1 INTRODUCTION

Near-ground helicopter operation modeling is a very challenging task. The flow around the helicopter is indeed made more complex by the interaction between the terrain and wake vortices. Moreover, from a piloting point of view, in-ground-effect flight procedures are much more difficult and dangerous due to a combination of factors: i) the reduced margin of maneuver; ii) the possible presence of gusts and wind shear; iii) the complexity of the tasks to be fulfilled. Note that, helicopter capability to hovering makes near-ground operations not limited to landing and take off, but also includes other tasks, like rescue operations.

Particularly severe threats to flight safety arise in landing over a ship moving deck [1]. This is due to several additional factors including the relatively small size of the flight deck, turbulence due to the wake released by ship or platform superstructures, and deck roll, pitch and heave motion induced by waves [2-4]. Thus, the ship deck effects on landing helicopter dynamics may be divided into two main categories: those deriving from the impingement of turbulent flow generated by the ship superstructure during motion, and those deriving from the presence of the deck below the vehicle that alters the rotor wake dynamics (ground effect). On first approximation, ship’s airwake turbulence and helicopter rotor downwash effects may be superimposed (thus neglecting coupling phenomena). The estimation of the ship turbulent airwake effect on the helicopter dynamics could be accomplished either through a control equivalent turbulence input approach, when suited experimental flight data are available [8], or taking advantage of dedicated numerical simulations of the flow-field of ship’s airwake shed from the superstructure [9-11].

On the other hand, the effect of ground presence on rotor/helicopter aerodynamics (of common importance to any near-ground operation), has been studied by several authors in the past decades, starting with the pioneering experimental work of Wiesner and Kohler [12], Yeager, Young and Mantay [13] and that of Empey and Ormiston [14], that was followed by the studies presented by Curtiss et al. [15], Hanker and Smith [16], Cimbala et al. [17] and Light [18].

More recently, this problem has been examined also through dedicated numerical models [19-20]. Among these, the adaptation of the well-known Peters and He’s dynamic inflow model including the effect of a surface below the rotor has been proposed [21-22]. It is of particular interest for the rotorcraft manufacturer/research community in that, due to its simplicity and reduced computational effort, the use of dynamic inflow models coupled with two-dimensional airfoil aerodynamics still remains a widely-used approach. Despite the aforementioned advantages, this modelling suffers from the accuracy limitations of analytical or semi-analytical models, that may be particularly critical when dealing with complex interaction phenomena or non-conventional operating conditions.

Here, the authors present in-ground-effect helicopter
aeromechanics analysis through application of the rotor dy-
namic inflow model recently introduced by Gennaretti et
al.\textsuperscript{24} It is derived from high-fidelity numerical aerodynamic
predictions as an extension of the out-of-ground-effect wake
inflow model introduced in the recent past\textsuperscript{25}\textsuperscript{26}\textsuperscript{27}\textsuperscript{28}. The modeling technique is completely general and is applicable
ground of arbitrary shape and in arbitrary motion.

In the following, first the proposed wake inflow modelling
technique is outlined, then the application to aeromechanic
analysis is described, and finally results of a numerical in-
vestigation concerning a rotor hovering in proximity of the
ground are discussed.

2 METHODOLOGY

In this section, the whole modeling scheme is presented.
First, the dynamic inflow model identification procedure is
illustrated, then the aerodynamic solver used for the inflow
simulations and the aeromechanic tool are described.

2.1 Dynamic inflow modeling

Two different finite-state, In-Ground-Effect inflow models are
here introduced and tested. The former, denoted as $\lambda - q$,
relates wake inflow with controls and flight dynamics cine-
matic degrees of freedom (namely blade pitch controls, hub
motion and rigid blade flapping variables), whereas the lat-
ter, $\lambda - f$, relates inflow with rotor thrust, roll and pitching
moment coefficients $\{C_T, C_L, C_M\}$, similarly to the Pitt and
Peters’ model\textsuperscript{25}\textsuperscript{26}\textsuperscript{27}\textsuperscript{28}.

