# MODELING OF THE DYNAMIC INFLOW ON THE MAIN ROTOR AND THE TAIL COMPONENTS IN HELICOPTER FLIGHT MECHANICS

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## ABSTRACT

*This article deals with the importance in helicopter flight mechanics of the modeling of the velocities induced by the main rotor wake. The dynamic inflow on the main rotor affects its on- and off-axis responses (pitch-roll cross-couplings). The interactions on the tail surfaces and the tail rotor affect mainly the pitch behaviour (pitch bump, phugoid mode, etc.) and secondarily the lateral-directional behaviour (bank angle, dutch-roll mode, etc.). These phenomena have been studied with an extended version of the Pitt and Peters dynamic inflow model and a dynamic multi-vortex-rings model.*

## 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
Dcol, Dlat, Dlong Pilot main rotor controls : collective, lateral, longitudinal stick input
$K_R$ Wake distortion parameter due to rates
$[\hat{L}]$ Gain matrix
[M] Apparent-mass matrix
p, q Roll and pitch body angular rates
R Rotor radius
$R_v$ Viscous core radius
$V_{airp}$ Airspeed in the airfoil plane
$V_H$ Horizontal speed
$(v_{i0}, v_{i1c}, v_{i1s})$ First harmonic coefficients of the induced velocity field on the main rotor
$\beta_{1c}$ Longitudinal flapping angle
$\beta_{1s}$ Lateral flapping angle
$\gamma_{ij}$ Local vortex strength
$(\gamma_0, \gamma_{1c}, \gamma_{1s})$ First harmonic coefficients of the vorticity on a vortex torus
$\Gamma_{ij}$ Local bound circulation on blades
$\psi$ Azimut angle
$\mu$ Advance ratio
$\Omega$ Rotor rotational speed

ABBREVIATIONS : MR for main rotor, H for horizontal tail, V for Vertical tail, TR for tail rotor.

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## INTRODUCTION

The prediction of the helicopter behaviour in flight including in the design phase, is a primordial industrial challenge. In a more and more competitive world market, such a simulation tool is a major trump to progress faster and further in the development of a rotorcraft. Indeed the flight tests will be all the more reduced and delayed in the design process since the simulation model will reach a good level of universality and fiability.

Within this context, a cooperation has been established between ONERA and Eurocopter France (ECF) in order that ONERA contributes to the development of a generic model **[1]** from the basis of the ECF S89 model **[2]**.

Only the characteristics of this initial model interesting this paper will be described here. The induced velocity field on the main rotor is represented by the Meijer-Drees first harmonic inflow model **[3]**, augmented with a first order dynamic on the mean induced velocity (an empirical time constant is used). Only the interaction between the main rotor wake and the horizontal stabilizer is taken into account in terms of a downwash component. This downwash seen by the horizontal tail is assumed to be instantaneously proportional to the mean induced velocity on the main rotor. The coefficient of proportionality requires to be adjusted with respect to flight test data.

The purpose of the present paper is to improve the representation of the velocities induced by the main rotor wake on the main rotor and the tail components. Motivated by the needs of the flight mechanics (non real time) simulation, the emphasis has been put on a dynamic and generic modeling of the main effects.

In a first step, a modified Pitt and Peters dynamic inflow model has been implemented in the S89 code. A synthesis of the improvements brought by this model and the remaining simulation weaknesses will be presented for the cases of forward flight and near hover, (the Bo105 flight test data provided by DLR **[4]** will be used as experimental reference). In particular, the initial model was too unstable to allow to take into account the aerodynamic perturbations induced by the main rotor wake on the rear parts. This first upgrade improving the rotor aerodynamic damping, so this enhancement provides the required stability for the modeling of the interactions.

Then a dynamic vortex rings model of the main rotor wake will be described. As a first application, this dynamic wake model will be used to calculate the mean induced velocities on the horizontal and vertical tail surfaces and on the tail rotor. The effect on trims will be examined with a focused interest on the pitch bump prediction. The improvements of the dynamic simulations will be shown in forward flight and near hover.

One of the other weaknesses being the pitch-roll cross-coupling representation, in a third and final part this problem will also be addressed by using both the main rotor dynamic inflow model and dynamic wake model.

# MODEL DEVELOPMENTS

## 1- Dynamic inflow rotor model

### *1.1- DESCRIPTION*

The dynamic inflow model implemented by ONERA in the S89 code is based on the Pitt and Peters non linear model formulated in **[5]**. The dynamic of the induced velocity field normal to the rotor is described in the hub axes up to the first harmonic ($\lambda_0$, $\lambda_c$, $\lambda_s$) are the dimensionless induced velocity coefficients) and governed by the following first order differential equations, where the aerodynamic loads $(C_T, C_L, C_M)_{ae}$ are the excitation terms :

$$\overbrace{\underbrace{[M].\begin{bmatrix}\dot{\lambda}_0\\ \dot{\lambda}_s\\ \dot{\lambda}_c\end{bmatrix}}_{\text{Transient response}}+\underbrace{\left[\hat{L}\right]^{-1}.\begin{bmatrix}\lambda_0\\ \lambda_s\\ \lambda_c\end{bmatrix}}_{\text{Quasi-steady response}}}^{\text{Dynamic inflow response}}=\underbrace{\begin{bmatrix}C_T\\ -C_L\\ -C_M\end{bmatrix}_{ae}}_{\text{Excitation}}$$

For the sake of brevity the matrices are not described here. The details of this model can be found in **[5]**. The only difference is the application of tip-loss correction to the mass- and gain- matrices.

### *1.2- RESULTS*

This new representation of the induced velocity field on the rotor has been implemented in the main rotor model and compared with the former one on : trims, transfer functions of isolated rotor and time simulations near hover and in forward flight **[6]**. Only the more important results will be presented here.

*- Time simulations in forward flight* : **Fig. 1** shows the effect of the new dynamic inflow model on the correlations with the Bo105 flight tests at 80kts for "DLR-3.2.1.1" inputs.

→ The stability of the simulations is well improved.

→ The magnitude of the on-axis responses are better predicted, especially the longitudinal on-axis behaviour as can be seen on (q **Fig. 1-c**).

→ The results concerning pitch to roll cross-coupling responses are also improved in phase and magnitude (p **Fig. 1-c**).

This latter effect on cross-couplings is even more significant for a longitudinal cyclic step input (**Fig. 2**), since the new model permits to predict the roll off-axis responses with the same sign and magnitude than the one of flight test data.

*- Time simulations near hover :* **Fig. 3** shows the effect of the Pitt and Peters model on the correlations with the Bo105 flight tests at low speed for "DLR-3.2.1.1" inputs.

Globally, the time simulations remain less realistic than in forward flight :

→ In spite of the significant improvement brought by the new dynamic inflow model, the main problem at low speed is that the simulations are still more unstable than the flight tests.

→ The roll on-axis response is improved (**Fig. 3-b**). But the damping on the other on-axis responses are still underestimated, (p **Fig. 3-a**, q **Fig. 3-c**).

→ The lower is the speed, the less important is the effect of the Pitt and Peters model on the cross-coupling responses (e.g. roll to pitch **Fig. 3-b**). Indeed, in hover the matrices of this model are diagonals.

More details can be found in **[1, 6]**.

This prior upgrade of the rotor aerodynamic damping representation allows now to account for the aerodynamic perturbations induced by the main rotor wake on the tail components.

In order to improve the physical representation of the phenomena and still have a reasonable computational time, ONERA has developed a rotor wake model based on a vortex rings approach.

## 2- Dynamic vortex rings model

### *2.1- DESCRIPTION*

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

*- The wake geometry :* the vortex wake is represented by vortex rings: radially distributed (they represent the trailing vortices generated along the blades during the same rotor revolution), and distributed along the rotor wake (they represent the trailing vortices emitted during each of the previous rotor revolutions) (**Fig. 4**). A circular vortex element is in fact represented by a torus in order to take into account the volumic distribution of

the vorticity (inside a vortex line) by means of a viscous core radius ($R_V$).

