'Extended momentum theory' leads to a new formulation of the relation (2) valid in hover and forward flight:

$$2v_i \sqrt{(V_0 \cos \alpha)^2 + (V_0 \sin \alpha + v_i)^2} = u_i \left( \Omega r - \frac{u_i}{2} \right), \text{ with } u_i \text{ and } v_i \text{ functions of } r \quad (5)$$

Solving this equation for the swirl velocity  $u_i$  gives:

$$u_i = \Omega r - \sqrt{\Omega^2 r^2 - 4 \sqrt{(V_0 \cos \alpha)^2 + (V_0 \sin \alpha + v_i)^2} v_i} \quad (6)$$

Note that for  $\alpha=90^\circ$  and  $V_0 \sin \alpha = V_{0Z}$ , (6) is equivalent to (3).

### 3 GROUND EFFECT

When hovering in ground effect, it has been shown that the wing download decreases with the height above the ground (Ref. 4,5,12,13). This is due to two aspects:

- Ground proximity constrains the rotor wake, decreasing the rotor-induced velocities.
- A ground fountain flow generated under the aircraft by the interaction of the two rotors wakes on the ground gives an upwash at the wing and fuselage level (figure 20).

#### 3.1 Mean rotor induced velocity decrease

A law taking into account the decrease of the induced velocity with the height above the ground is already implemented in the HOST code:

$$\frac{v_{i_{IGE}}}{v_{i_{OGE}}} = f_{GE} \left( \frac{H}{R} \right) \quad (7)$$

Figure 16 shows the resulting evolution of the ratio  $v_{i_{IGE}}/v_{i_{OGE}}$  in comparison with experimental data issued from various references reported in Prouty's book (Ref.10). The decrease of the induced velocity is well predicted.

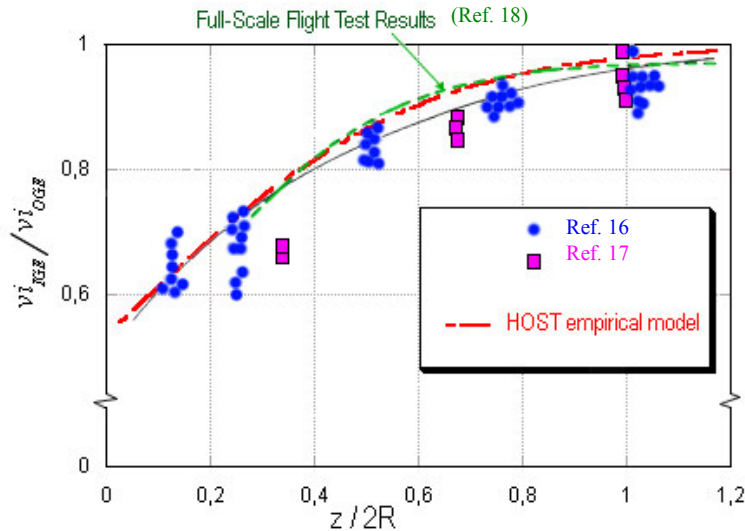


Figure 16: Ground effect on Mean Induced velocities.

Figure 23 shows the comparison of the predicted download including this effect with experimental ones (reported in Ref. 4). The reduction of the predicted download is not enough to catch all the download reduction observed experimentally.

### 3.2 Ground fountain flow

The reduction of the induced velocity cannot explain the rate of reduction of the download and even more the apparent upload force produced when a tiltrotor is very close to the ground (see the experimental results of F.F.Felker and Marr and al. reported on figure 23).

If we consider the interaction of the two rotor wakes in expansion on the ground, there is a resulting fountain flow formed just under the aircraft centre line and the wing. This ground fountain flow effect will produce an upload force that counteracts the download. This upwash can also impact the tail plane producing a pitch moment on the aircraft (figure 20).

A modelling of this ground fountain flow phenomenon is now presented.

#### 3.2.1 Rotor outwash in ground effect

A first step is the modelling of the rotor outwash velocities in ground effect ( $v_2$  on figure 17) that will give the strength of the fountain flow due to the confrontation of the two rotor's outwash.

