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IMPROVED VORTEX RING MODEL FOR HELICOPTER PITCH UP PREDICTION

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Brite Euram project BE-95-1311 HELIFLOW includes investigations into specific problems of helicopter flight mechanics. Task n°1 of that project is dedicated to the pitch-up phenomena. Wind tunnel tests have been performed in a DERA wind tunnel on a model designed by AGUSTA and DERA. Local flow measurements were performed by CIRA. A vortex ring model for the rotor wake has been developped in ONERA to compute the interaction with the horizontal stabilizer. This paper describes this vortex ring model and presents the improvements and the validation of the improved model by comparison of the computed results with wind tunnel tests results obtained for trimmed level flight configurations. This work was supported by the EUROPEAN UNION under the Brite Euram programme.

NOTATION

b	Number of blades
c	Local blade chord
C_z	Airfoil lift coefficient
R	Rotor radius
V_{airp}	Airspeed in the airfoil plane
$(v_{i0}, v_{i1c}, v_{i1s})$	First harmonic coefficients of the induced velocity field on the main rotor
γ_{ij}	Local vortex strength
$(\gamma_0, \gamma_{1c}, \gamma_{1s})$	First harmonic coefficients of the vorticity distribution on a vortex torus
Γ_{ij}	Local bound circulation on a blade-element
ψ	Azimuth angle
μ	Advance ratio
Ω	Rotor rotational speed

1-INTRODUCTION

For trimmed level flight of an helicopter configurations a main rotor wake/horizontal stabiliser interaction occurs at low speed with the rotor wake "impacting" directly on the stabiliser and its consequence is the pitch up phenomenon characterised by an increase of the helicopter pitch angle for a certain range of forward speed. A rotor wake model is needed to compute such an interaction. In order to have a good compromise between realism and acceptable computing time needed for flight mechanics computations, a vortex ring model has been developed in ONERA in the past years.

In order to avoid infinite induced velocity values for a point close to a vortex ring, viscous core radii are required. However, the wake model being discontinuous the induced velocity at a given point will depend on its location relatively to the vortex rings and to the viscous core radii. In order to avoid a time marching method to obtain the average induced velocity at a given point that will lead to a large computing time, a new approach has been developed.

This model has been connected with the EUROCOPTER flight mechanics code HOST and comparisons with wind tunnel test results are presented.

2-WIND TUNNEL TESTS

The task 1 of the Brite Euram program HELIFLOW is dedicated to the pitch-up phenomena.

This phenomena is due to the interaction between the main rotor wake and fuselage components at low speed which modify the pitch attitude. For example, the download effect on the horizontal stabilizer is to increase the pitch moment of the helicopter around its gravity center position and therefore its pitch attitude.

From a quasi - vertical position under the rotor in hover, the main rotor wake is progressively swept back when the helicopter forward speed increases. This change in the relative position of the rotor wake and the stabilizer, produces on the curve of the pitch attitude w.r.t. the horizontal speed, a perturbation called the "pitch - bump".

The HELIFLOW pitch-up tests have been performed in the DERA Farnborough low speed wind tunnel on a model designed by AGUSTA and DERA : generic helicopter model with a streamline fuselage with no tail rotor and the possibility of 4 horizontal stabilizer locations (Figure 1).

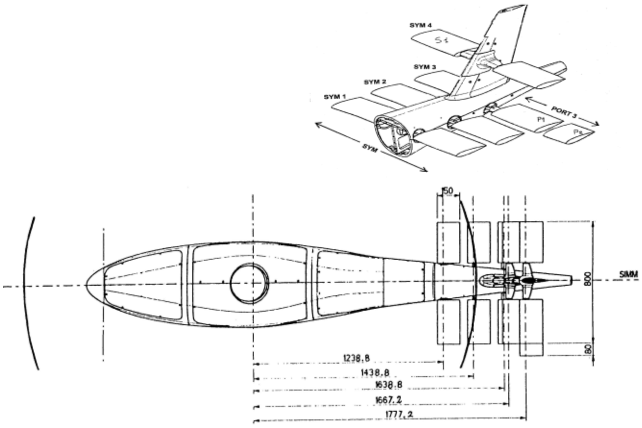

Fig. 1 : DERA Wind tunnel tests (Heliflow).

Local velocities at the location of the horizontal stabiliser and vertical forces on this stabiliser have been measured by CIRA and DERA for a sweep in advance ratios.

Detailed description of the tests and of the results is presented in **[1, 2]**.

The most direct indication of pitch-up is given by the evolution of tail plane normal force with the increase of advance ratio. This is shown in Figure 2 for each empennage position.

