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STUDY OF THE ROTOR WAKE DISTORTION EFFECTS ON THE HELICOPTER PITCH - ROLL CROSS - COUPLINGS

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The different phenomena which can have an influence on the pitch-roll couplings are evoked. This paper is focused on the wake distortion effects on the main rotor inflow. Parametric studies of the inflow gradients due to angular rates have been performed. The variations of the wake distortion effects are studied for numerous parameters : the airspeed, the center of rotation, the climb rate and the rotor thrust. In a last part, two modelling methods will be addressed : one based on the results of the parametric studies synthesized by a neural network is more adapted for real-time simulation (no vortex wake model being required), the other approach uses directly our dynamic vortex wake model for on-line and closed-loop simulations.

NOTATION

b	Number of blades
c	Local blade chord
$(C_T, C_L, C_M)_{ae}$	Rotor aerodynamic thrust, roll and pitch moment coefficients
C_Z	Airfoil lift coefficient
DDZ, DDL, DDM	Pilot main rotor controls : collective, lateral, longitudinal stick input
K_R	Wake distortion parameter in hover
Kp	Wake distortion parameter corresponding to roll
Kq	Wake distortion parameter corresponding to pitch
[L]	Gain matrix
[M]	Apparent-mass matrix
P, Q	Roll and pitch body angular rates
R	Rotor radius
V_{airp}	Airspeed in the airfoil plane
V_z	Vertical speed
$(v_{i0}, v_{i1c}, v_{i1s})$	First harmonic coefficients of the induced velocity field on the main rotor
X_{GH}, Z_{GH}	Position of the center of gravity relative to the hub
β_{1c}, β_{1s}	Longitudinal and Lateral flapping angles
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

INTRODUCTION

The flight dynamic response of an helicopter is made up of more couplings than in the case of aircrafts. This paper deals with the cross-couplings between the pitch and roll axes : the off-axis pitch response of the natural helicopter (without control laws) to a lateral input is significant (and reciprocally from pitch to roll). Up until recently, most of the simulation models have often given off-axis cross-responses with the opposite sign compared with the flight test **[1-3]**.

Several phenomena are involved, in order to simplify they can be divided in two groups :

1- those which introduce a phase lag in the blade response, for example the time delays due to : the kinematic transfers from the pilot control inputs to the blade pitch inputs, the airfoils unsteady aerodynamics (the compressibility effects which increase with the forward speed), etc. ;

2- those which act on the "cross-causes" (90° of phase difference), for example : the dynamic inflow on the main rotor, ...

The aerodynamic interactions between the main rotor wake and the airframe or the tail components may also have an effect. But it can be noticed that an isolated rotor is submitted to pitch-roll couplings (some wind tunnel tests to measure the rotor transfer functions showed that kind of behaviour).

The present paper is devoted to the influence on the pitch-roll couplings of the dynamic induced velocity field on the main rotor.

BACKGROUND

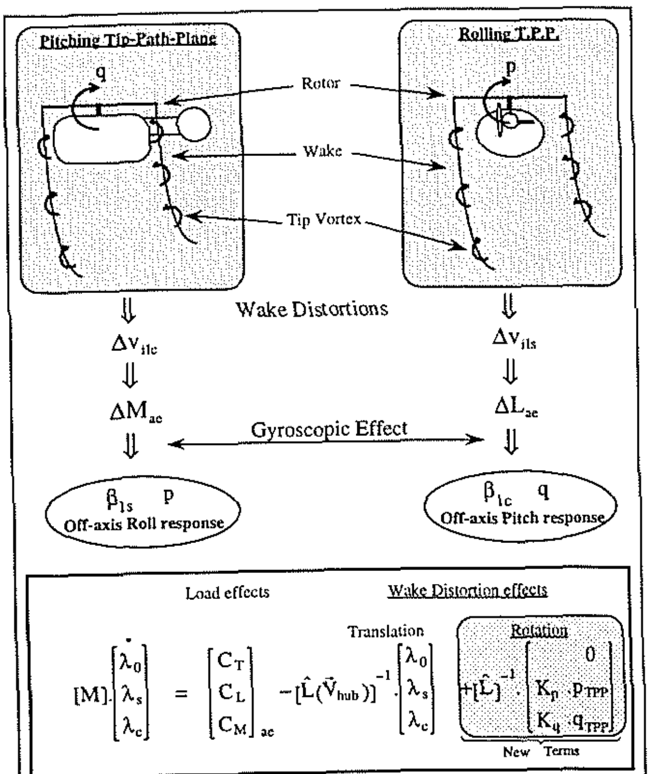
ABOUT THE CROSS-COUPLING MYSTERY

As mentioned in **[4]**, the dynamic inflow on the main rotor represented with the Pitt and Peters model **[5]** contributes in forward flight (Bo105 at 80 kts) to a better simulation of the pitch to roll cross-responses, but has no significant effect near hover on the cross-couplings. This induced velocity model **[5]** is formulated for practical applications in the rotor fixed frame coordinates system. In the transformation from the wind-axis to the rotor frame in **[5]**, the sideslip was implicitly assumed to be steady. The dynamic sideslip may have an effect on the pitch-roll couplings.

The blade flexibility may also contribute to the cross-couplings, especially in the case of hingeless rotors (like the main rotor of the Bo105).

But before examining these different influences, a first step for us is to study the wake distortion effects.

Indeed, a step forward in the understanding of the pitch - roll cross-couplings has been achieved recently with the idea that the inflow models used for flight dynamics simulations do not take into account the rotor wake distortion effects due to pitch and roll rates. The phenomenon is schematically explained on (**Fig. 1**). For instance, a roll motion affects the lateral distribution of the vortices emitted by the rotor. Therefore, the lateral gradient in the induced velocity field is also affected, and so the lateral distributions of the angles of attack and airloads. Due to the gyroscopic behaviour of the rotor, these lateral variations contribute to the pitch off-axis responses (β_{1c}, q).



$$[M].\begin{bmatrix}\dot{\lambda}_0\\ \lambda_s\\ \lambda_c\end{bmatrix} = \begin{bmatrix}C_T\\ C_L\\ C_M\end{bmatrix}_{ac} - [\hat{L}(\bar{V}_{hub})]^{-1}.\begin{bmatrix}\lambda_0\\ \lambda_s\\ \lambda_c\end{bmatrix} + [\hat{L}]^{-1}.\begin{bmatrix}0\\ K_p\cdot p_{TPP}\\ K_q\cdot q_{TPP}\end{bmatrix}$$

Fig. 1 : Wake distortion effect on pitch-roll couplings.

The need to improve the simulation models from this point of view is illustrated by the numerous attempts to deal with this problem **[4, 6-12]**. Applying the method proposed in **[7]**, we showed in **[4]** that the pitch off-axis response of the Bo105 helicopter to lateral inputs at low speeds is well improved by adding (see **Fig. 1**) in the dynamic inflow equations two linear terms function of the pitch and roll rates of the rotor. A value of 1.5 for these coefficients (in hover K_p=K_q=K_R) gives a good match with the flight test data (**Fig. 2**).

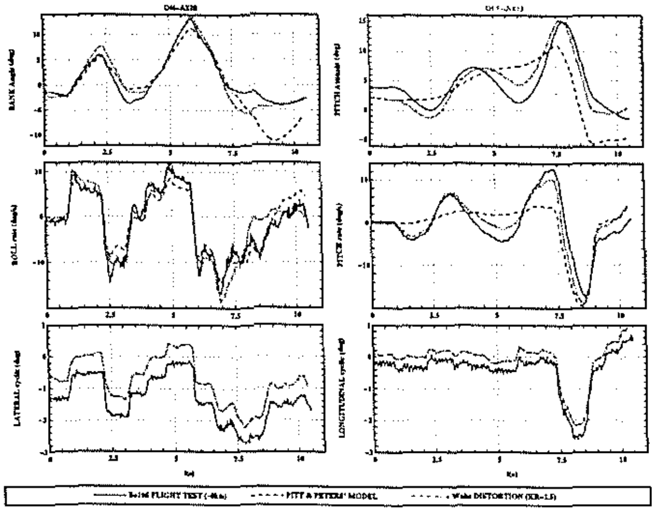


Fig. 2 : Effect on a Bo105 flight near hover obtained with the dynamic inflow model extended with the linear influences of the pitch and roll rates.