The advantage of such a vortex pattern is that it is both :

- sufficiently simple to reduce the computational time in comparison with those of more realistic representations which require a numerical integration of vortex segments influences [7];
- sufficiently sophisticated to be used in the whole flight envelope, whereas the flat vortex wake approximation (introduced by Vil'dgrube [8, chap. II, p. 30-37]) is not valid at low speeds $\left(\mu \leq 1.15 \times \sqrt{C_T}\right)$.

Indeed, a vortex method is rarely used in flight mechanics, and among the rare vortex representations used, the flat vortex wake approximation is generally prefered for its low computational time cost [9-11].

So, the vortex rings model seems to be a good compromise, well adapted to the requirements of the mathematical models of helicopter flight dynamics.

***- Induced velocity field by a torus :*** the rings are the vortex elements and their induced field can be formulated by means of elliptic integrals [12], if their vorticity is approximated by a Fourier series.

The description of the vorticity distribution on each ring is here limited to the first harmonic ($\gamma_0$, $\gamma_{1c}$, $\gamma_{1s}$). The velocity field induced by a vortex ring charged with the intensity ($\gamma_0$, $\gamma_{1c}$, $\gamma_{1s}$) is a linear combination of the three basic fields induced by a vortex torus charged respectively with : $(\gamma_0, \gamma_{1c}, \gamma_{1s}) \in \{(1,0,0), (0,1,0), (0,0,1)\}$.

Once the wake geometry approximated and the law of induction known, the remaining difficulty is to assess the vortex intensity.

***- Vortex intensities allocated to the rings :*** the vorticity carried along the wake by the trailing and shed elements of vorticity respectively correspond to the radial and azimuthal gradients of bound circulation ($\Gamma(r, \psi)$) on the blades.

In a first approximation, only the trailing vortices have been considered. They carry away the radial gradient $\left(\partial\Gamma(r,\psi)/\partial r\right)$. So two steps in the calculation of the trailing intensities can be distinguished :

- the local values of bound circulation at the middle of each blade element is assessed according to the Kutta & Joukowski law :

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

- then, the local trailing vorticity ($\gamma_{i,j}$) emitted in the wake between two blade elements or at the root and the tip of the blade is related to the bound vortex strengths as follows :

$$\begin{cases} \forall(i,j), \gamma_{i,j} = \Gamma_{i-1,j} - \Gamma_{i,j} & \text{(on the blade)} \\ \forall j, \quad \Gamma_{0,j} = \Gamma_{N_r+1,j} = 0 & \text{(otherwise outside)} \end{cases}$$

When all the local trailing vortex strengths are known on the discretized rotor disc, the harmonic coefficients describing the vortex strengths distribution on each ring (of radius ($r_i$)) are calculated by means of a classical Fourier analysis.

***- Dynamic wake model :*** the geometry and the vorticity distribution evolve dynamically in function of the rotor airloads and motions. During the time simulation process, a new group of concentric rings is generated every $\left(dt_{rings} = 2\pi/(b.\Omega)\right)$.

* <u>Dynamic geometry</u> :
Each group of concentric rings 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), the convection velocity is assumed to be the vector sum of the free stream velocity at the hub and the mean downwash velocity ($\vec{v}_{i0}(t)$). Each group of coplanar rings keeps the orientation given by the tip-path-plane base at the time of its generation.

So the wake deformations (**Fig. 4**) are in average representative of the rotor motions and of the flow across the rotor.

* <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 rotor airloads.

### 2.2- *RESULTS*

***- Trim results :*** one of the most important advantages of this model for trim calculations, is that it is sufficiently close to the physical interaction phenomenon to permit a good assessment of the speeds where the pitch-up effect occurs without any adjustement of the model to trim experimental data.

Flight tests without horizontal tail have been conducted by ECF. These flight test data has been used preferentially to study the ability of our wake model to predict the pitch bump.

With the vortex rings model, the airspeeds for which the pitch-up phenomenon arises are well predicted (**Fig. 5**). But the pitch-up magnitude is underestimated by the present interaction model. One of the possible causes of this underestimation is the interaction effect on the rear part of the fuselage which can hardly be taken into account without a geometric representation of the fuselage. Indeed the measures without horizontal stabilizer reveal a significant pitch-up resulting from the influence of the main rotor wake along the tail boom. So for some helicopters, it seems that a good assessment of the magnitude of the pitch bump requires to take into account the main rotor wake effect on the tail boom.

** Model refinements :*

The first goal of the development of this dynamic wake model by ONERA is to improve the simulation of the helicopter flight dynamics. However many modifications of the characteristics of the wake have been studied on trim calculations. The purposes of these model refinements are to study the main effects of some modifications of the wake geometry and vorticity and to demonstrate the potentiality of evolution of the vortex rings approach.

Concerning the vorticity, the effect of the viscosity of the air leads to reduce the vorticity in function of the "age of the vortices" (viscous dissipation) and to use an attenuation law of the vorticity inside the vortex torus. The "vortex ageing" leads also to increase the viscous core (viscous diffusion).

Concerning the geometry, the increase of the velocities inside the wake from the rotor towards the far wake produces a radial contraction and a longitudinal dilatation of the wake. The interactions with the tail components affect the distribution of the vortices inside the wake (the vortex density is increased near these elements). This vortex accumulation around the tail planes could explain a part of the pitch-up magnitude.

Some of these modifications are briefly presented here.

Vortex diffusion :

In the basic vortex rings model the viscous core is fixed : $\left(r_v = R_v/R = 0.0025\right)$. In order to take into account the viscous diffusion, an option has been implemented to increase the viscous core with respect to the "age" of each vortex torus **[8]**.

The effect of this viscous diffusion is to attenuate the local strong vortex interactions. For example, the sharp increase of ($V_{iHZ}$) near ($V_H \approx$ 15 km/h) disappears when an increasing viscous core is used (**Fig. 5**).

Wake contraction :

In the basic vortex rings model, each vortex ring keeps a constant radius. Yet, the Landgrebe's experimental studies for an isolated rotor in vertical flight (or in hover) have shown that the rotor wake is deformed by a radial contraction [13, p. 119]. Although only valid in vertical flight, the Landgrebe's empirical law of wake contraction has been implemented in the model.

The effect of this wake contraction is to make occur the interactions with the borders of the wake at other speeds and to increase the vortex ring influence in its inner field (**Fig. 5**).

*- TIME SIMULATION RESULTS*

***- Results in forward flight :*** the improvements brought by this new interaction model are shown for a "DLR-3.2.1.1" input on collective at 80 kts (**Fig. 6**). At this forward speed, a parametric study on the number of vortex rings indicates that about twenty of vortex groups composed of six concentric rings are sufficient to represent the effect of the wake on the tail components.

* Pitch effect :

Compared with the case without interaction and with the initial empirical model, the influence of the rotor wake on the horizontal tail improves the assessment of the phugoid mode (which appears after the excitation (t > 8,5 s)) (see curve MR/H in Fig.6).

* Roll and yaw effect :

The oscillations on roll and yaw axes (after the control inputs) are also better predicted thanks to the vortex rings model. On these axes compared with the pitching responses, it seems important to take into account the influences on the fin and the tail rotor (see curve MR/(H, V, TR) in Fig. 6). The contribution of the interaction on the horizontal tail is not negligible because of the pitch to roll cross-coupling.

***- Results near hover :*** the simulations being more unstable at low speeds, it is better to consider the case where the simulations are the most stable (because the perturbations due to the rotor wake tend to increase the unstability). With the Pitt and Peters dynamic inflow model, the case of a lateral input is the better one at low speeds (the agreement with the flight test data and the stability are good enough, **Fig. 3**).

At low airspeeds, the vortices staying closer to the helicopter than in forward flight, the number of groups of rings along the rotor wake must be increased. In the flight case considered here, about fifty vortex groups appear to give a good estimation of the effects of a "theoritical infinite wake".

The main improvement is obtained on the lateral - directional mode. Among the rear parts, the tail rotor being the most effective one at low airspeeds, the influence of the rotor wake on this element produces therefore the main effect (**Fig. 7**). So at low airspeeds, the "dutch-roll" mode seems to be better predicted by taking into account the influence of the rotor wake on the tail rotor. This effect should be studied more specifically.