Let consider an actuator disk of area  $S$  and total thrust  $T$  to represent the rotor. It is assumed that the loading is distributed uniformly over the disk. Let  $v_i$  be the induced velocity at the rotor disk and  $v_2$  be the wake induced velocity parallel to the ground and far from the rotor wake centre of impact. Let also assumed that the pressure in the far wake in expansion on the ground (station 2) is at ambient level  $P_o$ .

Applying Bernoulli's equation between station 0 and  $I^-$  along  $LC1$  gives:

$$P_o = P_1^- + \frac{1}{2} \rho . v_i^2 \quad (8)$$

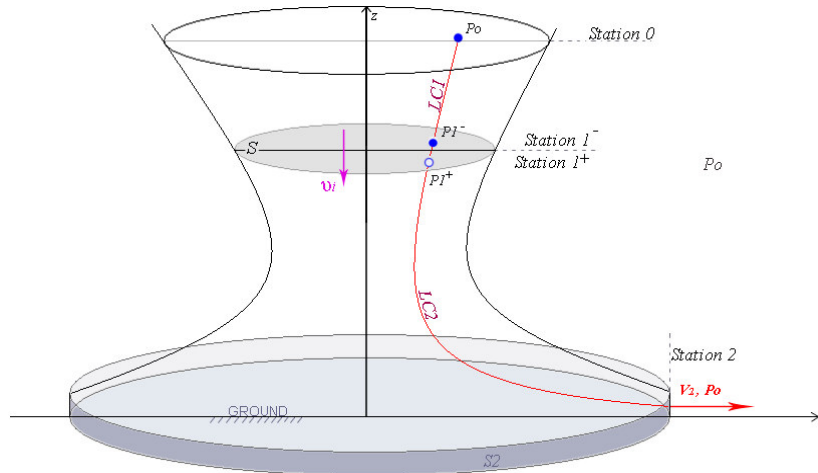


Figure 17: Flow model for rotor outwash analysis in ground effect.

Then between station  $I^+$  and 2 along  $LC2$  gives :

$$P_1^+ + \frac{1}{2} \rho . v_i^2 = P_o + \frac{1}{2} \rho . v_2^2 \quad (9)$$

Combining these equations, we obtain :

$$T = \Delta P . S = (P_1^+ - P_1^-) . S = \frac{1}{2} \rho . S . v_2^2 \quad (10)$$

If  $v_{iOGE}$  is the induced velocity of the rotor when out of ground effect, momentum theory gives the following relation between the thrust  $T$  and  $v_{iOGE}$ :

$$T = 2 . \rho . S . v_{iOGE}^2 \quad (11)$$

Equations (10) & (11) give the following relation between  $v_2$  and  $v_{iOGE}$ :

$$T = 2 \cdot \rho \cdot S \cdot v_{iOGE}^2 = \frac{1}{2} \rho \cdot S \cdot v_2^2$$

$$\Rightarrow v_2 = 2 \cdot v_{iOGE} \quad (12)$$

This result has been compared with experimental results issued from flight test in hover of a tiltwing (*CL-84*) and a tiltrotor (*XV-15*) but also with results issued from the *ROTWASH* (Ref. 14) program for various tiltrotors. Figure 18 shows a fair agreement between this estimation (Equation 12) and the peak velocity of the experiments or the *ROTWASH* results.