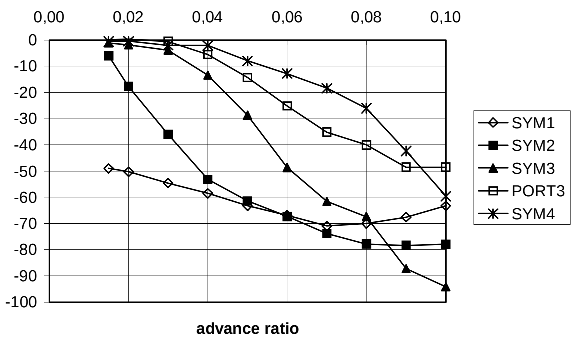

Fig. 2 Horizontal stabilizer normal force.

At the most forward position SYM1 (for this position the horizontal stabilizer quarter-chord is about at 83% of rotor radius behind the hub), the empennage is in the main rotor wake for the complete advance ratio range considered and therefore carries download.

From the position 2 to 4, we can see that the interaction between the wake and the stabilizer is shifted in μ as function of the position of the empennage.

As conclusion, these measurements confirm that pitch-up occurs at higher speeds for more rearward location of the tailplane and it also shows that the peak contribution to pitching moment also increases with more rearward tail positions.

<u>3-ROTOR WAKE MODEL</u>

A rotor wake model based on vortex rings has been developed by ONERA for the needs of helicopter flight mechanics. The vortex wake is represented by groups of concentric and coplanar vortex rings representing the evolution of the circulation along the blade with azimuth (**Fig. 3**).

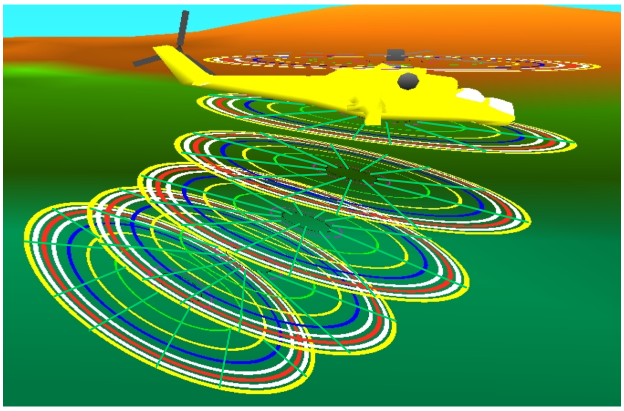

Fig. 3 : Geometry of the rotor wake model.

As in any vortex model, the velocity vector induced by the main rotor wake is calculated at any point in space with the Biot and Savart law. This law of induction requires the knowledge of the wake geometry and its vorticity distribution.

<u>*WAKE GEOMETRY AND KINEMATICS*</u>

*** Geometry :**

The trailing vortex lines generated between the blade elements are produced by the gradient of circulation along the blade span. The shed vortices emitted parallel to the trailing edge of the blade are due to the time variation of the circulation around each blade element.

Each of the helical vortex lines is decomposed into a serie of vortex rings distributed along the wake. The <u>trailing vortices</u> produced during one rotor revolution are represented by a group of concentric and coplanar vortex rings. Their radius correspond to the radial discretisation of the blade, a trailing vortex line is emitted at the root and the tip of the blade and between the blade elements.

In the plan of each group of vortex rings, radial segments are added between two azimuth directions occupied by the blade in order to model the <u>shed vortices</u>.

Thus, the vortex wake is finally represented by vortex rings with radial vortex segments (**Fig. 3**). Furthermore, the model is completed by vortex segments distributed along the blade span in order to model the direct effect of each blade element on the airflow by means of <u>bound vortices</u>.

Viscous core radii are required in order to take into account the volumic distribution of the vorticity (around a vortex line) which explains that the induced velocities do not take infinite values near a vortex element. A circular vortex is in fact represented by a torus and a segment by a tube.

*** Kinematics :**

The orientation of each plan of vortices is given by the rotor attitude when they are shed in the wake.

The initial position of the center of each vortex group corresponds to the position of the rotor center at the time of its generation. Then, each vortex group is convected away from the rotor by the resultant fluid velocity across the rotor at the time of the vortex ring emission. The convection velocity is assumed to be the vector sum of the free stream velocity and the mean downwash velocity (v_{i0}) :

$$\vec{V}_{convec}^{i_{age}} = \vec{V}_{air_{CTR}}\left(t_{emis}\left(i_{age}\right)\right) + \vec{V}_{i0}\left(t_{emis}\left(i_{age}\right)\right)$$

Therefore the mean line of the wake is representative of the rotor trajectory and of the evolution of the mean aerodynamic load ($v_{i0} = f(C_T)$).