## 3- Pitch-roll cross-couplings

A common weak point of most of the helicopter flight dynamics models is to correctly predict the pitch axis response to a lateral input and reciprocally (roll axis response / pitch input). The problem of "the cross-coupling mystery" as expressed by Mr. Prouty **[14]** is an actual challenge. Many researches all over the world are devoted to the modeling of this phenomenon.

An interpretation in the form of a "virtual inertia effect" linked to the rotor airmass has been proposed by DLR **[15]**. The Technion-Israel Institute of Technology **[16]** showed that the rotor wake distorsions due to rotor pitch and roll motions produce variations of the induced velocity field on the rotor which contribute to the pitch-roll cross-couplings. The local unsteady aerodynamics of the rotor airfoils also participate to the coupling by introducing a time-phase lag as shown recently by the NASA Ames Research Center [17].

The idea arises that the pitch-roll cross-coupling results from the combined actions of different phenomena. So ONERA works to be able to represent these different effects. In a first step each of them is considered separately.

Based on the approach presented in [15], an "induced gyroscopic couple" has been introduced in S89. When this effect is applied individually, comparisons with the Bo105 flight test data near hover have shown that physical values of the "virtual angular momentum" produce too weak effects. Indeed, if the rotor airmass apparent inertia is significant as underlined in [15], the induced angular velocity is too weak (around 0.3 rad/s) to produce an important gyroscopic effect. So the result of our study is that the only consideration of the "virtual inertia effect" can not explain all the pitch-roll cross-coupling.

A more detailed presentation of the work done to take into account the wake distorsion effect is proposed here.

The phenomenon is schematically exposed in **Fig. 8**. For instance, a pitch motion affects the longitudinal distribution of the vortices emitted by the rotor. Therefore, the longitudinal gradient in the induced velocity field is also affected, and so the fore-aft distributions of the angles of attack and airloads. Due to the gyroscopic behaviour of the rotor, these longitudinal variations contribute to the roll off-axes responses ($\beta_{1s}$, p).

### *3.1- LINEAR PARAMETRIC METHOD*

A simple method to account for this phenomenon consists in adding in the dynamic inflow equations two linear perturbation terms in function of the pitch and roll motions of the tip-path-plane [18-20].

Indeed in [5], the effects of the airloads and of the translational speeds are already taken into account, but not those of the rotor angular speeds. So considering the linearized formulation near hover, the addition of the effect of the rotational speeds leads to the equations presented at the bottom of **Fig. 8**.

The coefficient ($K_R$) can be determined thanks to a non-rigid wake model or identified from flight test data. These linear terms have been added to the non-linear dynamic inflow model in S89. In a first application, the coefficient ($K_R$) has been fitted to improve the correlation with the Bo105 flight test data for the case of a lateral "DLR-3.2.1.1" input near hover. A value of ($K_R$ = 1.5) gives good agreement as shown in **Fig. 9**.

The pitch off-axes responses are well improved (pitch attitude and q **Fig. 9**) and at the rotor level also the longitudinal tilt ($\beta_{1c}$). These improvements are brought here by the perturbations on ($v_{i1s}$) produced by the direct roll motion. The correlation on the roll on-axes responses are good. The input on the longitudinal cyclic between t ∈ [7.5 s, 9 s] produces a perturbation on the pitch rate which is transmitted to ($v_{i1c}$) by the augmented model. The roll responses (attitude and rate, **Fig. 9**) are affected by this off-axis excitation.

The limitation of this approach is the identification of the coefficient ($K_R$) which requires a "flexible wake model" to be used during the rotorcraft development phase (flight data being not available). So the ability of the dynamic vortex rings model to represent the wake distorsion effect will be now analysed.

### *3.2- VORTEX METHOD*

It should be first underlined that when ($K_R$) has been identified from UH60-A flight test data near hover [19], it has been found a value twice ($K_R$ = 3) compared with the one determined with a simplified vortex tube analysis ($K_R$ = 1.5) [18]. This discrepancy reinforces the idea that several phenomena simultaneously contribute to the pitch-roll cross-couplings. So to reach a modeling helpful during the helicopter design process, it is important to obtain a physical assessment of the contribution of each phenomenon.

The vortex rings model described previously has been used to calculate a first harmonic approximation ($v_{i0}$, $v_{i1c}$, $v_{i1s}$) of the induced velocity field on the rotor. The local and normal induced velocities are calculated at four locations on the rotor corresponding to its "cardinal points" ($r=R$, $\psi \in \{0°, 90°, 180°, 270°\}$).

Four kinds of models are compared in **Fig. 10** :
- on the one hand, the Pitt and Peters model [5] and its improvement with the identified rotational speed contributions ($K_R$ = 1.5) ;
- on the other hand, the rigid vortex rings model (without distorsions) and the dynamic rings model (with distorsions).

The oscillations on ($v_{i1s}$) due to the wake distorsions (difference between rigid and dynamic wake models results) are well correlated with those required to match up with the measured cross-coupling response (difference between Pitt and Peters model and the extended version results).

This result demonstrates the capacity of the ONERA dynamic vortex rings model to represent the wake distorsions.

A simple rotor wake model able to compute the interactions and the downwash on the main rotor could be conceivable on the basis of the dynamic vortex rings model. Yet this unified modeling will increase the computational time. Indeed to obtain a good description of the induced velocity field on the rotor, some refinements of the near wake model are required and also more points of calculation on the rotor.

A first and more realistic prospect will be to assess only the wake distorsion effects on the rotor downwash thanks to the vortex rings model. For this aim two approaches could be adopted :

- to determine an analytic law of evolution of ($K_R$) in function of the advance ratio and other parameters or to generate tables by computing the wake distorsion effects on ($v_{i0}$, $v_{i1c}$, $v_{i1s}$) with a vortex rings model outside of the helicopter simulation code ; this "external approach" for parametric studies has been used in **[18, 20]** ;
- to calculate ($v_{i0}$, $v_{i1c}$, $v_{i1s}$) with the rigid and flexible wake models directly in the helicopter code and using the differences between these two fields as wake distorsion corrections in the analytical dynamic inflow model.

For this last approach, it is important to work with a relatively simple vortex pattern in order to keep reasonable computational time. **Fig. 11** (flight case of **Fig. 9-10**), shows the effects of reducing respectively the longitudinal ("Rings 1.10 / 1.50") and radial ("Rings 1.50 / 8.50") distributions of vortex rings. The distorsion effects, which appear here mainly on the variations of the lateral gradient ($v_{i1s}$) due to the roll rate, are predicted even by the wake model reduced to the first ten tip rings near the rotor ("Rings 1.10"). Nevertheless, when the in-board wake is neglected or the length of the wake shortened, the variations are underestimated. With the complete wake model these variations are nearly of the same order of magnitude than those required to match the flight test data. So the number of vortex rings should be adapted to the desired compromise between accuracy and computational cost. A possible explanation of the discrepancy between the values of the wake distortion parameter ($K_R$) obtained in **[18]** ($K_R$=1.5) and in **[19]** ($K_R$=3) could be the fact that the wake model used in **[18]** (and even the free wake model used in **[20]**) take into account only the tip vortices.

The comparisons in **Fig. 11** also show that if the distorsion effects can be approximate by using only the tip rings, the direct airloads effects on ($v_{i1c}$) required a more complete radial distribution. The mean induced velocity ($v_{i0}$) is underestimated even with the complete wake model ("Rings 8.50"). As indicated before, capturing not only the variations of the rotor downwash but also its mean value, requires some refinements of the vortex pattern close to the rotor and more than the four points of calculation on it used up to now to assess the distortion effects.

ONERA will also work on an analytical extension of the dynamic inflow model in order to take into account the variations of the induced velocity field on the rotor due to its rotational speeds.

## CONCLUSIONS

The modeling of the induced velocities by the main rotor wake on the main rotor and the tail components has been studied for the simulation of the helicopter flight dynamics.

Concerning the dynamic inflow on the main rotor, the Pitt and Peters model presented in **[5]** is better fitted to time simulation of the helicopter flight dynamics than the former one ("Meijer-Drees + first order empirical dynamic on ($v_{i0}$)"). Indeed, this model is both : sophisticated enough (compared with quasi-static approaches) to represent the dynamic of the induced velocity field and simple enough (compared with vortex wake methods) to keep low computational costs. Thanks to this dynamic inflow model, the following improvements are obtained for a hingeless rotor, (they could be quantitatively less important for an articulated rotor) :

- the stability of the simulations is in better agreement with the one of the flight test data,
- the on-axis responses are better predicted (especially pitch motion in forward flight, roll motion near hover),
- the pitch to roll cross-coupling responses are also improved in forward flight.