However it remains some dark areas. To be helpful during the design process, flight test data being not available, the determination of that kind of coefficient requires a flexible wake model. But at the present time, on the value computed in hover rather large discrepancies appear between different numerical assessments by several researchers as underlined in **[12]** and sum up in **Table 1**.

Reference	Model	K_R
Rosen **[6]**	Prescribed wake	0.75
Keller/Curtiss **[7]**	Spiral vortex tube	1.5
Basset **[4]**	Spiral vortex ring	1.5
Peters et al. **[10]**	Momentum	0.5
	Prescribed wake	1.0
Bagai et al. **[11]**	Free wake	1.75

Table 1 : Wake distortion coefficient in hover.

So this subject remains a very topical problem. Moreover, except in **[12]** the other studies were devoted only to the hover case. It is clear that the effects on the main rotor inflow decrease with the forward speed, the wake being blown back. But for instance in forward flight at 80 kts, the value to improve the correlations with Bo105 flight test data is around (K_R = 1, with the non realistic assumption : K_p=K_q=K_R) as can be seen on (**Fig. 3**). From a physical point of view, this value seems to be overestimated. So to reach a physically funded modelling of these angular rates effects in the whole flight envelop, there is a need to enlarge the study of the wake distortion effects on the main rotor inflow.

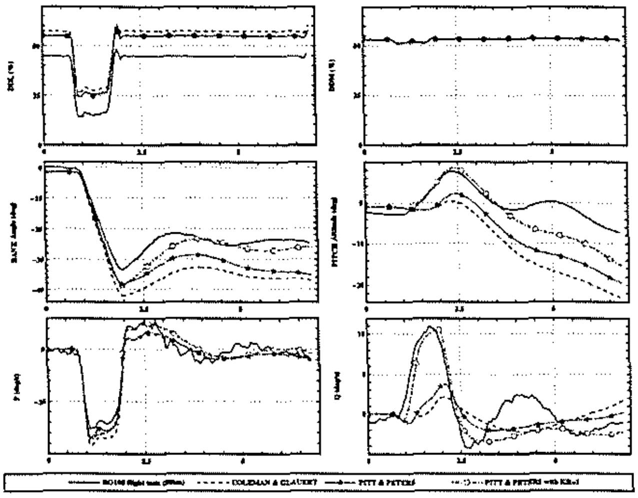


Fig. 3 : Effect on a Bo105 flight at 80 kts obtained with the dynamic inflow model extended with the linear influences of the pitch and roll rates.

As regards the simulation purposes, the global approach consisting in tuning values to best fit flight test data can be useful when the "universality" of the model is not required (e.g. for control law developments). Numerous previous attempts try to simulate these couplings by using only one modelling : equivalent aerodynamic phase lag **[8, 12-13]**, virtual inertia effect **[14]**. These methods can be efficient, but they lead to an overestimation of the physical quantities.

The approach researched in ONERA consists in trying to represent the combination of these phenomena (or the most important ones) contributing to the pitch - roll couplings. For this prospect, each phenomenon must be sufficiently known to be represented with a realistic physical modelling. Furthermore, to make the modelling more difficult, the contribution of each of them changes with respect to the flight point.

The present paper is focused on the wake distortion effects on the main rotor inflow, which seems to be the most important phenomenon near hover and low speeds. The goal of the study reported here is both : to analyse the variations of these effects with respect to the flight conditions and helicopter characteristics, and to propose modelling methods. After the description of the flexible rotor wake model used here, an important part of the paper will be dedicated to the parametric studies of these effects. They will contribute to better understand the physics of that kind of phenomenon, and also provide a data base for real-time simulation. The last part will deal with the modelling aspect. Two kind of modelling methods will be addressed : one based on the results of the parametric studies modelized by a neural network will be more adapted for real-time simulation (no vortex wake model being required), the other approach used directly our dynamic vortex wake model for on-line and closed-loop simulations.

ROTOR WAKE MODEL

The rotor wake model is the dynamic vortex rings model described in **[4, 15]**, which as been developed by ONERA especially for the needs of helicopter flight mechanics.

Dynamic vortex rings 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.

WAKE GEOMETRY AND KINEMATICS

*** Geometry :**

A rotating lifting-line (modelling the blade) generates a helicoid vortex sheet. The trailing helical 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 trailing vortices 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 being emitted from 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 shed vortices.

Thus, the vortex wake is finally represented by vortex rings with radial vortex segments (**Fig. 4**). 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 bound vortices.

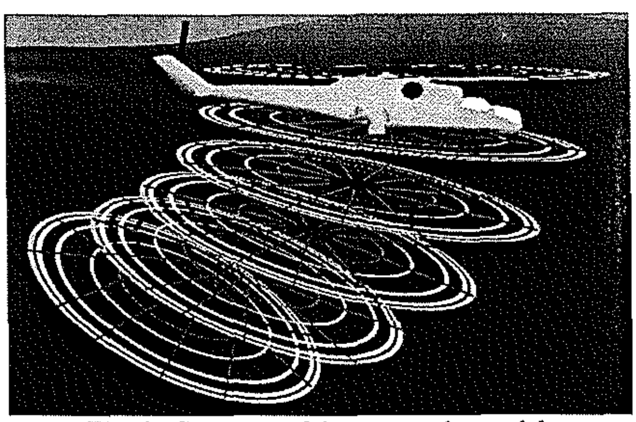


Fig. 4 : Geometry of the rotor wake model.

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. Therefore that kind of wake distortions due to the roll and pitch rates of the rotor are taken into account.

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. In a first approximation, (in agreement with the actuator disc theory **[16-17]**), the convection velocity is assumed to be the vector sum of the free stream velocity and the mean downwash velocity (v_{i0}) :

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

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. 5)**.

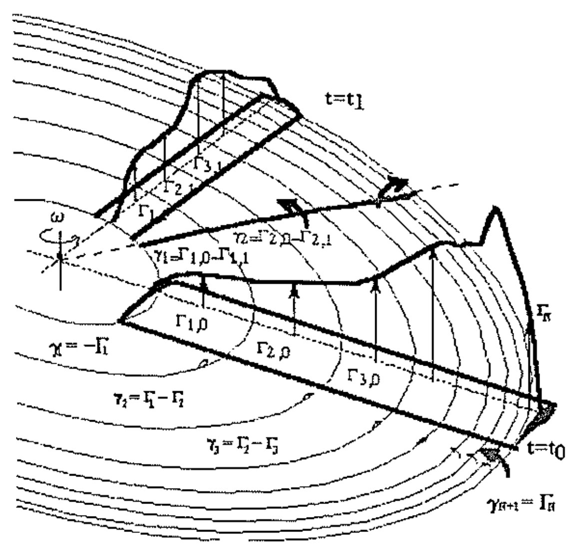


Fig. 5 : Vorticity of the rotor wake model.