VORTICITY

The vorticity distribution on each ring is approximated by a Fourier serie limited to the first harmonic. The coefficients (γ_0, γ_{1c}, γ_{1s}) for each *vortex ring* are calculated from the local intensities at the radial position corresponding to the considered ring. These local values are computed from the radial gradient of bound circulation $\left(\partial\Gamma(r,\psi)/\partial r\right)$ on the blades.

The vorticity of each *shed vortex* is calculated from the time derivative of the circulation around the associated blade element. The vorticity of the *bound vortices* is assessed by the circulation around each blade element. The local values ($\Gamma(r, \psi)$) of bound circulation at the middle of each blade element is calculated according to the Kutta & Joukowski law :

$$\Gamma\left(\frac{r_{i-1}+r_i}{2}, \psi_j\right) = \frac{c_{i-1}+c_i}{2} \times V_{air_{p_{i,j}}} \times C_{z_{i,j}}$$

where (c) is the chord, ($Vair_p$) is the airspeed in the airfoil plane and (C_z) is the lift coefficient.

The computation of these different vortex intensities are presented schematically on (**Fig. 4**).

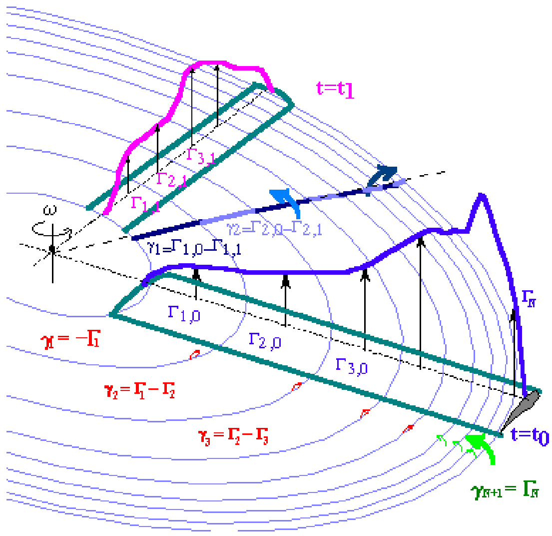

Fig. 4 : Vorticity of the rotor wake model.

INDUCED VELOCITY CALCULATION

The influence of the wake, defined by its geometry and by its vorticity, is expressed in terms of induced velocities by the Biot and Savart law :

$$\vec{V}_i(P) = -\frac{1}{4\pi}\int \gamma(M)\frac{\overrightarrow{MP} \wedge \overrightarrow{dl_M}}{|MP|^3}$$

The use of circular vortices is interesting because the contribution of all the elementary components of a vortex ring can be integrated and a global assessment of the induced velocity vector can be reached with a reduced computational cost The rings and vortex elements induced field can be analytically formulated with their vorticity approximated by a Fourier serie.

A complete description of this vortex of this vortex ring model is presented in **[3]** and **[4]**.

This simplified wake model for helicopter flight dynamics simulation has been implemented in the Eurocopter generic rotorcraft simulation software called HOST (Helicopter Overall Simulation Tool, **[5]**). The vortex rings wake model is discontinuous and so, the induced velocity calculated in a given point for a trimmed configuration depends on the localisation of this point relatively to the vortex rings and to the viscous core radii considered. In order to obtain a more continuous induced velocity field, a new approach has been developped.

4-IMPROVEMENT OF THE VORTEX RINGS MODEL

In order to avoid for trimmed configuration a peak due to the relative location between the vortex rings and the point at which the velocities are computed (Figure 5), a new approach has been considered.

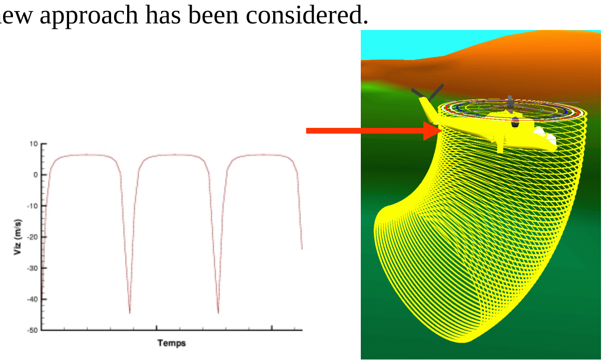

Fig. 5 : Previous model # Instantaneous Values.

The "mean" velocity at a point M is computed from the velocity computed at points M1 and M2 located on straight lines perpendicular to the wake edge and passing trough the middle point between two vortex groups (Figure 6).