Yet near hover, the pitch-roll cross-coupling remains quasi-ignored by the simulation model. This kind of cross-responses results from the combination of different phenomena introducing time-phase lags (e.g. unsteady aerodynamics) or acting on the cross-aerodynamics (e.g. relative motions of the rotor and its wake).

About this modeling problem, the present paper has been focused on the wake distortions effects. The addition to the Pitt and Peters model of linear effects from pitch and roll rates improves the correlations on the off-axis responses at low speeds. The wake distortion coefficient due to rates ($K_R$) has been identified from DLR Bo105 flight tests data near hover at a value ($K_R$≈1.5). But to be helpful even in absence of experimental data, this extension requires a more universal approach. The ability of the dynamic multi-vortex-rings rotor wake model to represent the wake distortions effects has been demonstrated. Furthermore, an on-line application could be prospected since the estimation of the wake distortion corrections requires a reduced number of rings and points of calculations on the rotor.

Above all, the inclusion of the effects of the pitch and roll kinematics of the tip-path-plane in the dynamic inflow model seems to be needed to predict the rotor off-axis responses. Other approaches could be viewed to capture not only the wake distortions effects but in a more general way all the effects due to the relative motions of the rotor and its wake.

Concerning the main rotor wake interactions on the rear elements, ONERA has developed a rotor wake model based on a multi-vortex-rings approach. Its geometry and vorticity distribution evolve dynamically in function of the rotor airloads and motions.

When this dynamic interaction model is used to calculate the induced velocity vector at the center of each rear component (horizontal and vertical tails and tail rotor), significant improvements are obtained :

- in pitch, the phugoid mode is better assessed mainly thanks to the influence on the horizontal tail, this effect is particularly appreciable in forward flight ;
- in yaw and roll, the lateral-directional mode is better predicted mainly thanks to the effect on the fin and the tail rotor, this last effect is the most important one at low speeds.

These models of dynamic inflow and interactions contribute to improve the reliability and the universality of the initial model, with a level of simplification that enables computational times compatible with practical applications.

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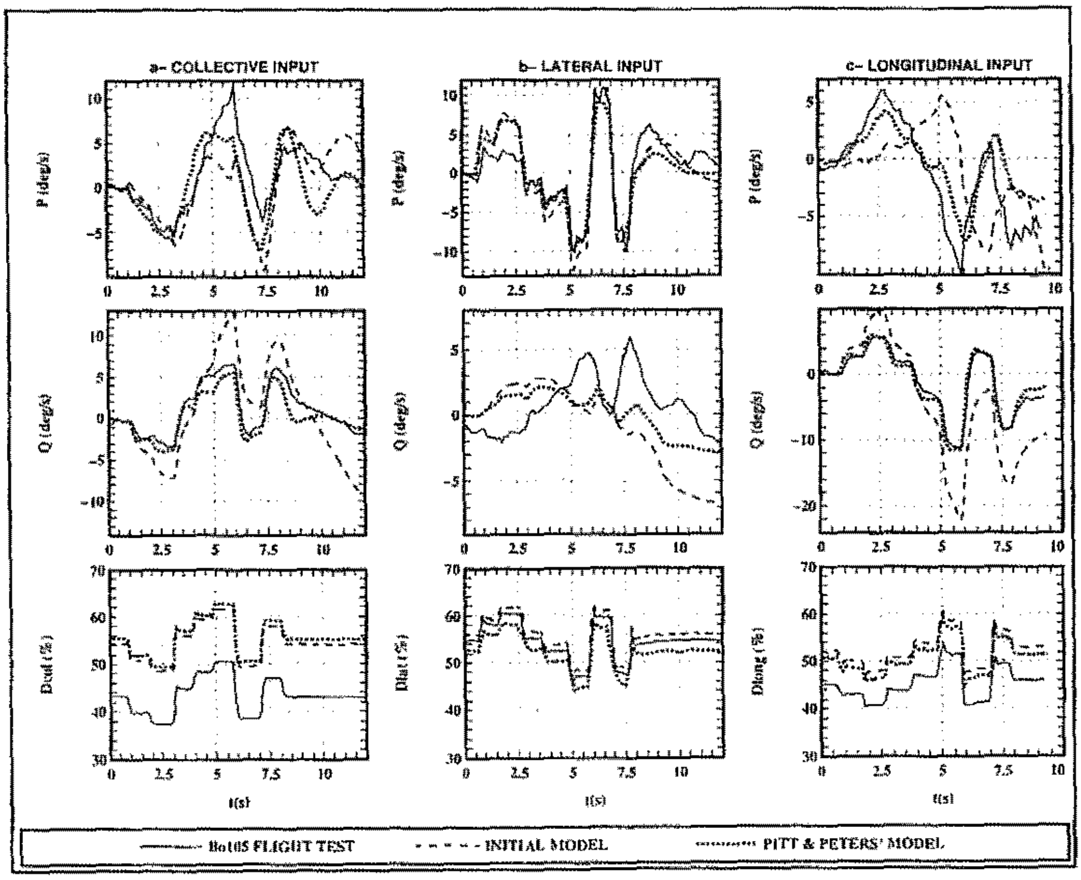


Fig. 1 : Effect of the main rotor dynamic inflow model (forward flight 80kts).

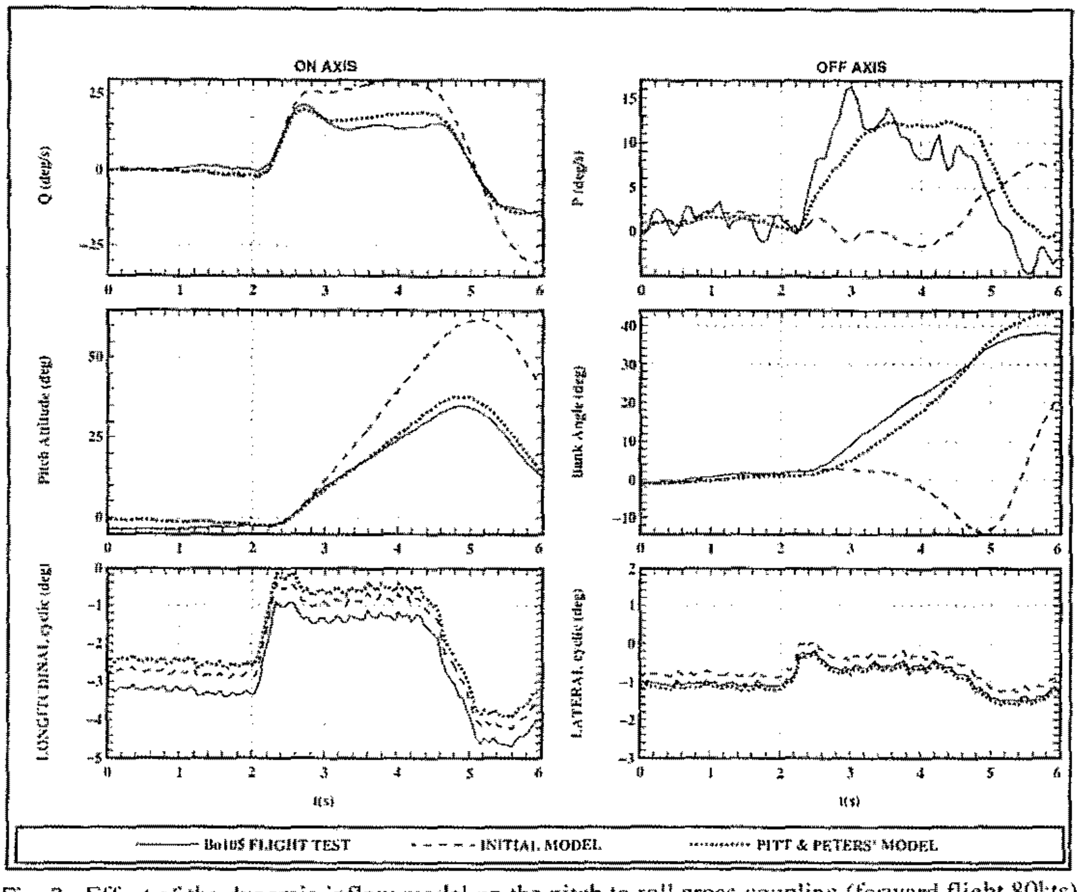


Fig. 2 : Effect of the dynamic inflow model on the pitch to roll cross-coupling (forward flight 80kts).