INDUCED VELOCITY FIELD BY A TORUS

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. A global assessment of the induced velocity vector can be reached with a reduced computational cost, the integration effort being done previously by the engineer. The complex final formula are based on the complete elliptic integrals [e.g. **18**] :

$$E(k) = \int_0^{\pi/2} \sqrt{1 - k^2 \sin^2 \phi}\,.d\phi$$

$$K(k) = \int_0^{\pi/2} \frac{1}{\sqrt{1 - k^2 \sin^2 \phi}}\,.d\phi$$

The rings are the vortex elements and their induced field can be analytically formulated with their vorticity approximated by a Fourier serie. The velocity field induced by a vortex ring charged with the (γ_0, γ_{1c}, γ_{1s}) is a linear combination of the three basic fields induced by a vortex torus charged respectively with {(1,0,0), (0,1,0), (0,0,1)}.

So the advantage of such a vortex pattern is that it is both :

- sufficiently simple to permit an analytical expression of the induced velocity field; therefore, the computational time is reduced in comparison with those of more realistic representations which require a numerical integration of each vortex segment influence [e.g. **11**];

- sufficiently sophisticated to be used in the whole flight envelope, whereas the flat vortex wake approximation (introduced by Vil'dgrube [**19**, chap. II, p. 30-37]) is not valid at low speeds.

In the rings model the priority has been given to the dynamic representativity rather than to the keenness of the wake representation. In the present model, the geometry and the vorticity distributions evolve dynamically in function of the rotor airloads and motions :

* <u>dynamic geometry</u> : the wake deformations are in average representative of the rotor motions and airloads variations ;

* <u>dynamic vorticity</u> : the vortex strength distribution on each ring is calculated in function of the bound circulation on the blade. So the wake vorticity keeps the memory of the flow across the rotor.

This simple dynamic wake model for helicopter flight dynamics simulation has been implemented in the Eurocopter generic rotorcraft simulation software called HOST (Helicopter Overall Simulation Tool, [**20**]).

PARAMETRIC STUDIES

<u>of the wake distortion effects on the main rotor inflow</u>

The goal here is to study the effect on the main rotor inflow of the geometric rotor wake changes due to pure pitch or roll rates. The variations produced by different parameters will be studied, such as : the airspeed, the climb rate, the airload, ...

Method

In order to impose a pure pitch or roll motion, we simulate an isolated rotor with its wake by using the blade element model of the HOST code and the vortex rings model. This software allows to compute trims with a sweep on different terms (forward speed, etc.). So we perform these parametric studies in the case of steady pitch (or roll) rates with a fixed-set of states (e.g. attitude angles of the rotor, etc.) and with a sweep on the forward speed successively for different values of the sensitivity parameters (airload, rate of climb, etc.).

To assess only the wake distortion effects due to pure pitch or roll rates, we have to compare the two induced velocity fields on the rotor computed : on the one hand with the *undistorted* model (rigid wake), and on the other hand with the *distorted* model (flexible wake, **Fig. 6**).

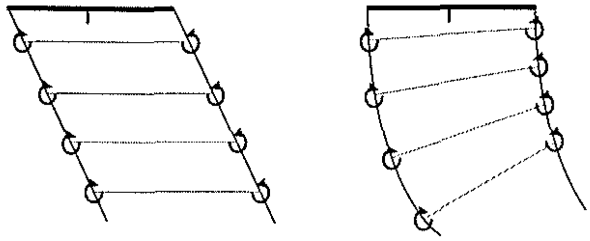


Fig. 6 : Wake distortion due to a steady angular rate.

At each computational step, these two rotor wake models differ only by the change of geometry due to pitch or roll motions. The flexible wake model takes into account :

- the curvature of the mean-line, whereas in the rigid model the vortex rings centers are distributed on a rectilinear line,

- the different attitudes that the rotor has occupied retrospectively during its pitch or roll motion, whereas in the rigid model all the vortex rings have the same attitude plane than the rotor in its final position.

The two wake representations have the same vortex strengths which come from the aerodynamic field on the rotor. This aerodynamic field depends on the rotor inflow which is computed with the model presented in [**5**]. In other words, the parametric studies are done in an open-loop (there is no feed-back from the vortex rings model towards the rotor).

<u>PROCEDURE</u>

Two steps in the computation of the wake distortion effects can be distinguished :

- <u>First</u> : Calculation of the two induced velocity fields on the rotor by the rigid and flexible wakes at each point of a polar grid (rotor plane).

N.B. : All the computations where realised with 20 points along the blade span and 24 azimuth positions : $(R\times\psi)=(20\times24)$ grid. The more the number of points is important, the more are reduced the numerical oscillations (peak values) which may appear at high forward speeds when the first vortex rings under the rotor are very closed to the computational points.

For example, the following illustration shows the two fields computed in hover with a pitch rate (Q= 20 deg/s) :

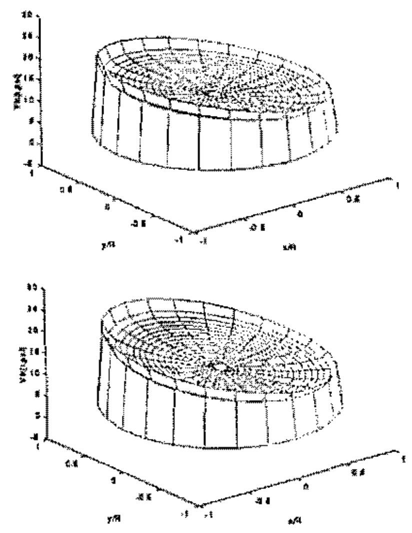


Fig. 7 : Induced velocity fields in hover for (Q=20 deg/s) with the rigid (top) and flexible (bottom) wake models.

Although the rotor is in hover, the cyclic control inputs are not null to achieve this pitch rate. Therefore the airloads lead to a non-uniform vorticity distribution with a strong longitudinal gradient (γ_{1c}). Hence, there is a longitudinal gradient (v_{i1c}) even with the rigid wake model (field at the top of **Fig. 7**). This gradient is magnified by the distortions of the flexible wake model (field at the bottom of **Fig. 7**).

- <u>Second</u> : The purpose being to complete the dynamic inflow model **[5]**, which is usually used in a first harmonic formulation, we estimate the wake distortion effects on a first harmonic approximation of the previously computed velocity fields. So a classical Fourier analysis is performed :

$$\lambda = \frac{v}{\Omega R} = \lambda_0 + \lambda_{1s}\bar{r}\sin\psi + \lambda_{1c}\bar{r}\cos\psi$$

with $\bar{r} = \frac{r}{R}$

$$\text{Where : } \begin{cases} \lambda_0 = \dfrac{1}{\pi}\displaystyle\int_0^{2\pi}\int_0^1 \lambda\bar{r}d\bar{r}d\psi \\ \lambda_{1s} = \dfrac{4}{\pi}\displaystyle\int_0^{2\pi}\int_0^1 \lambda\bar{r}^{-2}\sin\psi d\bar{r}d\psi \\ \lambda_{1c} = \dfrac{4}{\pi}\displaystyle\int_0^{2\pi}\int_0^1 \lambda\bar{r}^{-2}\cos\psi d\bar{r}d\psi \end{cases}$$

These two steps are applied in "parallel" two times for each flight configuration to compute a first harmonic approximation of the velocity field induced respectively by the rigid and flexible wake models.

MODEL CONFIGURATION

*** Number of rings :**

- The number of rings defining the length of the wake is determined as the number giving an inflow gradient due to angular rate very closed to the asymptotic value corresponding to an infinite wake. This study to configure the model has been done in hover with (Q=20deg/s). As appears on (**Fig. 8**), beyond 200 rings along the wake, the vortices are to far from the rotor to produce a significant effect.

N.B. : Of course this number would have been lower with a law to take into account the decrease of the vorticity due to viscous effects.