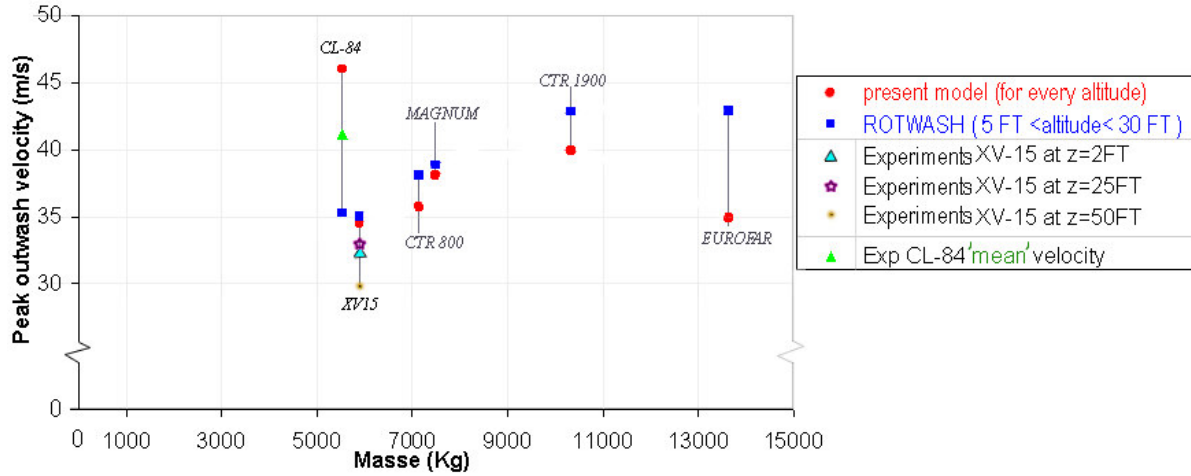


Figure 18: Comparison of peak outwash velocity in ground effect.

The experimental results of the *XV-15* show a small decrease of the outwash velocity for height between 2ft and 50ft. The experimental results of the *XV-15* as well as the *ROTWASH* results (figure 19) show that the peak outwash velocity is always reached for a distance of about  $1,5 \cdot R$  from the impingement point of the wake.

In the hypothesis of radial wall jet behaviour, the decrease of the velocity with the distance from the impingement point  $y$ , will follow:

$$v_2(y) = 2v_{iOGE} \sqrt{\frac{1,5R}{y}}, \text{ for } y \geq 1,5 \cdot R \quad (13)$$

(For  $y < 1,5 \cdot R$  a linear law is taken starting from a zero outwash velocity on the impingement point). Figure 19 shows a good agreement with experiments and *ROTWASH* results.

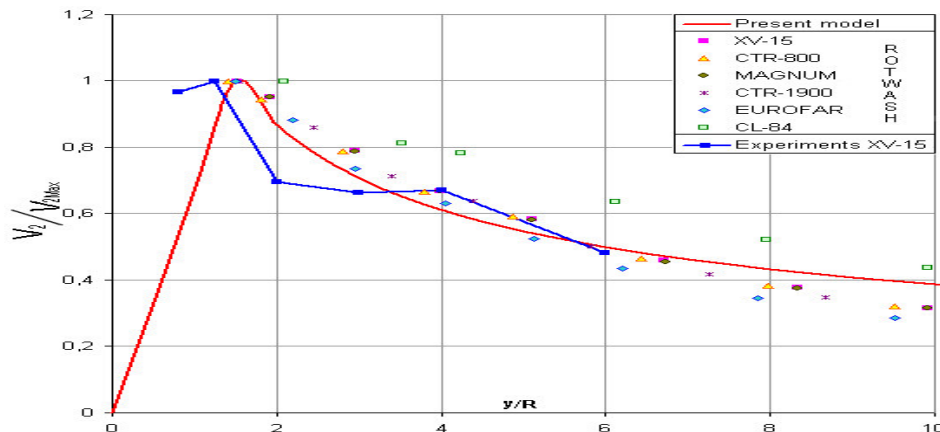


Figure 19: Decrease of peak outwash velocity in ground effect with lateral displacement.

The rotor outwash velocity obtained from equations (12 and 13) will be used to compute the ground fountain flow effect.

### 3.2.2 Impinging jets modelling in hover

The ground fountain flow is also experienced by jet VSTOL aircraft having more than one jet propulsion device (Ref. 19). If the swirl component of the induced velocity is neglected, we can assimilate the rotors wake to two jets impinging on the ground. This configuration has been well studied and modelled by D.R.Kotansky in the case of jet VSTOL aircraft (Ref. 19). The hover case with symmetric conditions on the rotors is now considered.