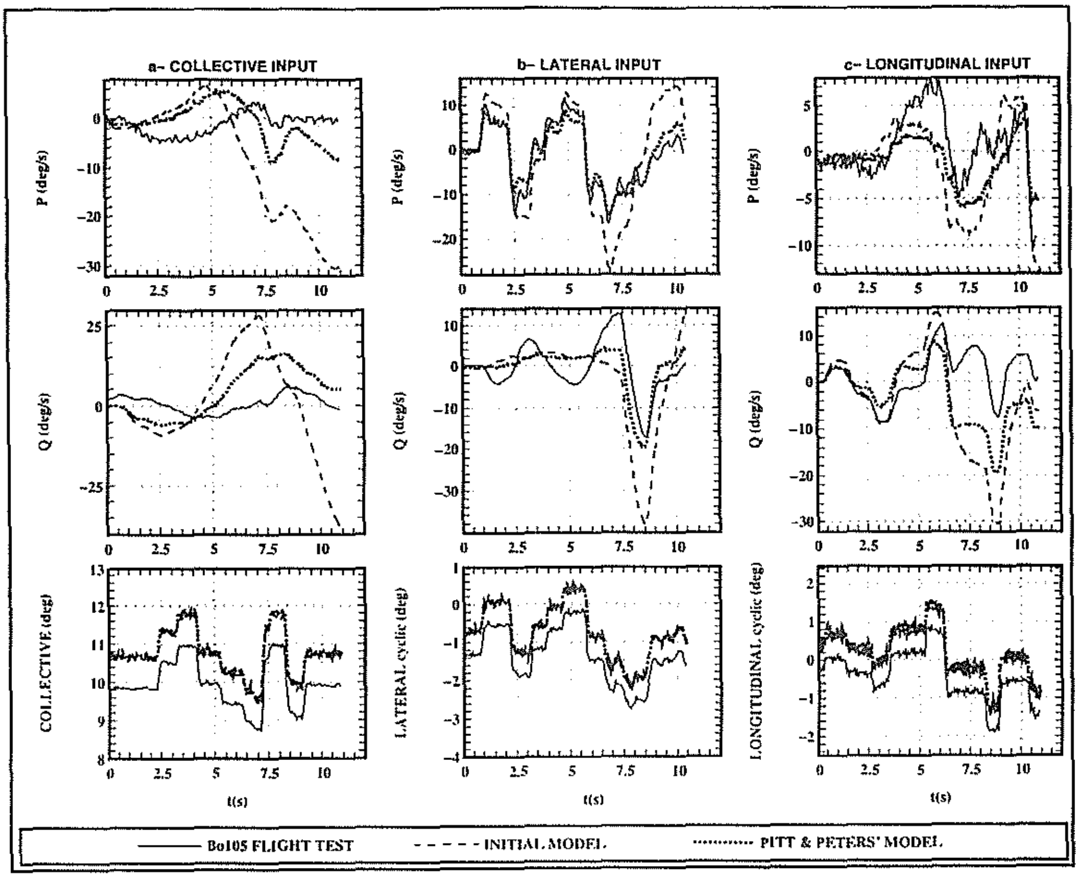


Fig. 3 : Effect of the dynamic inflow model (near hover).

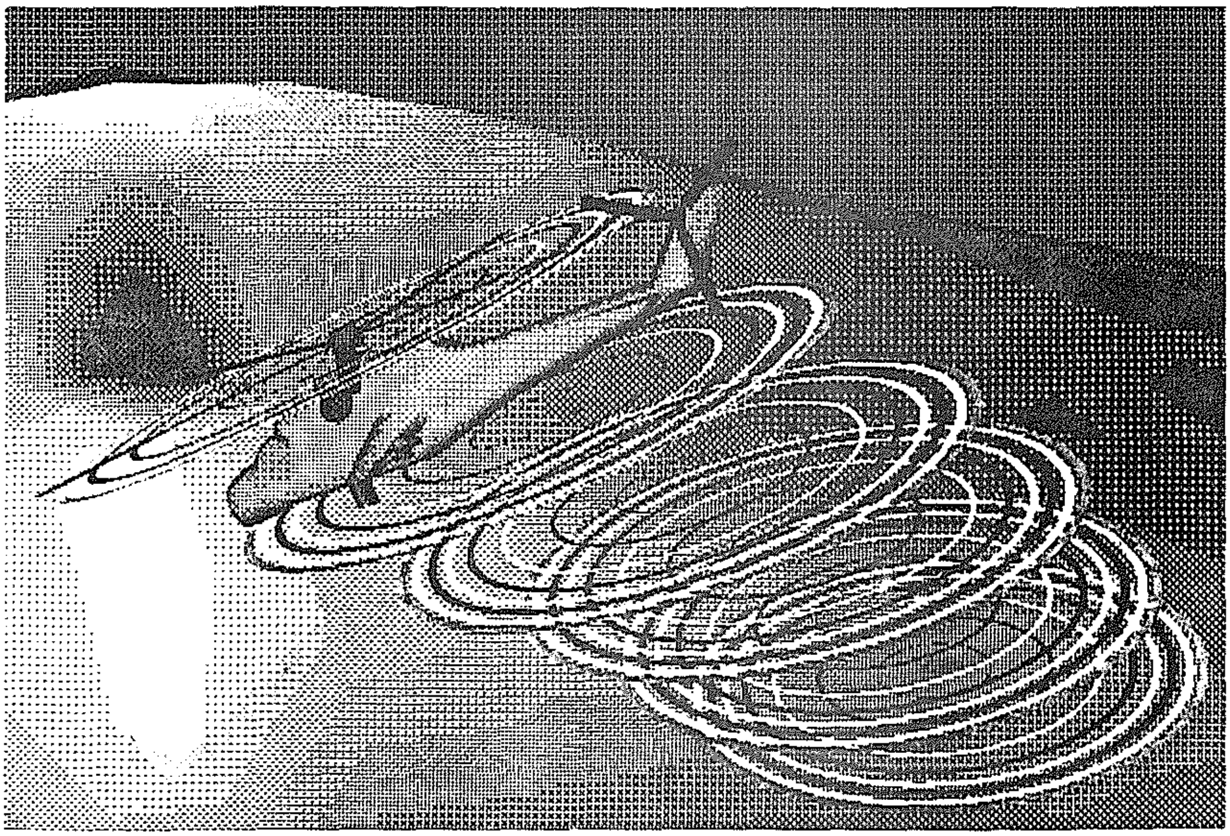

Fig. 4 : Dynamic multi-vortex rings model,
(for the sake of clarity only a reduced number of groups of coplanar rings are represented).