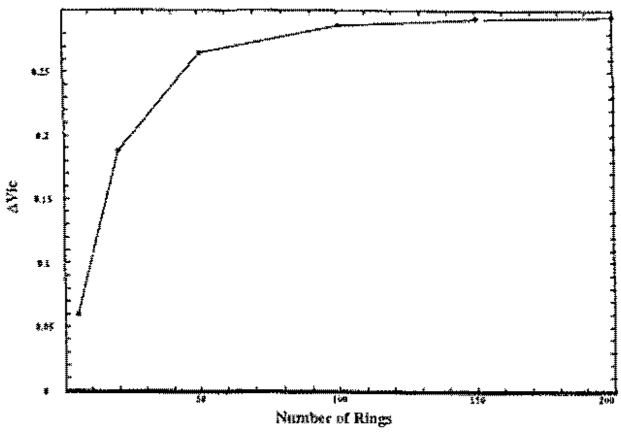


Fig. 8 : Number of rings defining the length of the wake.

- The number of rings radially distributed allows to better take into account the spanwise distribution of the wake vorticity generated by the gradient of the bound circulation along the blade span. The **figure 9** shows the longitudinal inflow gradient due to a pitch rate (Q=2deg/s) computed with 200 groups of vortex rings composed : on the one hand with only the tip vortices and on the other hand with the 9 rings emitted by the 8 blade elements. Two significant effects can be seen :

→ the value in hover is lower with all the radial distribution, which may be explained by a lower mean value of the vortex strength compared with the vorticity of the tip vortices,

→ the evolution with respect to the forward speed is smoother when all the rings generated along the blade are represented.

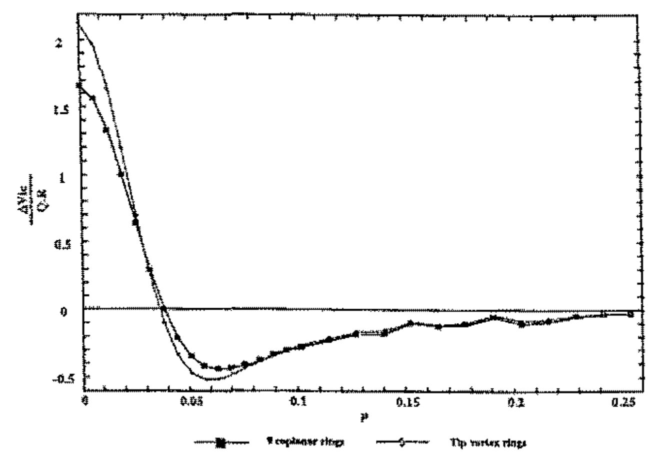


Fig. 9 : Effect of the number of rings radially distributed.

Finally, the adopted model configuration for the following computations is a rotor wake represented with 200 groups of 9 coplanar and concentric vortex rings (that is to say with all the trailing vortices emitted by the 8 blade elements). In a first approximation, the shed vortices are not taken into account here for the study of the wake distortions (of course the bound vortices are not affected by the wake distortions).

LINEARITY

Considering the first harmonic, the inflow gradients due to angular rates are highly linear in hover as in forward flight. For instance, the effect of a pitch rate on the longitudinal gradient (v_{i1c}) remains quasi-proportional to the pitch rate in a large area as can be seen on (**Fig. 10**).

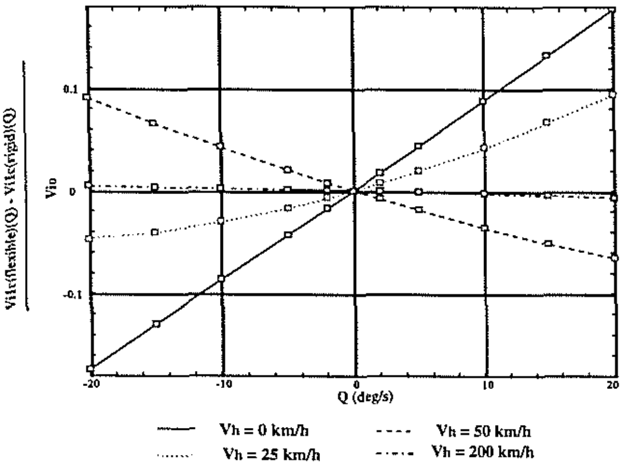


Fig. 10 : Linearity of the pitch effect on (v_{i1c}).

So in the follow-up to this paper, we will present the wake distortion effects represented by these coefficients of proportionality K_q and K_p :

$$\begin{cases} Kq = \dfrac{\lambda_{1c}(flexible)(Q) - \lambda_{1c}(rigid)(Q)}{\dfrac{Q}{\Omega}} \\ Kp = \dfrac{\lambda_{1s}(flexible)(P) - \lambda_{1s}(rigid)(P)}{\dfrac{P}{\Omega}} \end{cases}$$

N.B. : The coupling terms (K_{qp}, K_{pq}) were also assessed and appeared to be negligible compared with the direct coefficients (K_q, K_p).

Results of the parametric studies

Here are presented the variations of the wake distortion coefficients (K_q, K_p) with respect to : the forward speed, the location of the center of rotation, the climb rate and the rotor thrust.

EFFECT OF THE FORWARD SPEED

On (**Fig. 11**) we can see the evolutions of (K_q, K_p) with the advance ratio. From a common value around 1.6 in hover, the wake distortion effects decrease with the airspeed as can be expected since the wake is swept back. So the value (K_R=1) which improves the correlations with Bo105 flight tests at 80 kts (see **Fig. 3**), is clearly overestimated according to this model (see **Fig. 11** at $\mu \approx 0.2$).

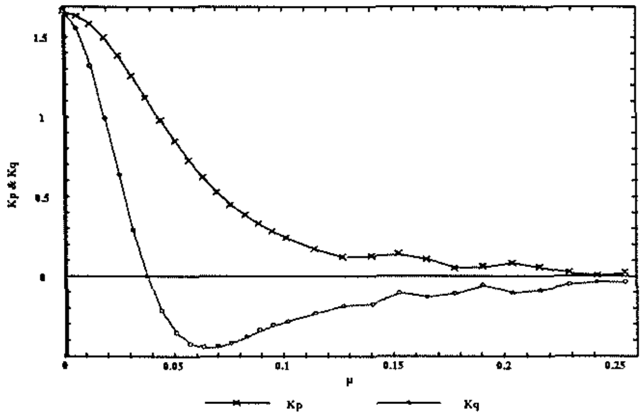


Fig. 11 : Effect of the forward speed.
(Z_{GH}/R =0, V_Z=0, C_T=0.0049)

An other interesting result is the change of sign of K_q (the coefficient of proportionality between the pitch rate and the variation (due to wake distortions) of the longitudinal gradient in the rotor inflow). This peculiarity means that the same pitch rate may have opposite effect depending on the forward speed.

This tendency may be magnified by the model, but it also brings out to the fore an actual characteristic of the phenomenon. Indeed, the geometrical variations of the relative position between the rotor and the vortices depend on the skew angle of the wake. A schematic explanation is proposed on (**Fig. 12**) considering one vortex ring with a uniform vorticity.

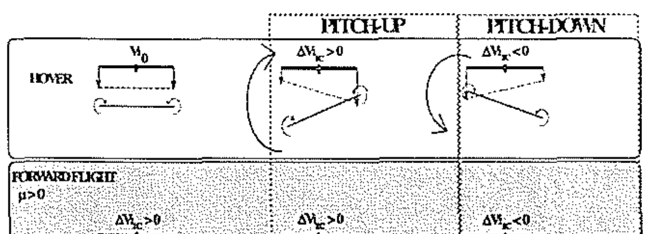


Fig. 12 : About the effect of a pitch rate on (v_{i1c}) with the forward speed.