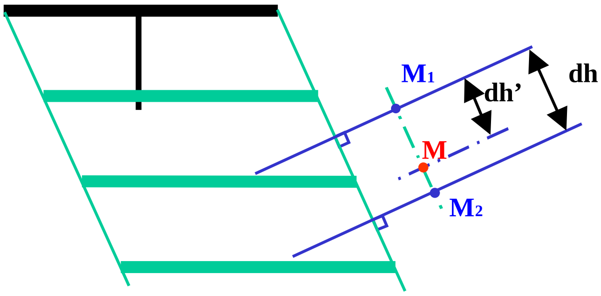

Fig. 6 Improved vortex rings model.

The induced velocity calculated at the point M is then given by :

$$Vi(M) = \alpha Vi(M_2) + (\alpha - 1) Vi(M_1)$$

with $\alpha = \frac{dh'}{dh} \in [0;1]$. With this new approach for trim steady configurations, the relative location of the point where the induced velocities are computed and the discrete vortex groups has no influence anymore as it is demonstrated in Figure 11.

5-COMPARISON BETWEEN EXPERIMENT AND CALCULATION

Comparison are performed both for the local velocities considered on the horizontal stabilizer and for the loads.

WAKE MODEL CONFIGURATION

In a first step, some tests have been performed with the initial model on the influence on the local velocities in the wake of :

- the number of groups of vortex rings along the wake (Figure 7)
- the number of vortex rings in each group (Figure 8)
- the contraction effect that occurs at very low advance ratio (Figure 9)
- the first vortex group position (Figure 10).

The local velocities presented on the following figures have been computed at the location of the left horizontal tailplane for an advance ratio μ=0.04 (X=0 meaning the leading edge of the horizontal stabilizer in position 2).

The experimental results have been obtained by CIRA **[2]**.

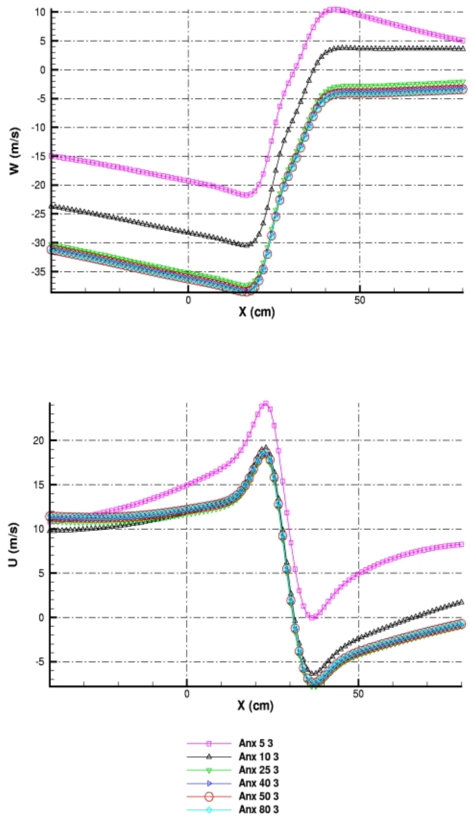

Fig. 7 : Effect of the number of rings groups.

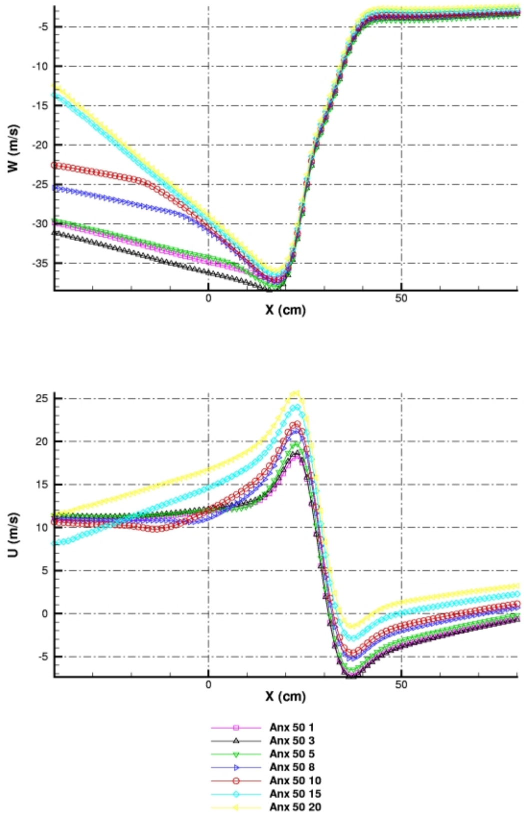

Fig. 8 : Effect of the number of radial rings.