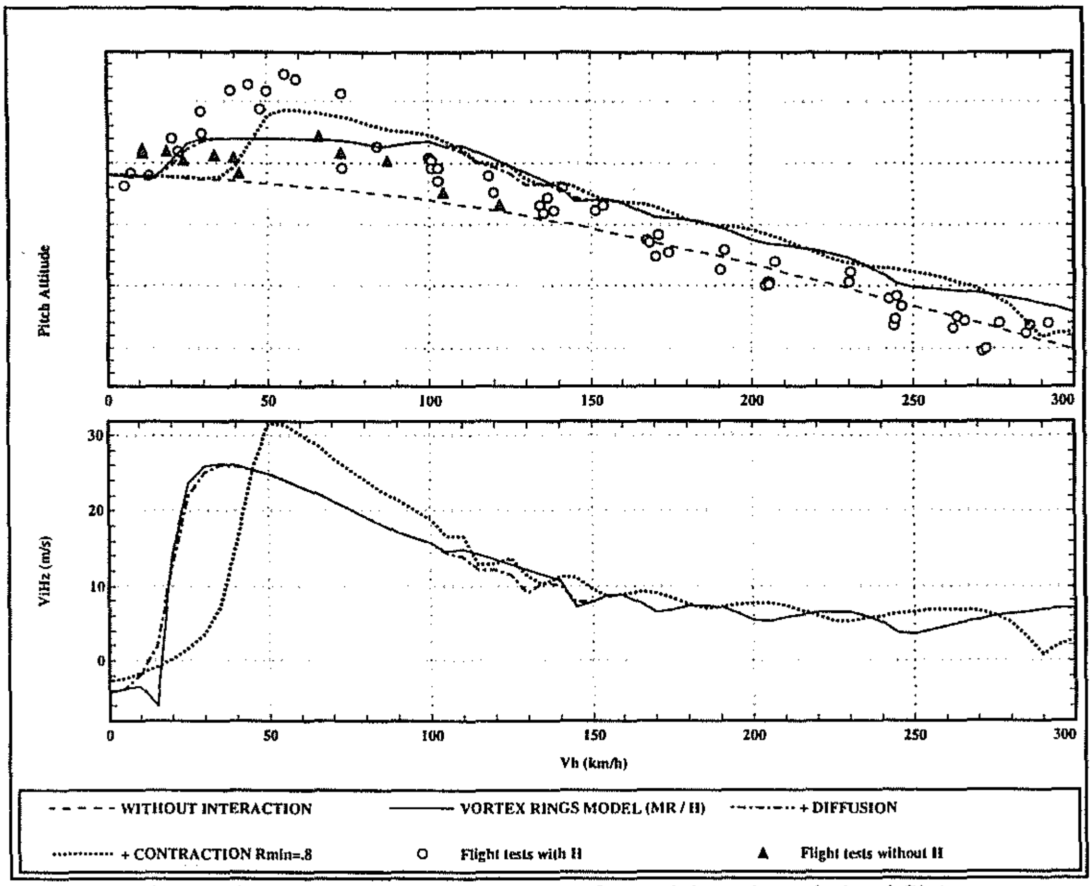


Fig. 5 : Pitch bump comparisons on trims for straight and steady level flights.

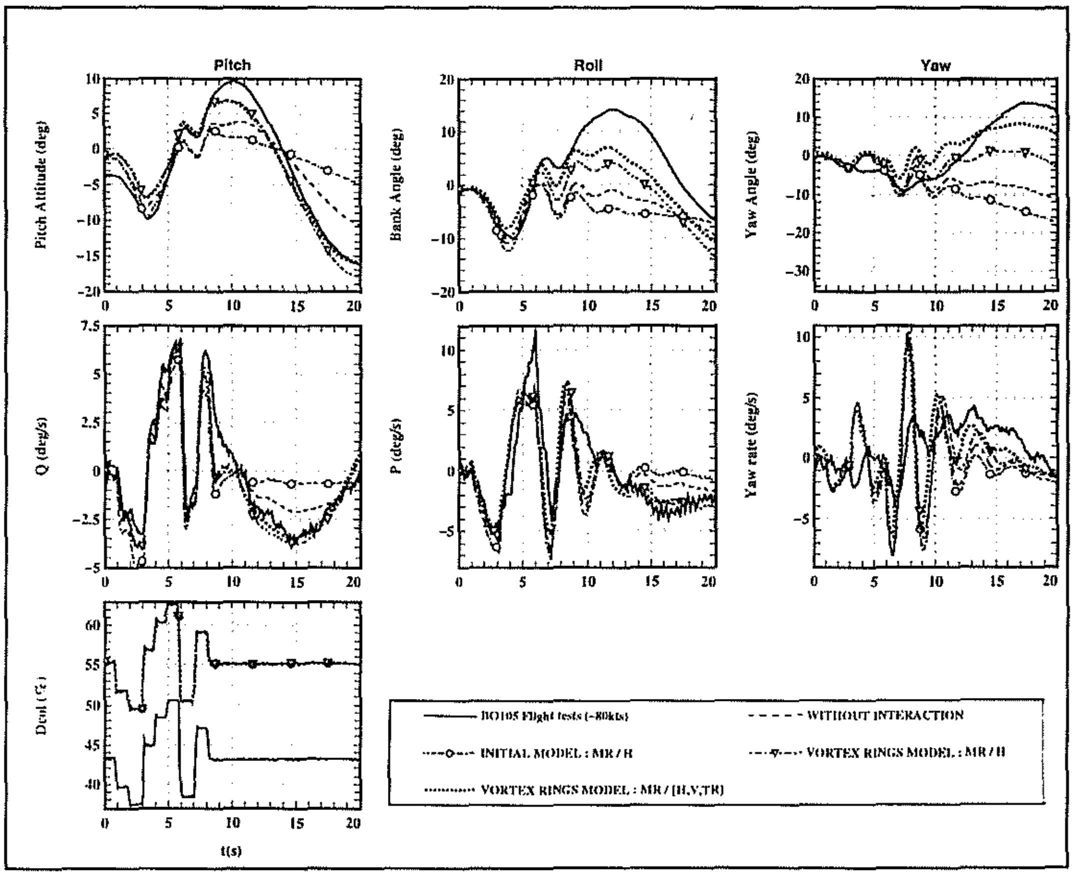


Fig. 6 : Effect of the models of the main rotor wake interactions on the tail components, (forward flight 80kts).

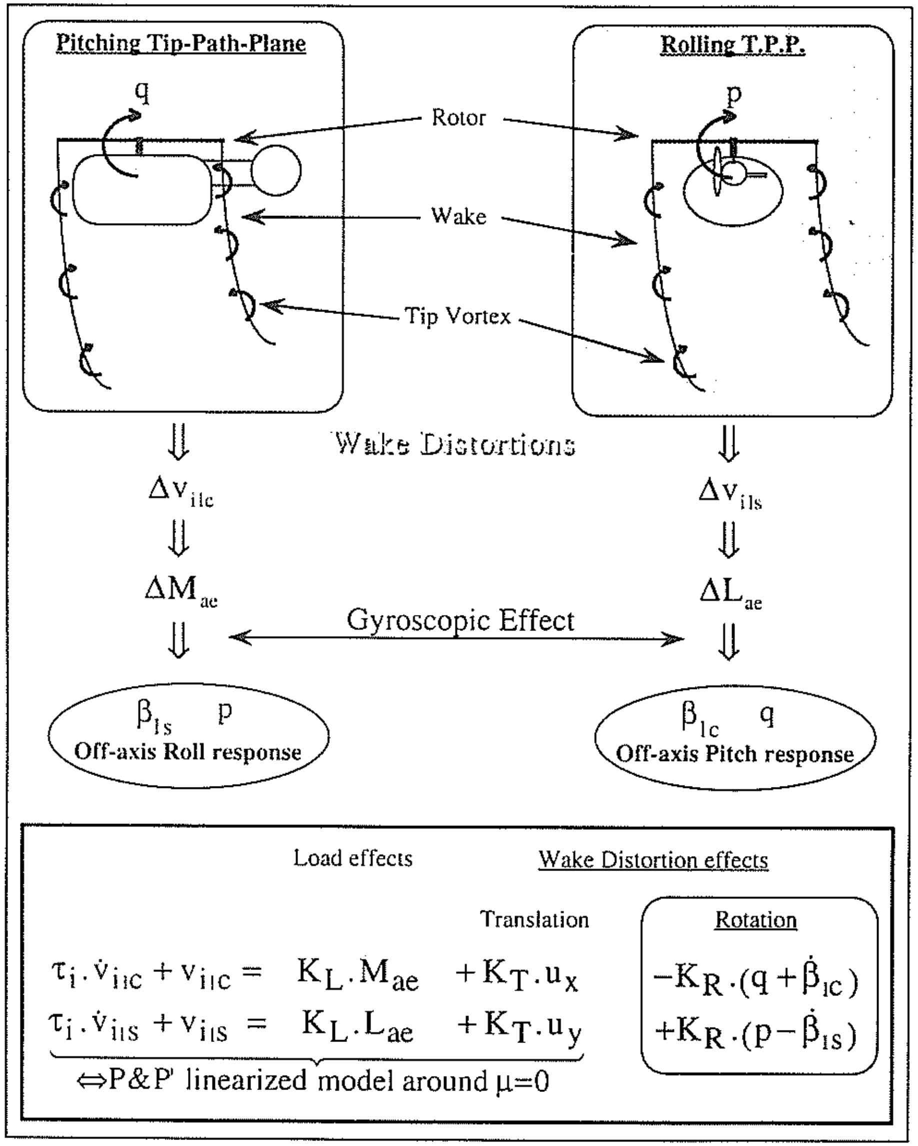


Fig. 8 : Wake distortion effects due to rates of the tip-path-plane and their modeling compared with the Pitt and Peters linearized model near hover.