Near hover (μ<0.04), for instance a rotor in a steady pitch-up motion (Q>0) generates a wake where the vortices are closer to the rear part of the rotor compared to the case of the undistorted wake. In such a case, the wake distortions increase the longitudinal gradient (Δv_{i1c}>0). But for higher speed flights (especially around $\mu \approx 0.06$, on **Fig. 11**), the wake distortions produced by the same pitch rate are swept back due to the skew angle of the wake. So the effect on the downwash longitudinal gradient can be opposite (Δv_{i1c}<0).

EFFECT OF THE CENTER OF ROTATION

The previous studies **[4, 7-12]** were done with a rotor tilting around the hub center. In order to be closer to the physical mechanisms for helicopter flight dynamics, we simulate a rotor pitching around the helicopter center of gravity.

Two effects on the wake geometry has to be represented **(Fig. 13)**:
- the lever arm between the cg and the hub introduces additional velocity at the hub ($GH \times \Omega$);
- the previous positions of the rotor from where the vortices were emitted have to be considered.

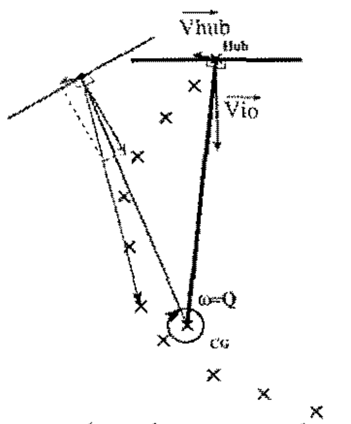


Fig. 13 : Effects on the wake geometry due to a rotation about the cg instead of the hub center.

The effects on the wake distortion coefficients are shown on **(Fig. 14)**.

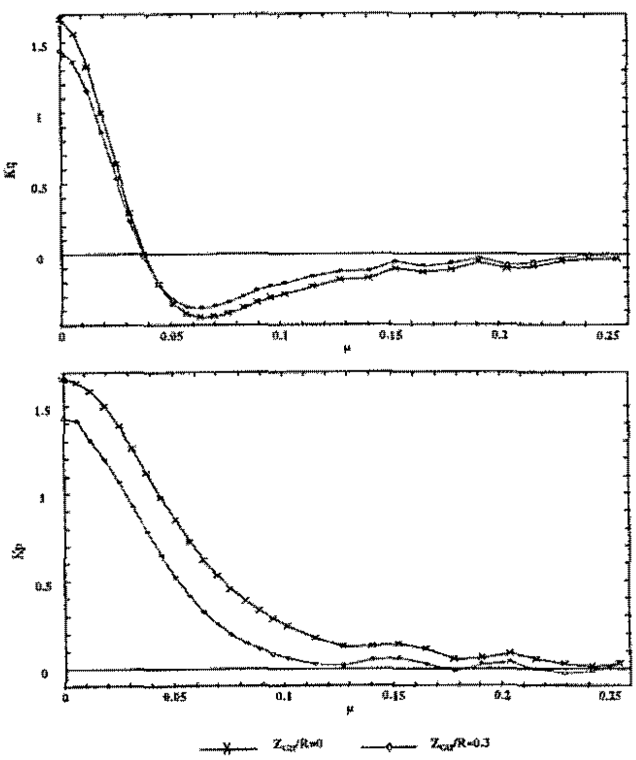


Fig. 14 : Rotation about the cg instead of the hub center. *(Vz=0, C_T=0.0049)*

In absolute value, the coefficients are smaller with a rotor tilting about the helicopter cg. This tendency can be explained thanks to **(Fig. 15)**, where the mean-lines of the rigid and flexible wakes have been drawn in hover for the two cases : rotation about the cg and rotation about the hub.

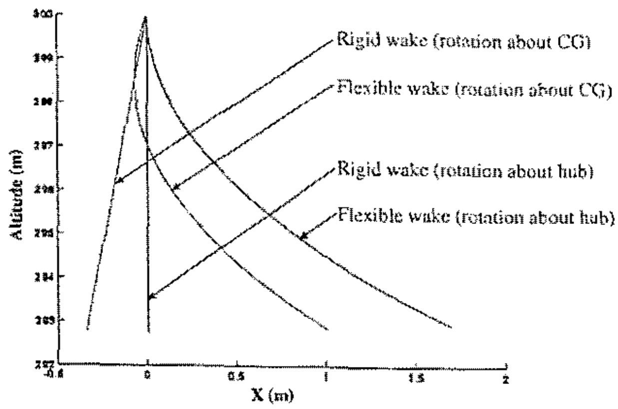


Fig. 15 : Trajectories of the vortex rings centers in hover for a rotation about the helicopter cg and for a rotation at the hub center.

In the case of the rotation about the cg, the two mean-lines of the rigid and flexible wakes remain closer than in the case of the rotation about the hub. The two geometries being closer, the wake distortion effects on the rotor inflow are lower in absolute value.

EFFECT OF THE CLIMB RATE AND THRUST

*** Effect of the vertical speed (V_z) :**

The vertical speed has a direct impact on the vertical thread (dH) separating two vortex layers emitted during two successive rotor revolutions. So it is understandable that the wake distortion effects on the main rotor decrease when the climb rate increases, because the vortices are farther from the rotor compared with the case of steady level flights (or hover). On the contrary, in descent flights the vortices being closer to the main rotor, the wake distortion effects are stronger. These tendencies appear clearly on **(Fig. 16)**.

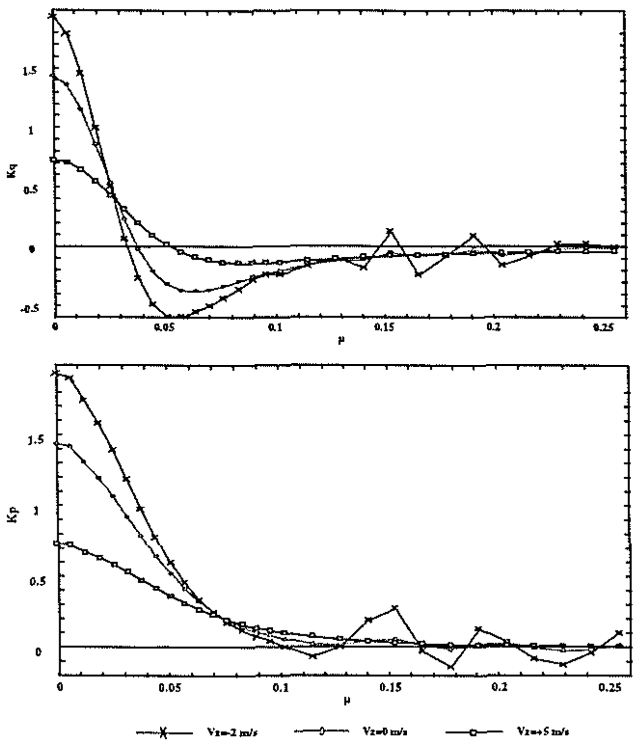


Fig. 16 : Effect of the vertical speed.
(Z_{GH}/R =0.3, C_T=0.0049)

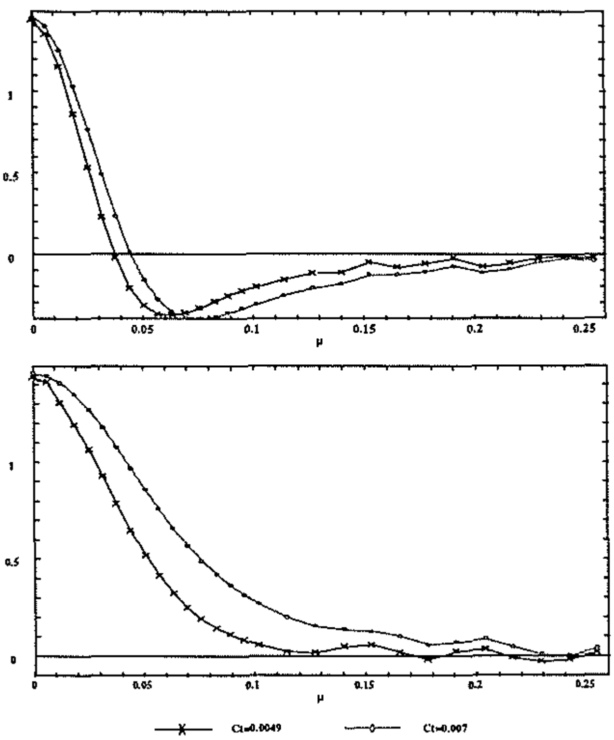


Fig. 17 : Effect of the rotor thrust.
(Z_{GH}/R =0.3, Vz=0)

The proximity of the first vortices under the rotor is even more important when the forward speed increases, because the mean downwash decreases. That is why some oscillations (or discontinuities) appear above ($\mu \approx 0.1$) in descent flights.