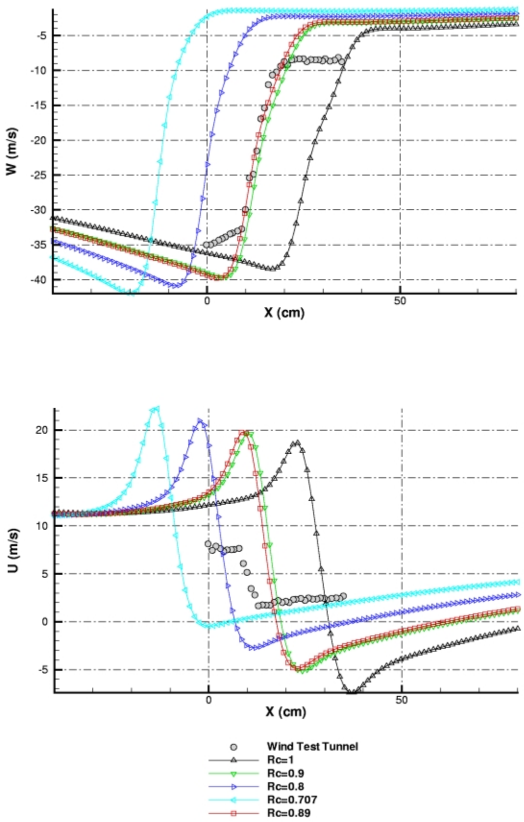

Fig. 9 : Contraction radius effect (Anx 50 3).

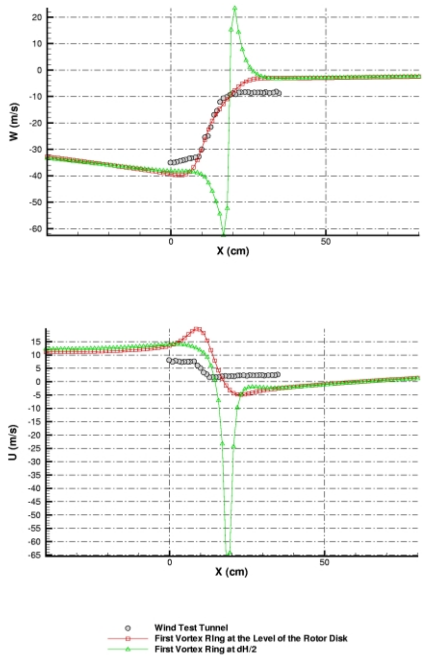

Fig. 10 : Effect of the rings position (Anx 50 3).

Finally, the adopted model configuration for the following computations is a rotor wake represented with 50 groups of 3 coplanar and concentric vortex rings (that is to say with all the trailing vortices emitted by the 2 tip blade elements) and a contraction radius of 0.89.

The results of Figure 10 show the dependency of the rings location on the local induced velocities. With the new approach for trim steady configurations the relative location of the point where the induced velocities are computed and the discrete vortex groups that represent the wake has no influence and the peaks on the velocity that can be encountered when the point is close to a vortex ring disappear (Figure 11).

The computed loads on the horizontal plane are also in better agreement with the experimental ones (Figure 12). In particular the peak predicted by the previous model on the Fz for μ=0.05 disappear with the new model.

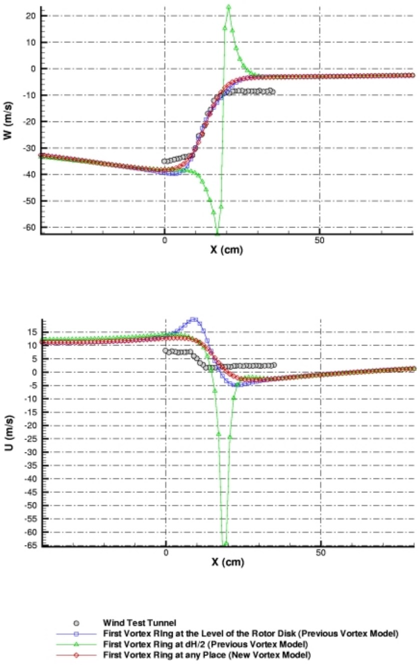

Fig. 11: The new vortex rings model.