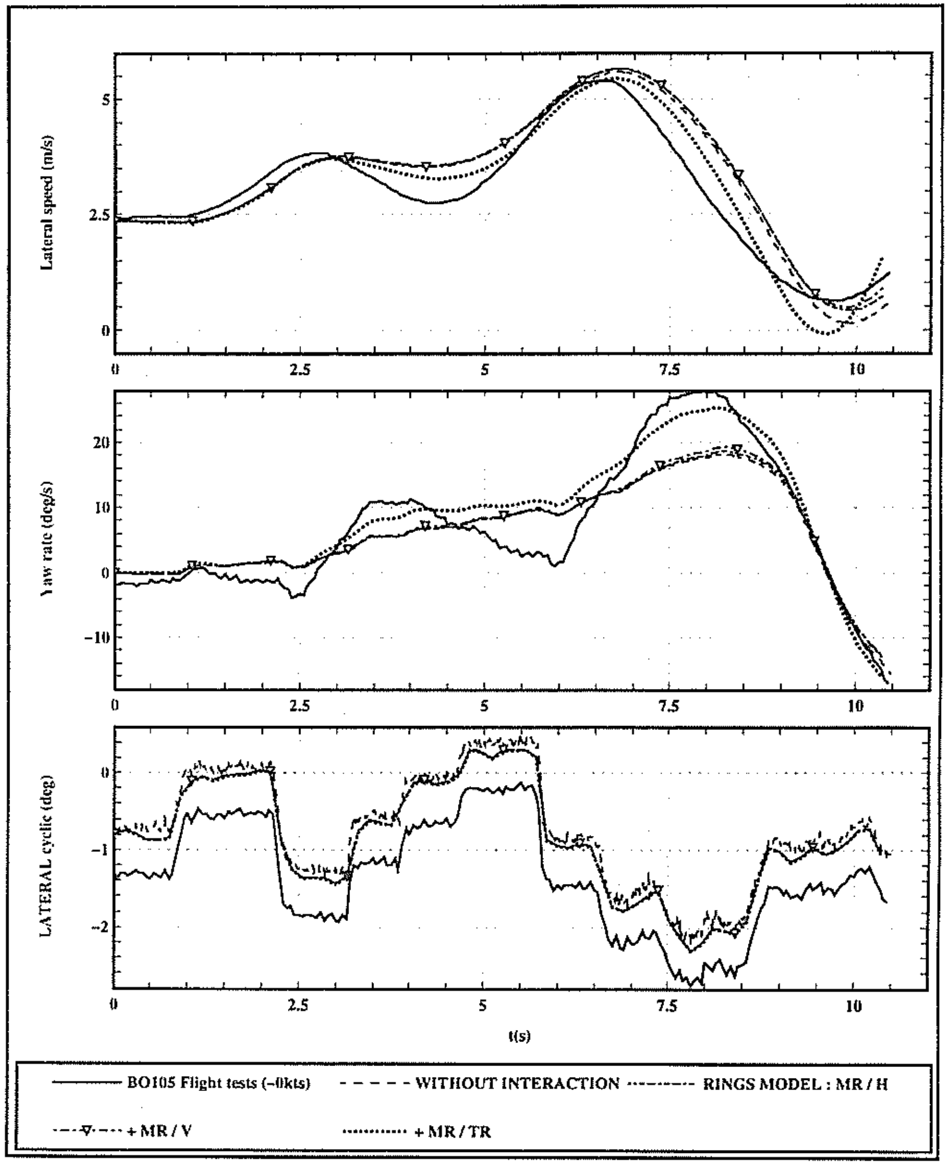


Fig. 7 : Effect of the interactions on the tail elements represented with the vortex rings model (near hover).

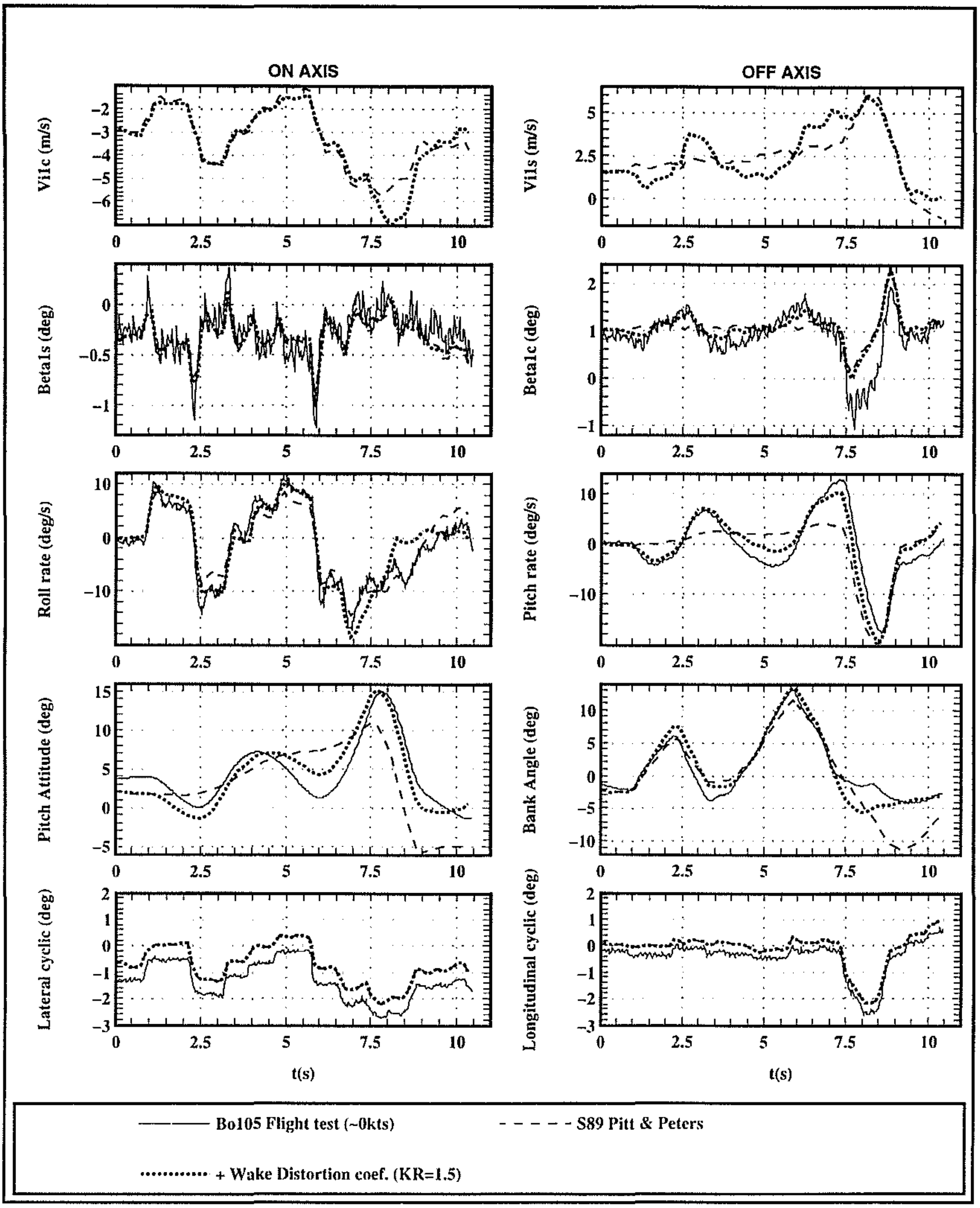


Fig. 9 : Effect on the roll-pitch cross-couplings near hover, obtained with the dynamic inflow model extended with the linear influences of the pitch and roll rates of the main rotor tip-path-plane.