* **Effect of the rotor thrust coefficient (C_T) :**

The effect of the rotor thrust is more complex since it acts both on the geometry and on the vorticity of the wake. On the geometry, the thrust plays a similar role compared with the climb rate. The more the thrust increases, the more the mean inflow (v_{i0}) blows down the vortices. So this influence on the wake geometry tends to decrease the distortion effects when the thrust increases. But as can be seen on (**Fig. 17**), the effect on the wake vorticity seems to be stronger.

Indeed the airloads have also an influence on the wake vorticity. The more the thrust is high, the more the mean value of the bound circulation on the blades is important. Depending on the radial gradient of the bound circulation along the blade, the vortex intensities may be stronger. As mentioned earlier, these vortex strengths are the same for the rigid and flexible wakes. But they play a role on the distortion effects. Indeed according to the Biot and Savart law, the influences of the geometrical differences between the two wakes are multiplied by the vortex intensities. So this effect on the vorticity counters the influence on the geometry. With an higher rotor thrust, the slope coefficients (K_q, K_p) decrease more slowly with respect to the forward speed (see **Fig. 17**).

These two antagonistic effects may explain that the impact of the (C_T) on the distortion coefficients seems lower than those of the vertical speed.

MODELLING

of the wake distortion effects on the main rotor inflow

Two kinds of method are studied at ONERA to represent the wake distortion effects on the main rotor inflow :

- one is more adapted for realtime applications and is based on the previous parametric studies;
- the other one is a more general approach requiring the on-line simulation of the flexible wake geometry.

Real-time Simulation - Neural approach

Apart from tables look-up, the previous parametric studies can be used to build analytical laws to compute the distortion coefficients (K_q, K_p). We try to achieve this analytical approximation by using the neural-networks approach.

Artificial neural networks are well adapted to the modelling of non-linear multivariable systems. First of all, we have to choose the inputs.

"WAKE DISTORTION INPUTS"

As we said previously, the inflow gradients due to angular rates are produced by the differences between the distorted and undistorted wake geometries multiplied by the vortex strengths.

Rather than using the basic flight mechanics variables (μ, $V_z/(\Omega.R)$, C_T, etc.), it can be more pertinent to use physical quantities more directly representative of the rotor wake.

*** "Geometrical inputs" :**

For instance, the vertical distance (dH) between two groups of vortices generated during two successive rotor revolutions sums up the effects of (V_z) and (C_T) on the wake geometry. The helical thread (dH) allows also to take into account the number of blades (b) and the rotor rotational speed (Ω) :

$$dH = \frac{(V_z - v_{i0}) \times dt_{rev}}{R}$$

with :

$$dt_{rev} = \frac{2\pi}{b\Omega}$$

As we noticed previously, an angular rate (in pitch or roll) has two kinds of effect on the wake geometry :

- the curvature of the mean-line,
- the change of the vortex density (or repartition) under the rotor (more distended under the rotor edge tilting-up, **Fig. 18**).

This last effect is represented in our wake model by the change of the vortex rings planes. This attitude plane depends on : the angular rate, the "vortex age" (Iage : number of rotor revolutions since the generation of the considered vortices), the time step between the emission of two groups of vortex rings (dt_{rev} : rotor revolution time). For example in the case of a pure pitch motion, the pitch attitude of the rings group (Iage) is :

$$\theta(\text{Iage}) = Q.dt_{rev}.\text{Iage}$$

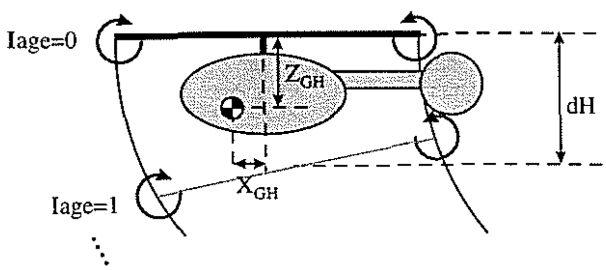


Fig. 18 : Effect of a pitch rate on the wake geometry.

About the curvature of the mean-line, we have to consider the differences between the lines joining the rings centers in the rigid (rectilinear) and flexible (curved) models. For instance for a rotor in a pure pitch motion, these trajectories in the rotor wind coordinate system are respectively :

Rigid wake (with pitch rate only : Q) :

$$\begin{cases} x(Iage) = [-Q.Z_{GH} + V_x].dt_{rev}.Iage \\ y(Iage) = 0 \\ z(Iage) = [V_{i0} + Q.X_{GH} + V_z].dt_{rev}.Iage \end{cases}$$

Flexible wake (with pitch rate only : Q)

$$\begin{cases} x(Iage) = X_{GH}(\cos\theta - 1) + Z_{GH}.\sin\theta + \\ \quad [V_{i0}.\sin\theta - Q.Z_{GH}.\cos\theta + Q.X_{GH}.\sin\theta + V_x].dt_{rev}.Iage \\ y(Iage) = 0 \\ z(Iage) = -X_{GH}.\sin\theta + Z_{GH}(\cos\theta - 1) + \\ \quad [V_{i0}.\cos\theta + Q.Z_{GH}.\sin\theta + Q.X_{GH}.\cos\theta + V_z].dt_{rev}.Iage \end{cases}$$

N.B. : Similar equations can be obtained with a roll rate.

Theses equations show us that for a given pitch (or roll) rate, the trajectories in the wind-axis depend on five parameters : $\mathbf{V_{i0}}$, $\mathbf{X_{GH}}$, $\mathbf{Z_{GH}}$, $\mathbf{V_X}$ and $\mathbf{V_Z}$.

Some complementary studies lead to decrease the number of parameters :

- X_{GH} has no significant effect compared with Z_{GH},
- the data couple (V_{i0}, dH) defines the couple (V_X, V_Z). There is a bijective relation between these variables, since (V_{i0}) is a monotonic decreasing function of the forward speed, and (dH) a monotonic increasing function of (V_Z).

So the "geometrical inputs" retained here to compute the wake distortion coefficients in the wind-axis are : λ_{i0}, dH, Z_{GH}/R.

*** "Vorticity inputs" :**

As already mentioned, the vortex strengths have an influence on the inflow gradient due to angular rate. In the present wake model, the vorticity distribution is approximated on each ring by the first harmonic terms (γ_0, γ_{1c}, γ_{1s}).

In a first approach, we choose to use only the thrust coefficient (C_T) as a representative term of the global vorticity.