The approximated expression of the wake inflow distribu-
tion over the rotor disc, $\lambda_{\text{app}}$, is expressed by the widely
used linear interpolation formula, defined in a non-rotating
polar coordinate system, $(r_c, \psi)$.

\begin{equation}
\lambda_{\text{app}}(r_c, \psi, t) = \lambda_0(t) + r_c \left( \lambda_s(t) \sin \psi + \lambda_c(t) \cos \psi \right)
\end{equation}

where $r_c$ denotes distance from the disc center, $\psi$ is the az-
imuth angular distance from the rear blade position, and the coef-

cients, $\lambda_0$, $\lambda_s$, and $\lambda_c$, represent, respectively, instan-
taneous mean value, side-to-side gradient and fore-to-aft
gradient.

For the $\lambda - q$ model, once the wake inflow over the
blades corresponding to chirp-type perturbations about the
steady state rotor kinematics variables (namely, hub motion
components, blade flapping components, and blade
pitch controls) is determined by the high fidelity aerody-
namic solver, input and output signals are windowed and
transformed into frequency domain in order to determine the
sampled transfer matrix $H(\omega)$ such that

\begin{equation}
\tilde{\lambda} = H \tilde{q}
\end{equation}

where $\lambda = \{\lambda_0, \lambda_s, \lambda_c\}^T$ and $q = \{q_0, q_\psi, q_\phi, q_\theta\}^T$, with
$q_0 = \{u, v, w\}^T$ and $q_\lambda = \{\lambda, \psi, \phi, \theta\}^T$ collecting, respectively,
the hub linear and angular velocities, $q_\psi = \{\beta_0, \beta_\psi, \beta_\phi\}^T$ the
blade flap components, and $q_\theta = \{\theta_0, \theta, \phi\}^T$ the

blade pitch controls.

Then, performing a rational-matrix approximation of $H(\omega)$\textsuperscript{25}\textsuperscript{27}, and transforming into time domain provides the fol-

\begin{equation}
\lambda = A_1 \dot{q} + A_0 q + C x
\end{equation}

\begin{equation}
\dot{x} = Ax + B q
\end{equation}

\begin{equation}
\tilde{x} = \tilde{A} x + \tilde{B} f
\end{equation}

where $x$ is the vector of the additional states represent-
ing the wake dynamics effects, whereas matrices $A_1, A_0, A, B, C$ are real, fully populated matrices derived from the rational-matrix approximation process.

Starting from the approach proposed above, an alter-
native procedure providing a dynamic inflow model relating the
wake inflow coefficients, $\lambda$, to rotor loads perturbations
(akin to the well-known Pitt-Peters model) can be devel-
oped. It requires the additional identification of the tran-
sfer function matrix $G$ between the kinematic input variables
perturbations and the corresponding rotor loads, $f$\textsuperscript{25}.

\begin{equation}
\lambda = \hat{C} x
\end{equation}

\begin{equation}
\dot{x} = \hat{A} x + \hat{B} f
\end{equation}

similar to that in Eq. (5), but given in terms of rotor loads\textsuperscript{25}, and with the polynomial part removed due to the asymptotic
behavior of $G$.

Equivalent (but different) inflow models can be obtained
starting from each triplet of kinematic DOFs considered in
$\lambda - q$ model.

2.2 Aerodynamic Solver

The Boundary Element Method solver\textsuperscript{32}\textsuperscript{33} here used for
wake inflow prediction, is suited for rotors in arbitrary mo-
tion and is capable of accurate simulations taking into ac-

count free-wake and aerodynamic interference effects in
multi-body configurations, as well as severe body-vortex in-

teractions; a finite ground below the rotor is modeled as an
additional body\textsuperscript{24}.

Considering incompressible, potential flows such that $\vec{i} = V \vec{\phi}$, the aerodynamics formulation applied assumes the poten-
tial field, $\vec{\phi}$, given by the superposition of an incident
field, $\vec{\phi}_i$, and a scattered field, $\vec{\phi}_s$ (i.e. $\vec{\phi} = \vec{\phi}_i + \vec{\phi}_s$). The scattered
potential is determined by sources and doublets

distributions over the surfaces of the bodies, $S_{b_i}$, and by
doublets distributed over the wake portion that is very close
to the trailing edge from which emanated (near wake, $S_W^N$). The incident potential field is associated to doublets distributed over the complementary wake region that compose the far wake $S_W^F$.