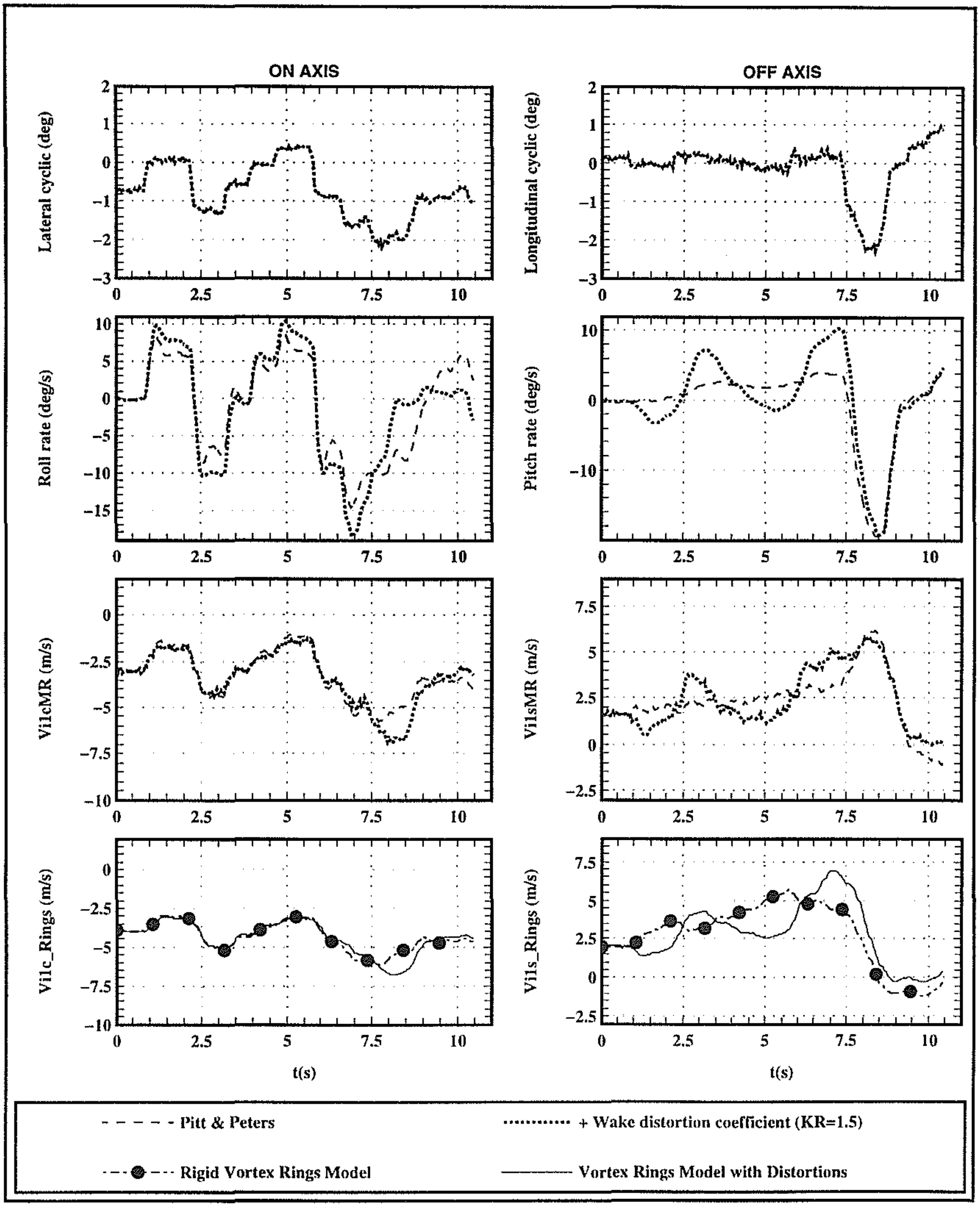


Fig. 10 : Wake distortion effects near hover on the gradients in the induced velocity field on the main rotor, (Bo105 flight case of Fig. 9).

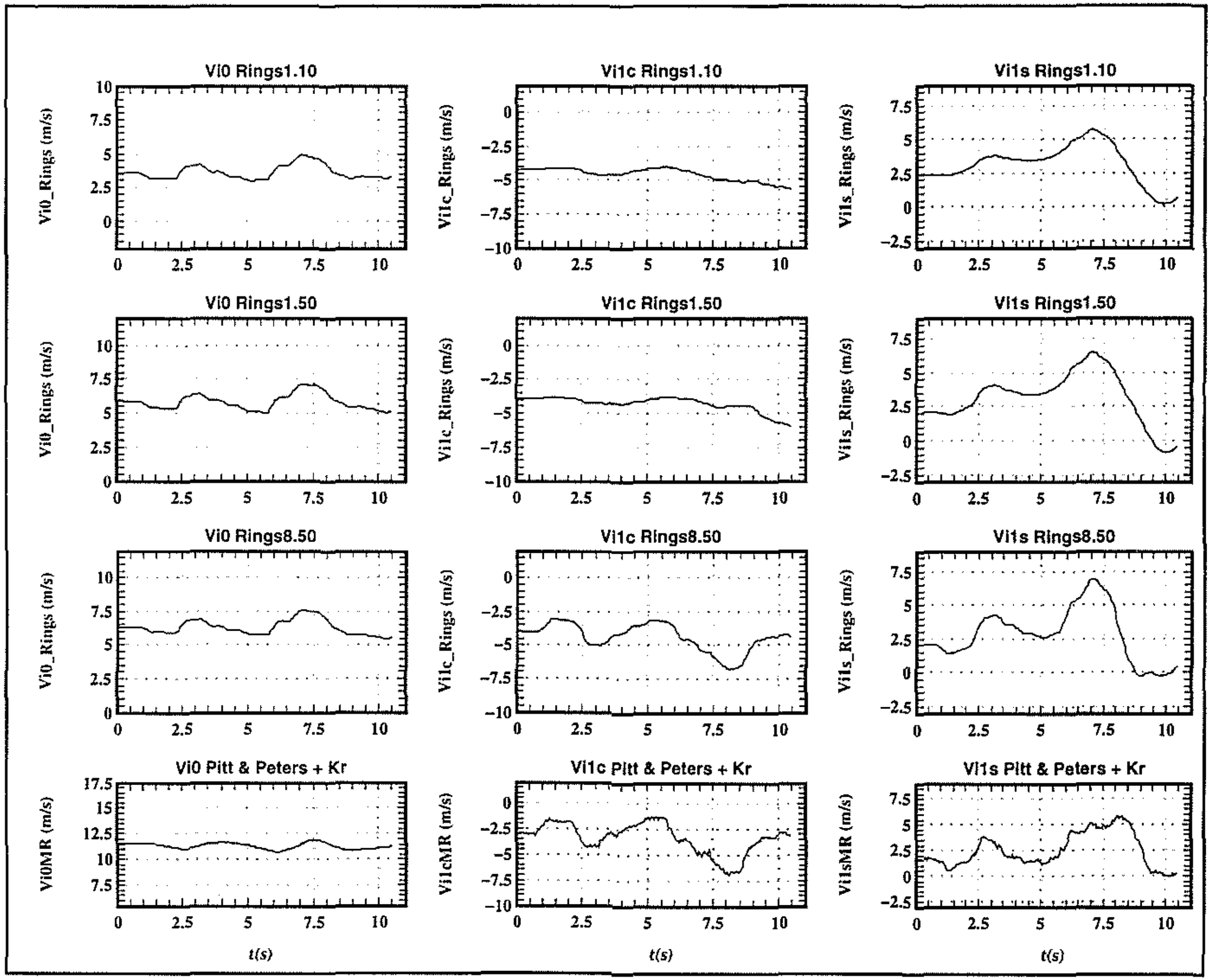


Fig. 11 : Induced velocity fields on the main rotor calculated with the extended Pitt and Peters model and the wake model with : the first ten tip vortices (Rings 1.10), fifty tip vortices (Rings 1.50), or fifty groups of concentric rings containing all the radial distribution (Rings 8.50).