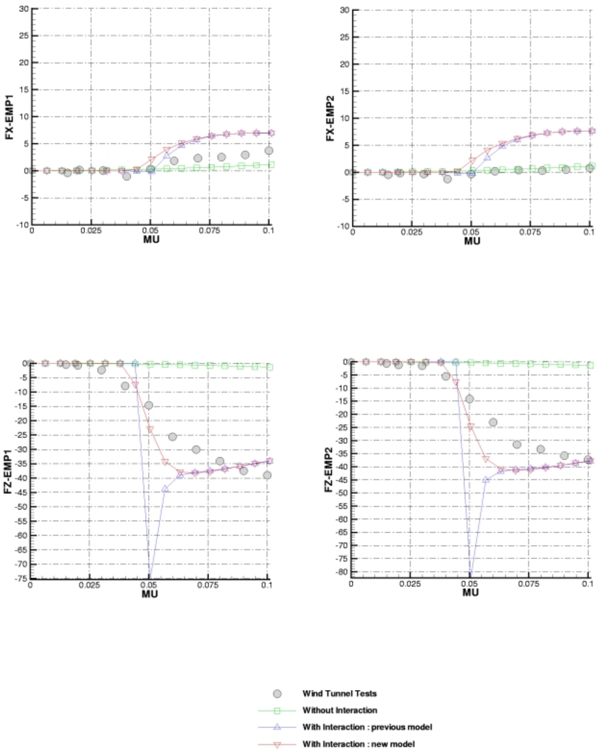

Fig. 12 : Simulation CT/σ=0.08, As=2°, position 3.

RESULTS

Comparisons between computed and experimental results are presented for local induced velocity measurements (Figures 13-14) and for the loads on the horizontal stabilizer (Figures 15-19).

The local velocities (vertical and longitudinal components) are better predicted with the new model (Figure 14) than with the previous one (Figure 13) in particular for the longitudinal component. Indeed, the shift in μ of the entrance in the wake as function of the tailplane position is well predicted and moreover, the amplitude of the longitudinal velocity component is less over-estimated with the new model (Figure 14).

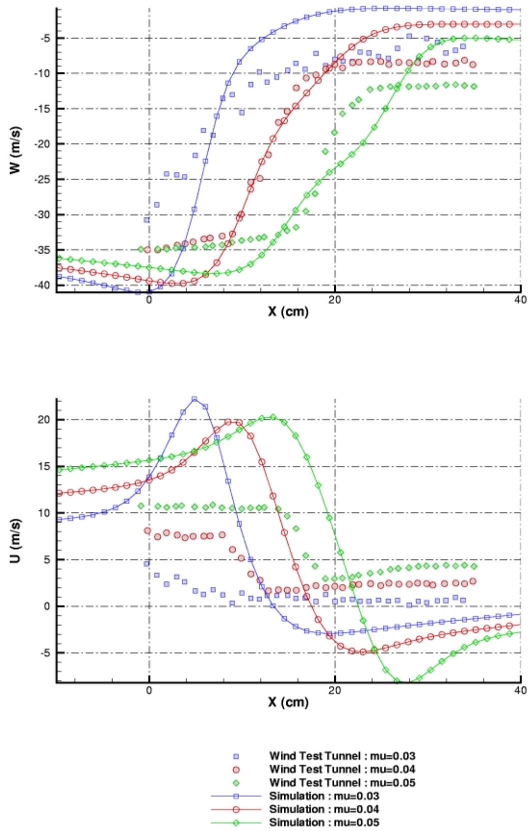

Fig. 13 Influence of μ (previous vortex model).

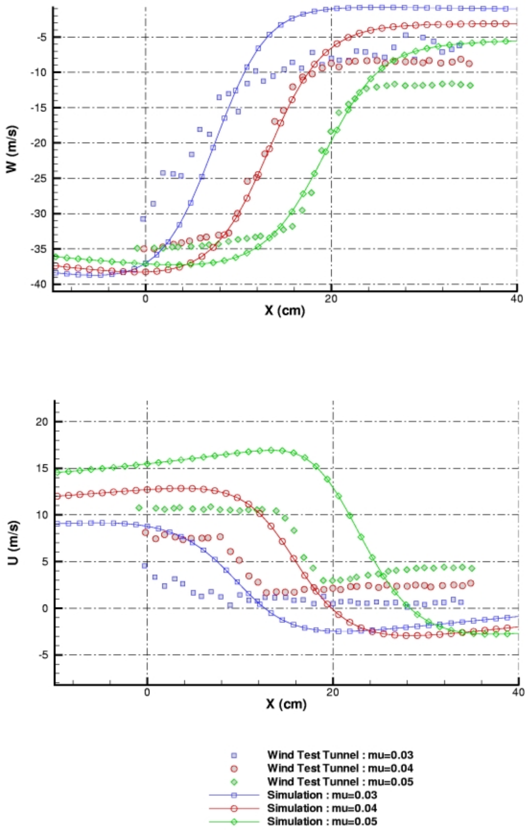

Fig. 14 Influence of μ (new vortex model).