To compute the fountain flow effect due to these impinging jets it is needed to have:

- The stagnation line (figure 20) resulting from the confrontation of two jets impinging on the ground,
- The fountain upwash direction defined with the two local angles  $\varpi$  (upwash inclination) and  $\kappa$  (sidewash inclination),

In the fountain flow region:

- The velocity profile,
- The spreading rate with distance  $\zeta$  along the upwash direction in order to have the wing area concerned with this upwash flow,
- The velocity magnitudes decrease with distance  $\zeta$  along the upwash direction.

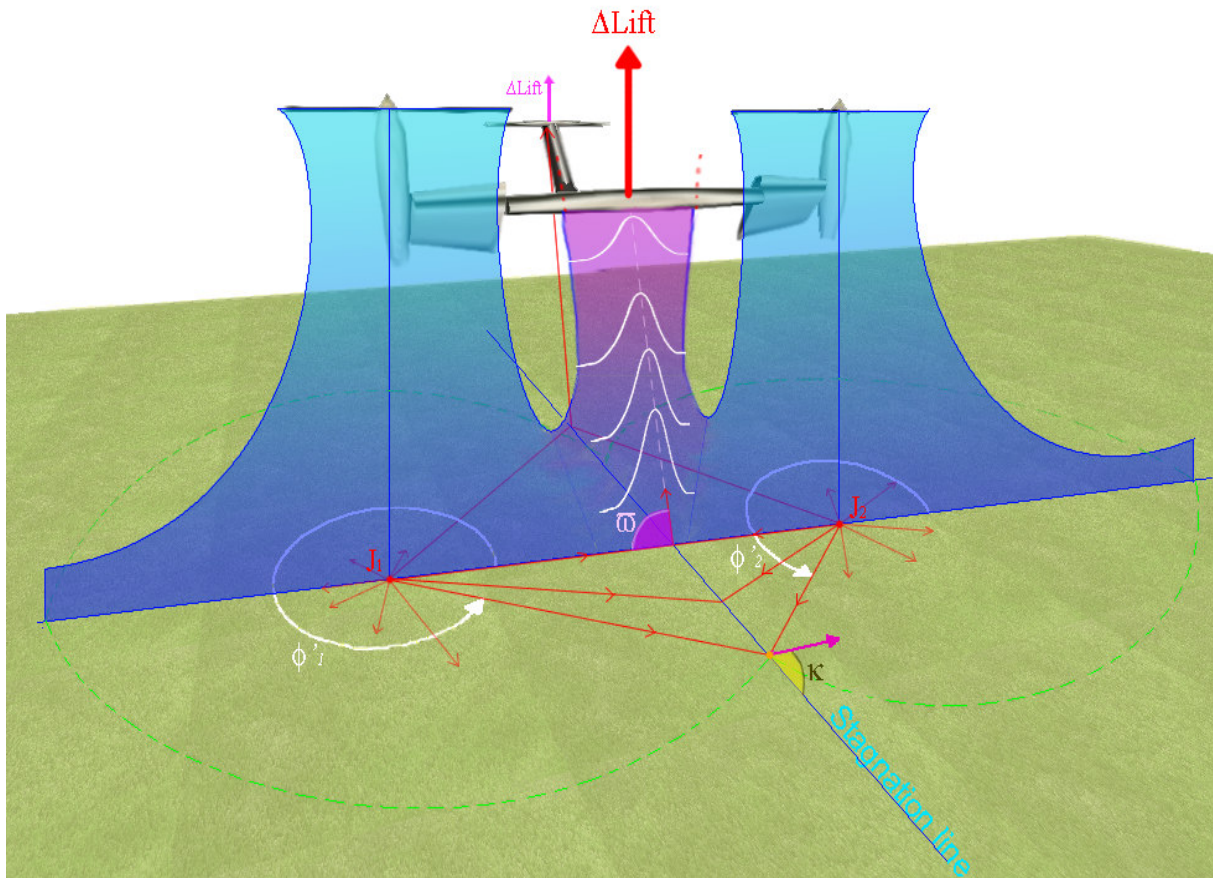


Figure 20: Schematic ground fountain effect modelling with impinging jets.