In this formulation, the incident potential affects the scattered potential through the induced-velocity which modifies the boundary conditions of the scattered potential problem, while the scattered potential affects the incident potential by its trailing-edge discontinuity that is convected along the wake and gives the intensity of the vortices of the far wake. Exploiting the vortex-doublet equivalence, the incident velocity field is evaluated through the Biot-Savart law. In order to assure a regular distribution of the induced velocity field, and thus a stable and regular solution even when body-vortex impacts occur, a Rankine finite-thickness vortex model is used in the Biot-Savart law. The shape of the wake surface is determined as part of the solution by moving the panel vertices with the velocity field induced by wakes and bodies.

Once the potential field is known, the Bernoulli theorem yields the pressure distribution from which, in turn, aerodynamic loads can be readily evaluated.

2.3 Helicopter simulation tool

The HELISTAB code is a comprehensive helicopter code developed in the last decade at Roma Tre University. It considers rigid body dynamics, blade aeroelasticity, airframe elastic motion, as well as effects from actuators dynamics and stability augmentation systems. Passive and active pilot models are included, and both linear and nonlinear analyses may be performed. HELISTAB has been validated and applied within the activities of the European Project ARISTOTEL, addressed to the study of Rotorcraft-Pilot Couplings phenomena.

The linearized equations of aeromechanics are written as a first order differential system,

$$ \dot{z} = Az + Bu $$

where $z$ collects Lagrangian coordinates of elastic blade and airframe deformations and their derivatives, airframe rigid-body (center-of-mass) linear and angular velocity components, Euler angles and inflow states, $x$, whereas $u$ collects main and tail rotor controls and their first and second order derivatives, namely, $u = \{\theta_0, \theta_0, \theta_0, \ldots, \theta_p\}^T$.

In the following, details concerning the derivation of matrices $A$ and $B$ in Eq. (6) are provided for aeromechanics formulations using both kinematic-based and loads-based dynamic inflow models.

2.4 Kinematic-based inflow

Recasting the vector of state variables as $z = \{y \, x\}^T$, coupling the rotor and airframe dynamics equations with the dynamic inflow model of Eq. (3) yields the following aeromechanics model

$$ \begin{align*}
\dot{y} &= A_y y + C_y \lambda + B_y u \\
\dot{\lambda} &= A_{\lambda} y + A_{\lambda} \lambda + \lambda \dot{C}_y x + A_{\lambda u} u \\
\dot{x} &= B_y y + A_x x + B_x u
\end{align*} $$

(7)

with $C_y$ collecting the derivatives of the aerodynamic generalized forces of the aeromechanical model with respect to $\lambda$. In addition, the matrices of the wake inflow model in Eq. (7) are obtained by re-organizing those in Eq. (3), to be consistent with the vectors of variables of the aeromechanical model (for instance, hub linear velocities considered in Eq. (6) are given as a combination of the airframe dofs considered in the vector $y$).

Then, substituting the inflow model in the rotor/airframe dynamics equations, the following set of first-order differential equations governing the helicopter dynamics are obtained

$$ \begin{align*}
\dot{y} &= (I - C_y A_y^{-1})^{-1} \left( A_y y + C_y \lambda + B_y u \right) + C_y \dot{C}_y x + \left( B_y + C_y A_y^{-1} \right) u \\
\dot{x} &= B_y y + A_x x + B_x u
\end{align*} $$

(8)

from which matrices $A$ and $B$ of Eq. (6) may be easily identified.