HOST calculations of horizontal stabilizer loads with and without main rotor wake / horizontal stabilizer interaction using the vortex ring model have been performed for the different empennage positions : position 1 (Figure 15), 2 (Figure 16), 3 (Figure 17) and 4 (Figure 18).

Once again the calculations with interaction show the shift in μ of the entrance into the wake as function of the position of the empennage. However, these entrance in the interaction is more sharp in the calculation results than in the test data. In order to reduce this effect the induced velocities on the empennage could be calculated in several points in chord and in span. For example, Figure 19 shows improved results when two points on the horizontal stabilizer are considered.

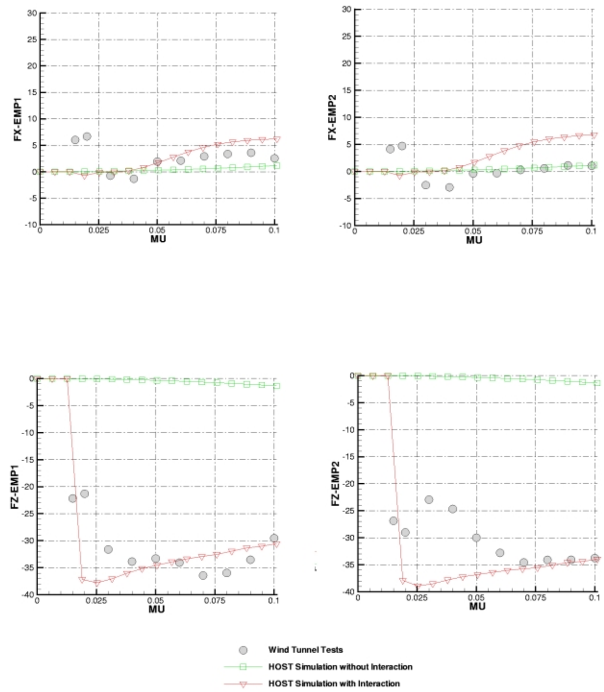

Fig. 15 : Simulation CT/σ=0.08, As=2°, position 1.

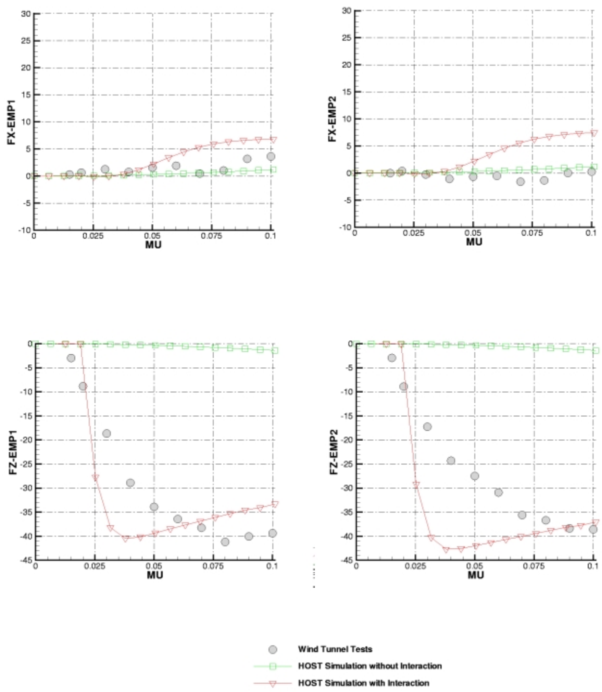

Fig. 16 : Simulation CT/σ=0.08, As=2°, position 2.