Hence, the chosen non-dimensional parameters to compute the wake distortion coefficients in the wind-axis are finally : λ_{i0}, dH, C_T, Z_{GH}/R.

$$\boxed{\begin{cases} Kp = f(\lambda_{i0}, dH, C_T, Z_{GH}/R) \\ Kq = g(\lambda_{i0}, dH, C_T, Z_{GH}/R) \end{cases}}$$

Of course they are not independent, since (λ_{i0}) and (C_T) are directly linked and (dH) takes (λ_{i0}) into account. But they seem to be sufficiently closed to the rotor wake characteristics to sum-up different effects, and sufficiently simple to be calculated without a wake model.

N.B. : Instead of (λ_{i0}), the wake skew angle could also be chosen (as a more representative parameter of the wake geometry).

For instance, for a given couple (C_T, Z_{GH}/R), a compilation of the parametric studies leads to the surface shown on (**Fig. 19**) in the plane (λ_{i0}, dH).

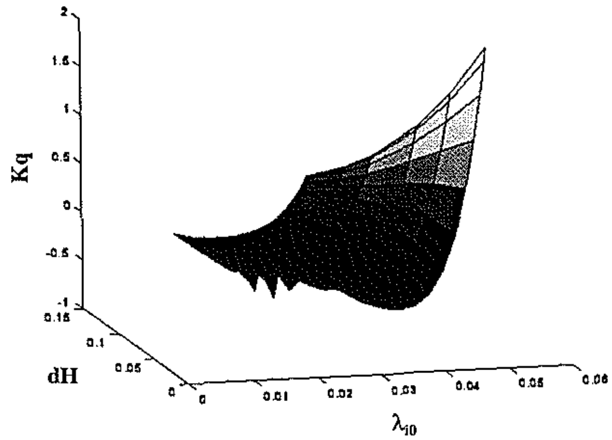


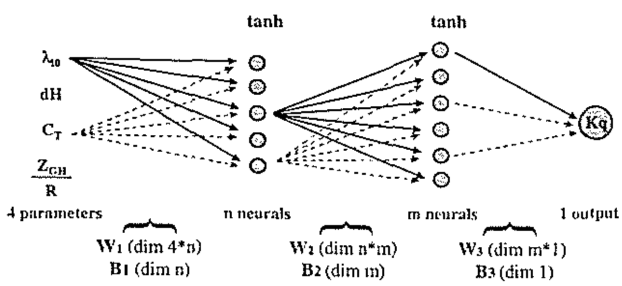
Fig. 19 : Results of the parametric studies : Kq = f(λ_{i0}, dH) for given values of (C_T=0.0049, Z_{GH}/R=0.3).

The previous parametric studies were done for the main rotor of the BO105. We verified that the same surfaces are obtained for the main rotor of the Dolphin, which indicates a good level of "universality" of these results.

NEURAL NETWORKS APPLICATION

The ability of artificial neural networks to approximate arbitrary nonlinear mappings is applied here to our parametric studies of (K_q).

This method will provide a modelling of our database that can be expressed in closed form as illustrated below :



$$Kq = [W_3].\tanh\left([W_2].\tanh\left([W_1].\begin{vmatrix}\lambda_{i0}\\ dH\\ C_T\\ \frac{Z_{GH}}{R}\end{vmatrix} + |B_1|\right) + |B_2|\right) + |B_3|$$

W_1, W_2, W_3 : are the weight matrices,
B_1, B_2, B_3 : are the bias vectors.

The basic function used here is the hyperbolic tangent sigmoid transfer function. Other more pertinent functions could help to reduce the number of neurons. But in the software used here, the choice is limited.

The choice of the number of layers and the number of neurons inside each layer is based on a compromise. The more these numbers are high, the more the learning and auto-adaptation process is rapid and accurate. But the model given by the resulting neural network will be also more heavy to use for computational simulations.

RESULT OF THE NEURAL NETWORK MODELLING

The network was trained on the data corresponding to the results of the previous parametric studies. A rapid learning phase was achieved with three layers composed respectively with 8 , 10 and 1 neurons.

The model corresponding to the resulting neural network provides a good approximation of the previous map of (**Fig. 19**), as can be seen on (**Fig. 20**). The sum-squared error on the 522 points is rather small as regards the number of points. The result is also smoother as regards the numerical oscillations present in the parametric studies for the low values of (λ_{i0}, dH) (see **Fig. 19**).

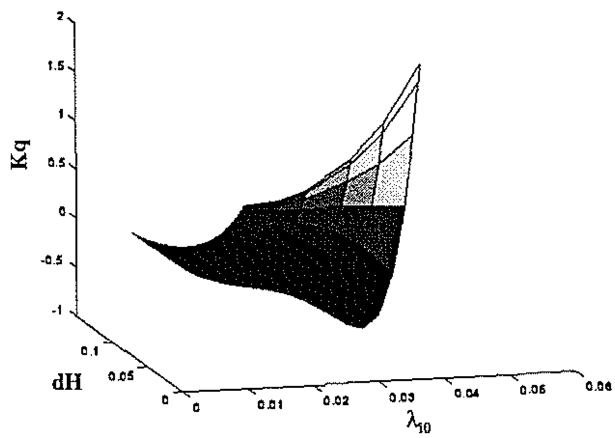


Fig. 20 : Results of the neural network approximation : Kq = f(λ_{i0}, dH) for given values of (C_T=0.0049, Z_{GH}/R=0.3).

Of course the number of neurons used in a first application, leads to big matrices which can not be written here. But this was done more to illustrate the potentiality of that kind of method, rather than to give a final result in closed form.

Non-real-time Simulation

On-line and closed-loop approach

The idea here is to use the dynamic (flexible) vortex rings model to assess the wake distortion effects in an on-line and closed-loop time simulation process. This wake model could be applied to calculate directly the induced velocity field on the rotor without using other inflow models. But in a first attempt, we prefer to compute only the wake distortion effects and to use these inflow gradients to complete the classical dynamic inflow models (like the Pitt and Peters model of [5]).

In order to assess the wake distortion effects on the rotor inflow, a solution without any approximation (except the assumptions inherent to the wake model) consists in calculating at each computational step the two wake geometries : the undistorted one (rectilinear cylindrical wake) and the distorted one (curved wake). Then, a first harmonic approximation of the effect on the inflow is required to complete the induced velocity model currently used in the helicopter HOST code (Pitt and Peters model or Meijer-Drees model, etc.). So by the same process described previously, the induced velocity field on the rotor is computed with these two wake geometries and the same vortex strengths.

The following corrections :

$$\Delta(v_{i0})_{Distortion} = (v_{i0})_{Flexible} - (v_{i0})_{Rigid}$$
$$\Delta(v_{i1c})_{Distortion} = (v_{i1c})_{Flexible} - (v_{i1c})_{Rigid}$$
$$\Delta(v_{i1s})_{Distortion} = (v_{i1s})_{Flexible} - (v_{i1s})_{Rigid}$$

are then used in the rotor inflow model to take into account the wake distortion effects due to the pitch and roll motions. This on-line assessment in a closed-loop simulation is exposed schematically on (**Fig. 21**).

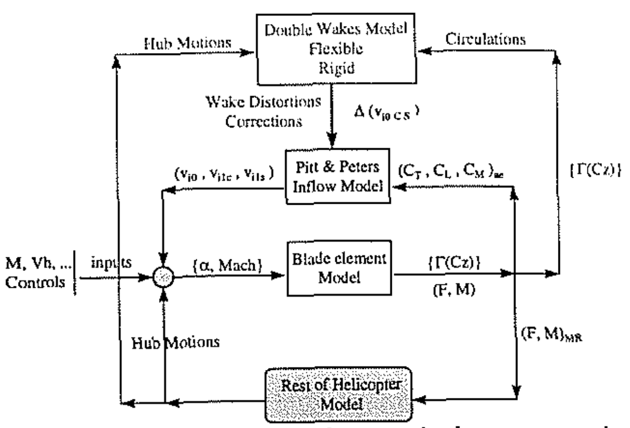


Fig. 21 : On-line and closed-loop method to compute the wake distortion effects.