2.5 Load-based inflow

When load-based inflow model is used, the aeromechanics equations may be written as

$$ \begin{align*}
\dot{y} &= A_y y + C_y \lambda + B_y u \\
\dot{\lambda} &= C_y x \\
\dot{x} &= A_x x + B_x f
\end{align*} $$

(9)

where the perturbative hub loads appearing in Eq. (9) are given by the following linearized form

$$ f = F_y y + F_x \lambda + F_u u $$

(10)

Finally, combining Eqs. (9) and (10) yields the following set of first-order differential equations governing the helicopter dynamics

$$ \begin{align*}
\dot{y} &= A_y y + C_y \dot{C}_y x + B_y u \\
\dot{\lambda} &= B_y y + \left( A_x + B_x F_i C_w \right) x + B_x u
\end{align*} $$

(11)

from which matrices $A$ and $B$ of Eq. (6) may be readily identified.

3 NUMERICAL RESULTS
### 3.1 Aerodynamics validation

Light’s work\textsuperscript{[18]} has been chosen as benchmark to validate the aerodynamics solver in ground effect, in terms of tip vortex geometry and thrust. In that experiment, an untwisted four-bladed rotor (whose main data are summarized in Tab.\textsuperscript{[1]} in hovering condition above a circular surface having a diameter of 6.62 rotor radii.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Span</td>
<td>1.105 m</td>
</tr>
<tr>
<td>Root Cut Off</td>
<td>0.425 m</td>
</tr>
<tr>
<td>Chord</td>
<td>0.18 m</td>
</tr>
<tr>
<td>Solidity</td>
<td>0.207</td>
</tr>
<tr>
<td>Airfoil</td>
<td>NPL 9165</td>
</tr>
<tr>
<td>Angular Velocity</td>
<td>172.3 rad/s</td>
</tr>
</tbody>
</table>

Table 1: Light’s Four-Bladed rotor characteristics.\textsuperscript{[18]}

Figures 1 and 2 show the numerical tip vortex reconstruction compared with the experimental results (obtained by shadowgraph) at two different heights, namely $z = 0.84 R$, having a disk loading of $C_T/\sigma = 0.071$ and $z = 0.52 R$ having $C_T/\sigma = 0.090$. The wake shape proposed by Landgrebe\textsuperscript{[38]} for OGE rotors is also shown as a reference.

In both cases a good agreement between experimental results and numerical simulations is achieved, in particular in terms of wake distortion caused by the presence of the ground, clearly highlighted by the comparison with the Landgrebe wake shape which is a good approximation for Out-of-Ground-Effect hovering rotors. The capability of the present aerodynamic solver to well predict ground effect also on rotor loads is proved by Fig. 3. For a fixed collective pitch and different values of $z/R$, this figure shows the comparison in terms of the ratio of thrust in ground effect and out of ground effect between experimental results, three approximated analytical equations proposed in literature\textsuperscript{[39]} and BEM numerical results.
3.2 Dynamic inflow model effect on aeromechanics

The test case examined is a mid-weight helicopter model inspired to the Bo-105, whose main data are reported in Sec. 3.2. Hovering flight at 1 diameter above the ground (simulated as a circle having twice the radius of the rotor) is examined, whereas the analysis in other steady conditions are left to future investigations. Moreover, only results obtained through the $\lambda - f$ model obtained perturbing rotor controls are presented. The perturbations consist of chirp signals from 2 to 18 rad/s.

<table>
<thead>
<tr>
<th>Mass</th>
<th>2200 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{xx}$</td>
<td>1430 kgm$^2$</td>
</tr>
<tr>
<td>$I_{yy}$</td>
<td>4975 kgm$^2$</td>
</tr>
<tr>
<td>$I_{zz}$</td>
<td>4100 kgm$^2$</td>
</tr>
<tr>
<td>$I_{xz}$</td>
<td>650 kgm$^2$</td>
</tr>
<tr>
<td>MR type</td>
<td>hingeless</td>
</tr>
<tr>
<td>MR radius</td>
<td>4.91 m</td>
</tr>
<tr>
<td>MR chord</td>
<td>0.27 m</td>
</tr>
<tr>
<td>MR angular speed</td>
<td>44.4 rad/s</td>
</tr>
<tr>
<td>MR blade twist</td>
<td>$-8^\circ$/m</td>
</tr>
<tr>
<td>MR number of blades</td>
<td>4</td>
</tr>
<tr>
<td>TR radius</td>
<td>1 m</td>
</tr>
<tr>
<td>TR chord</td>
<td>0.2 m</td>
</tr>
<tr>
<td>TR angular speed</td>
<td>230 rad/s</td>
</tr>
<tr>
<td>TR number of blades</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 2: Main helicopter data