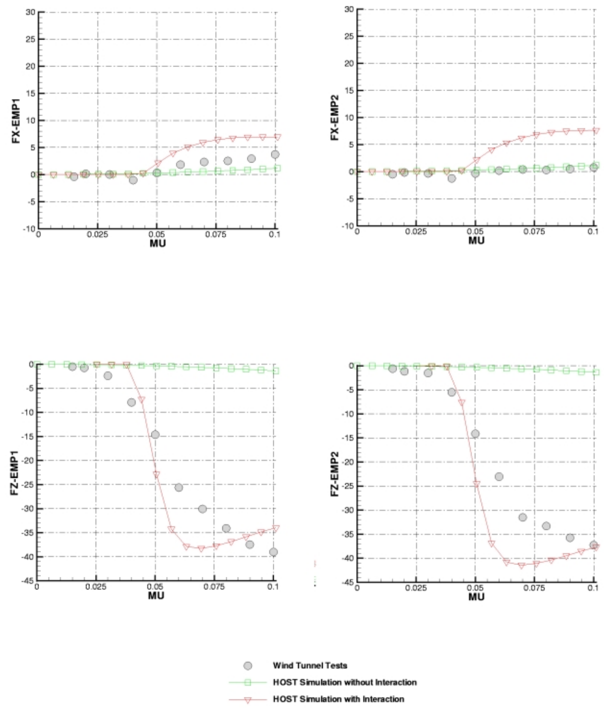

Fig. 17 : Simulation CT/σ=0.08, As=2°, position 3.

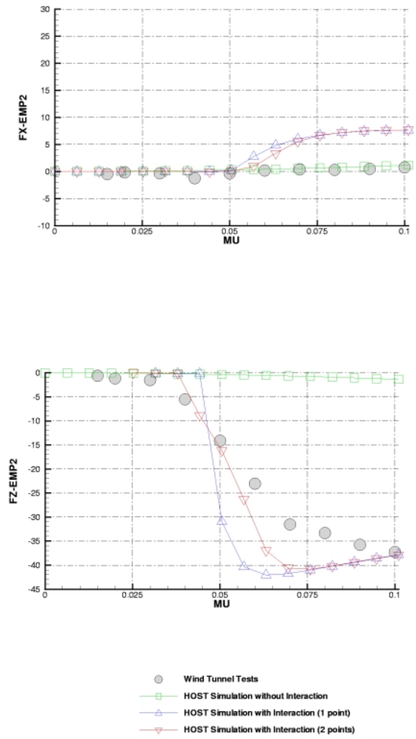

Fig. 19 : Simulation CT/σ=0.08, As=2°, position 3.

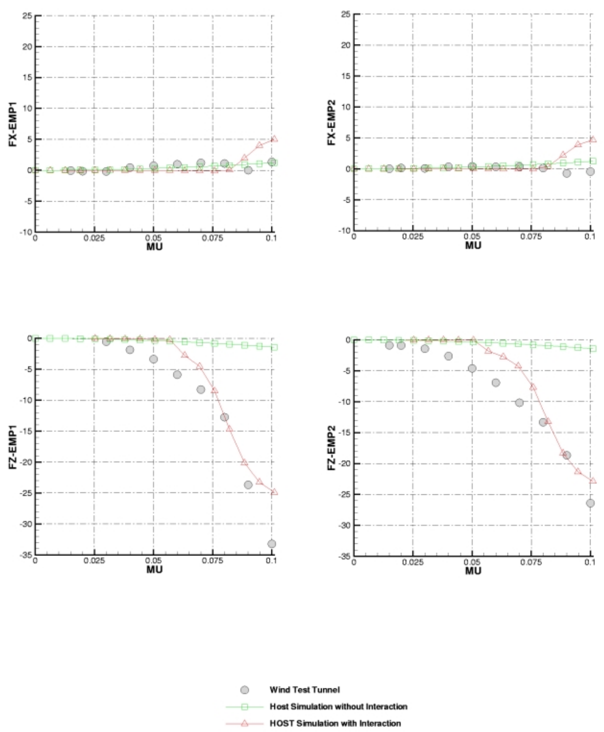

Fig. 18 : Simulation CT/σ=0.08, As=2°, position 4.

6-CONCLUSIONS

A rotor wake model previously developed by ONERA for the purposes of helicopter flight dynamics has been improved. Indeed, in order to avoid the peak of computed velocities due to the relative location between the vortex rings and the point at which the velocities are computed a new approach has been considered. The "mean" velocity at point M is now computed from the velocity computed at points M1 and M2 located on straight lines perpendicular to the wake edge and passing trough the middle point between two vortex groups.

The prediction of the pitch-up behaviour, mainly due to the main rotor wake influence on the horizontal tail, has been studied with this improved vortex rings model.

The computed results compared to the wind tunnel test results show that the computed method is able to predict the passage of the main rotor wake at the level of the horizontal stabiliser and its effect on the stabiliser airloads. These downloads on the stabiliser due to the main rotor wake interaction are at the origin of the pitch up phenomenon.

The improvement of the model allow to avoid the influence of the relative location of the point where the induced velocities are computed and the discrete vortex groups that represent the wake. Indeed, for trim steady configuration, the local velocities (vertical and longitudinal components) are better predicted with the new model in particular for the longitudinal component. The computed loads on the horizontal plane are also in better agreement with the experimental ones.

ACKNOWLEDGEMENTS

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