From symmetry conditions it is clear that:

- The stagnation line is a straight line equidistant from the centre of impact of the two jets,
- The upwash inclination  $\varpi$  is equal to  $90^\circ$  all along the stagnation line.

D.R.Kotansky gives in Ref. 19 for the sidewash inclination  $\kappa$ :

$$\tan \kappa = \frac{2}{\cot\left(\frac{\pi}{2} - \phi'_1\right) + \cot\left(\phi'_2 - \frac{\pi}{2}\right)} \quad (17)$$

with  $(\phi'_1, \phi'_2)$  locating the point considered on the stagnation line (see figure 20).

Still in Ref. 19, D.R.Kotansky gives an empirical two jets fountain spreading rate and the corresponding velocity profile illustrated on figures 21 and 22. The spreading rate follows:

$$\frac{\eta_f}{D} = 1.0 + 0.70 \frac{\zeta}{D} \quad (18)$$

In the present case this spreading is limited to the distance between the two rotor jets.

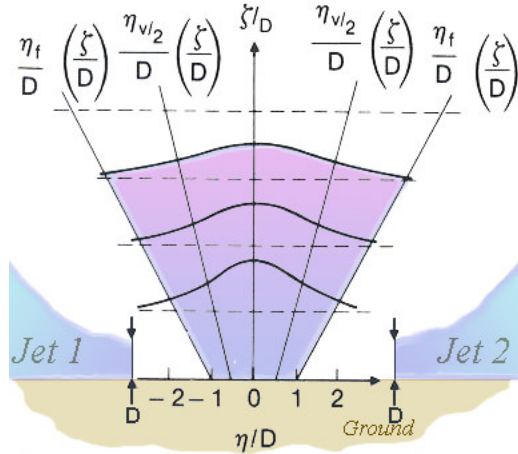


Figure 21: 2-jet fountain spreading characteristics (Ref. 19)

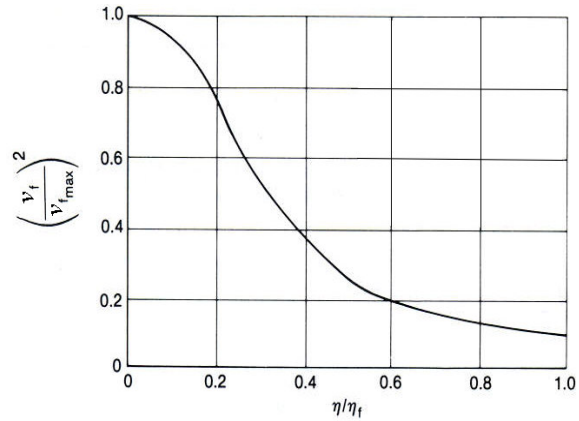


Figure 22: Empirical 2-jet fountain dynamic Pressure Profile (Ref. 19)

The velocity profile (figure 22) is the same all along the upwash direction (Ref.19).

The velocity magnitude decrease, with distance  $\zeta$  along the upwash direction, is given using plume jet behaviour:

$$v_{f \max}(\zeta) = v_{f \max}\left(\frac{\zeta}{D}=1\right) \cdot \frac{D}{\zeta}, \text{ for } \zeta \geq D \quad (19)$$

### 3.2.3 Fountain flow effect on download in hover

Part 3.2.1 gives the outwash velocity from each rotor in the wall-jet on the ground by equation 13, and from mass continuity the thickness of the jet  $D$  is also computed. Then using equations 18 and 19 provides the velocity magnitude decrease and the spreading rate along the upwash direction. Combined with the velocity profile figure 22, it is possible to compute the fountain flow along the wing span.

The fountain flow effect on the download behaviour has been evaluated and the results reported on figure 23 show a good correlation with the experimental results.