First, the effect of ground on inflow is analyzed in ?? and Fig. 5 which show OGE and IGE transfer functions along with the RMA approximation of IGE ones, in the range of frequency of interest for flight dynamics. The former relates axisymmetric variables ($\lambda_0$ vs $C_T$), while the latter antisymmetric ones ($\lambda_c$ vs $C_M$). Note that, due to the axial symmetry of the flight condition, the inflow transfer matrix is expected to be block diagonal, i.e. the thrust coefficient induces only $\lambda_0$ and rolling and pitching moment coefficients influence only $\lambda_c$ and $\lambda_c$. Here, the off-axis transfer functions $\lambda_c$ vs $C_M$ and $\lambda_c$ vs $C_L$ are not shown, being significantly smaller than the on axis $\lambda_0$ vs $C_L$ and $\lambda_c$ vs $C_M$ (which are, in turn, equivalent). The effect of ground is opposite on axisymmetric and antisymmetric transfer functions. In particular, the magnitude of $\lambda_0$ vs $C_T$ is reduced by the presence of the ground, whereas that of $\lambda_c$ vs $C_M$ is increased. Moreover, the phase of the transfer function $\lambda_c$ vs $C_M$ is significantly affected by the ground, which causes an additional delay with the respect to OGE case, in the frequencies range above 0.1 Hz (see Fig. 5).
Figure 6: Coherence between inflow coefficients and kinematic degrees of freedom.

Figure 7 shows the coherence between input (kinematic degrees of freedom) and output (inflow coefficients) signals. While the coherence from antisymmetric variables (e.g. $\lambda_s$ vs. $\theta_s$) is very high (above 0.9 in the range of frequency characterizing the input chirp signal), that between $\theta_0$ and $\lambda_0$ is significantly smaller, although acceptable. Note that the amplitude of perturbation on $\theta_0$ has been increased from 1 deg (used in this work for antisymmetric perturbations) to 3 deg, since for lower values the resulting coherence was even lower. This is probably due to numerical round-off and truncation errors. However, to clarify this aspect future additional investigations are required.

Figures 7 and 8 highlight the effect of the ground presence on the helicopter dynamic stability. The most relevant effect is the shift of the dutch roll poles complex pair, which increases his damping and natural frequency, as highlighted in Fig. 8. This fact has a significant impact on aeromechanic transfer functions, shown in Figs. 9 to 13. The former four report on axis transfer function, while the latter is related to cross-coupling dynamics.

Figure 8: Effect of the presence of the ground on root locus, detail.

Figure 9: $\omega$ vs $\theta_0$ transfer function in and out of ground effect.

Figure 10: $\psi$ vs $\theta_s$ transfer function in and out of ground effect.
4 CONCLUSIONS

Two different approaches to dynamic inflow modeling of rotor in ground effect conditions have been presented. In the first, inflow coefficients are related to the kinematic degrees of freedom, while the second one considers the relation between inflow coefficients and rotor loads (as in the well known Pitt-Peters’ model). The identification of the inflow transfer matrix is based on time marching Boundary Element Method simulation of the rotor in presence of the ground and is followed by a Rational Matrix Approximation, in order to obtain a state-space inflow model. The aerodynamic solver has been validated against experiments from the literature, showing a good accuracy in the prediction of both aerodynamic loads and wake shape. Its application to the identification of the dynamic inflow model in ground effect has been more difficult with respect to that in out-of-ground-effect case. In particular, the identification process of the transfer functions involving axisymmetric components of the inflow has been significantly more difficult, requiring an appropriate regularization of numerical free-wake algorithm to take into account the presence of the ground. Finally, from the preliminary aeromechanic analysis performed in this paper, the most relevant effect of the ground presence has been noticed in the shift of the dutch roll poles, which primarily affect roll response to cyclic controls.

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References