This approach is more general and closer to the physical phenomenon than the previous one.

Indeed, the previous parametric studies are done for a rotor in a steady (pitching or rolling) motion, so at each time step they will lead to corrections corresponding to a fully developed spiral wake under the current value of the angular rate. However in a practical case, the control inputs (like the classical "3211" multi-step inputs) lead to dynamic evolutions of the pitch and roll rates. So when we will perform time histories comparisons with flight test data, the on-line dynamic flexible wake model will have a more complex geometry than an arc of spiral as resulting from the steady conditions used in the parametric studies.

Moreover, a limitation of the approach used in [7, 12] and here for the parametric studies, is that the rotor in a steady pitch (or roll) rate is not in a trim condition. We consider the rotor and its wake in a certain frozen state and we give to the vortex rings of same radius the same vorticity distribution. But in fact, the vortices composing the wake were emitted from different rotor positions where the airloads were different. So the vorticity distributions should vary along the wake. This effect is represented in the dynamic wake model used in time simulation (since each new group of vortex rings is charged with a vorticity distribution corresponding to the rotor airloads under the current conditions of the rotor).

Another positive point is that this last approach is comprehensive in the meaning that both the pitch, roll and yaw rates about the cg affect dynamically the wake geometry.

The only drawback is the computational time. Therefore the interest of performing parametric studies is to allow to take into account the wake distortion effects without a representation of the rotor wake (by analytical laws or by tables look-up) and thus with a lower computational cost, as can be required for real time simulations.

CONCLUSIONS

The wake distortion effects on the main rotor inflow caused by pitch and roll rates have been studied by using the dynamic multi-vortex-rings model.

From the parametric studies with pure steady pitch or roll rates, the following tendencies may be drawn.

← The effects on the inflow gradients (v_{i1c}, v_{i1s}) in a first harmonic approximation, are highly linear.

← The wake distortion coefficients (K_q, K_p) decrease with the forward speed. According to this model, there is a significant change of sign at low speeds on (K_q).

← In absolute value, these slope coefficients are smaller in the more realistic case of a rotor tilting about the helicopter cg compared with a rotation about the hub.

← The inflow variations due to angular rate decrease with the climb rate and increase in descending flights.

← With a stronger rotor thrust, the drop down with the forward speed of (K_q, K_p) is slower in absolute value.

For the modelling of the wake distortion effects on the main rotor inflow, two kinds of method are studied at ONERA.
- One is more adapted for realtime applications and is based on the previous parametric studies. The modelling of this database by a neural network

provides a close form approximation which could be used in realtime simulation codes.

- The other one is a more general approach requiring the on-line simulation of the flexible wake geometry in a closed-loop time simulation process.

When more flight test data at low speeds will be available, a validation study of these simulation methods will be performed. In particular, an interesting point will be to verify if the change of sign of (K_q) improves the correlations (mainly for : $0.04 < \mu < 0.12$).

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REFERENCES

[1] ***R.W. Prouty***, "The case of the cross-coupling mystery", *Rotor & Wing International, June 1994.*

[2] ***M. D. Takahashi***, "A flight-dynamic helicopter mathematical model with a single flap-lag-torsion main rotor", *N.A.S.A. TM-102267, Feb. 1990.*

[3] ***M. G. Ballin, M. A. Dalang-Secretan***, "Validation of the dynamic response of a blade-element UH-60 simulation model", *J$^{\underline{al}}$ of the American Helicopter Society, Vol. 36, Oct. 1991.*

[4] ***P.-M. Basset***, "Modelling of the dynamic inflow on the main rotor and the tail components in helicopter flight mechanics", *22$^{\underline{nd}}$ E.R.F., Brighton (UK), paper n° 104, September 1996.*

[5] ***D.A. Peters, N. HaQuang***, "Dynamic inflow for practical applications", *J$^{\underline{al}}$ of the American Helicopter Society, T. N., vol. 33, n° 4, pp. 64-68, October 1988.*

[6] ***A. Rosen, A. Isser***, "A New Model of Rotor Dynamics during Pitch and Roll of Hovering Helicopter", *50$^{\underline{th}}$ Annual Forum of the A.H.S., Washington, D.C., pp. 409-426, May 11-13 1996.*

[7] ***J.D. Keller***, "An Investigation of Helicopter Dynamic Coupling using an Analytical Model", *21$^{\underline{st}}$ European Rotorcraft Forum, St. Petersburg (Russia), Aug. 30- Sept. 1 1995.*

[8] ***U.T.P. Arnold, J.D. Keller, H.C. Curtiss*, G. Reichert**, "The Effect of Inflow Models on the Dynamic Response of Helicopters ", *21$^{\underline{st}}$ European Rotorcraft Forum, St. Petersburg (Russia), Aug. 30-Sept. 1 1995.*

[9] ***J.D. Keller, H.C. Curtiss***, "The Effect of Inflow Models on the Dynamic Response of Helicopters", *52$^{\underline{nd}}$ Annual Forum of the A.H.S., Washington, D.C., pp. 841-851, June 4-6 1996.*

[10] ***E. Barocela, D.A. Peters, K. R. Krothapalli, J. V. R. Prasad***, "The effect of wake distortion on rotor inflow gradients and off-axis coupling", *A.I.A.A.-97-3579, 1997.*

[11] ***A. Bagai, J.G. Leishman, J. Park***, "A free vortex rotor wake model for maneuvering flight", *A.H.S. Technical Specialists Meeting for Rotorcraft Acoustics and Aerodynamics, Williamsburg, VA, October1997.*

[12] ***J.D. Keller, H.C. Curtiss***, "A critical examination of the methods to improve the off-axis response prediction of helicopters", *54$^{\underline{th}}$ Annual Forum of the A.H.S., Washington, D.C., pp. 11341-1147, May 1998.*

[13] ***M.H. Mansur, M. B. Tischler***, "An Empirical Correction Method for Improving Off-Axes Response Prediction in Component Type Flight Mechanics Helicopter Models", *AGARD Flight Vehicle Integration Panel Symposium on "Advances in Rotorcraft Technology", Ottawa, Canada, 27-30 May 1996.*

[14] ***W. von Grünhagen***, "Dynamic inflow modelling for helicopter rotors and its influence on the prediction of crosscoupling", *A.H.S. Aeromechanics Specialists Conference, Fairfield County, CT, October 11-13 1995.*

[15] ***P.-M. Basset***, "Contributions to the Improvement of a Simulation Model of the Flight Mechanics of Helicopters", *Doctoral Thesis of the Mediterranean University Aix-Marseilles II, Laboratoire ONERA-Ecole de l'Air, 29 September 1995.*

[16] ***M. Joglekar, R. Loewy***, "An actuator-disc analysis of helicopter wake geometry and the corresponding blade response", *USAAVLABS Technical Report 69-66, december 1970.*

[17] ***R. A. Ormiston***, "An actuator-disc theory for rotor wake induced velocities", *AGARD CPP-111, september 1972.*

[18] ***P. F. Bird, M. D. Friedman :*** "Handbook of elliptic integrals for engineers and scientists", *Springer-Verlag University Press, 2$^{\underline{nd}}$ edition, 1971.*

[19] ***V.E. Baskin, L.S. Vil'dgrube, E.S. Vozhdayev, G.I. Maykapar***, "Theory of the lifting airscrew", *N.A.S.A.-T.T.F.-823, Feb. 1976.*

[20] ***P. Eglin***, "Aerodynamic Design of the NH90 Helicopter Stabilizer", *23$^{\underline{rd}}$ E.R.F., Dresden, Germany, paper n° 68, 16-18 September 1997*