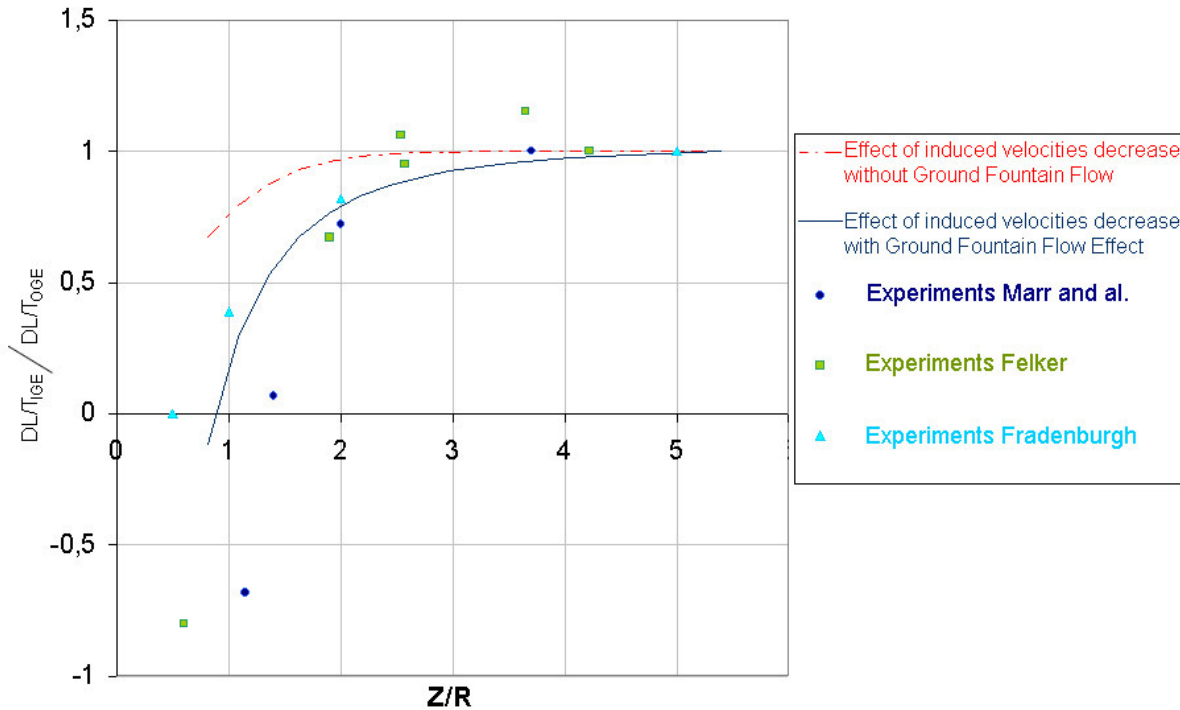


Figure 23: Download evolution in ground effect with tilt-wings at  $D_{WING}=0^\circ$ .

#### 4 CONCLUSION

The use of a non-linear lifting line model in the HOST code for the modelling of a tilt rotor wing and a rotor wake/wing interaction model have been applied to the ERICA tiltrotor concept. The main results presented in this paper focus on:

- The tilt-wing angle influence on download in hover and forward flight for different nacelles angles: the results demonstrate that by putting the tilt-wing in the slipstream direction the download force due to rotors wake/wing interaction is minimised and therefore the total power required,
- Time marching simulation for an acceleration between hover and  $V=120\text{km/h}$ ,
- Lateral flight with rotor wake/wing interaction: the results show that the rotors wake dissymmetric displacement on the wing due to the lateral velocity has an influence on the roll moment on the wing,
- Swirl velocity induced in the rotor wake in hover conditions: the results presented show the effect of the swirl on the download and also the effect of rotor direction of rotation.
- In hover the ground effect including both the decrease of the rotor induced velocity and the ground fountain flow effect have been modelled. The global effect on the download has been evaluated.

Future activities will concern in particular:

- Extension of the swirl in forward flight conditions for conversion mode,
- Extension of the ground fountain flow effect on the tail plane in hover conditions,
- Extension of ground effect modelling to low speed forward flight conditions,
- Addition of the ground effect on the wing,
- Validation of the results with specific wind tunnel tests.



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