A CFD Framework for Analysis of Helicopter Rotor

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A CFD method suitable for the analysis of hovering and forward-flying rotors has been developed and validated against experimental data. The Caradonna and Tung as well as the ONERA 7A/7AD1 rotors have been simulated and results were found to be in excellent agreement with wind tunnel measurements. As a second step the method was coupled with a trimming algorithm devised using rotor blade element theory. The coupled algorithm demonstrates the rapid convergence to prescribed thrust coefficient values and no deterioration of the convergence rates relative to simulations of untrimmed rotors.

I. Introduction

During the last decades, CFD methods for the numerical simulation of the flow around fixed-wing aircraft have improved significantly.1 Modern CFD methods can with relative ease, at design conditions, predict with good accuracy wing lift and with fair accuracy total wing drag. For rotary-wing aircraft, however, the situation appears to be more complicated and the application of CFD in the rotorcraft industry has not reached the same level of maturity. It appears that CFD analysis of flows around rotary-wing aircraft is significantly harder in comparison to the fixed-wing case.2–10 There are several reasons contributing to this situation: i) Rotor flows are complicated and rich in fluid mechanics phenomena.11 CFD methods have to cope with strong interacting vortices, the formation of a vortex wake that spirals down below the rotor disk, transition to turbulence and a wide variation of the Mach and Reynolds numbers in the radial direction and around the azimuth. ii) There is a strong link between the aerodynamics and aeromechanics for rotor flows. This includes both the ‘rigid blade’ motions of the rotor blades about hinges in the rotor hub and the elastic deformation of the rotor blades. In level forward flight, the rotor blade motions form part of the problem, as are the control setting of the rotor to achieve the required flight state. This is known as the rotor trimming problem which further complicates the numerical simulations of the flow field created by a rotor in forward flight.

Figure 1 introduces the frame of reference used here, i.e. the rotor shaft axis is the z-axis and the rotor revolves in anti-clockwise direction. The angle ψ defines the azimuthal position. The coordinate system x corresponds to the helicopter-fixed frame of reference. In this system, the rotor moves in the negative x-direction. For a typical helicopter rotor, the rotor blades are attached to the rotor head by a set of three hinges: the flap hinge allowing the blade to flap up and down, the lead-lag hinge allowing the blade an in-plane forward or backward motion and the feathering hinge, required to change the blade pitch. In a number of modern helicopters one or more of these hinges is replaced by a flexible connecting beam. The degrees of freedom about the hinges are necessary for achieving a balance of forces and moment on the helicopter. The construction of rotor heads is fully explained in many text books.12–14 A rotor with these degrees of freedom for the blades is called fully articulated. Figure 1 shows the linear transformations from the helicopter-fixed frame of reference to a blade-fixed frame of reference. The control input consists of a ‘collective’ pitch, i.e. a revolution averaged pitch that is identical for all blades, and a ‘cyclic’ pitch, i.e. a periodic pitch change in the azimuthal direction. The deflections in flapping and lead-lag result from balances of inertial and aerodynamic forces. In the case of hover, the blade encounters a constant blade normal velocity, and as a result, no cyclic pitch change is needed to balance the helicopter. In this case, a cyclic pitch is set

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and a constant flapping deflection (‘coning’) results. In forward flight, the blades experience a blade normal velocity that depends on the azimuthal position. For a radial station \( r/R \) of a rotor blade, the blade normal Mach number is

\[
M_n(\psi) = M_{tip} \frac{r}{R} + M_\infty \sin \psi = M_{tip} \left( \frac{r}{R} + \mu \sin \psi \right)
\]

where \( \mu = M_\infty / M_{tip} \) is the advance ratio of the rotor.

Level forward flight of a helicopter requires that the rotor generates the required upward and forward thrust, while at the same time having no rolling or pitch-up moment. Assuming that the rotor creates forces normal to the tip-path plane, this plane is tilted forward to create the needed forward thrust. A level forward flight of a helicopter involves the following unknowns: the forward tilt of the tip-path plane, the collective normal to the tip-path plane, this plane is tilted forward to create the needed forward thrust. A level forward flight of a helicopter requires that the rotor generates the required upward and forward thrust, while at the same time having no rolling or pitch-up moment. Assuming that the rotor creates forces normal to the tip-path plane, this plane is tilted forward to create the needed forward thrust. A level forward flight of a helicopter involves the following unknowns: the forward tilt of the tip-path plane, the collective normal to the tip-path plane, this plane is tilted forward to create the needed forward thrust.

The main objective of this work is to present and validate all the extensions necessary to convert a CFD method for hover and in (trimmed) forward flight.

The simulation of a trimmed rotor in forward flight is far more challenging than the hover problem, both in terms of the problem formulation and the CPU requirements.

The extensions of the CFD method for rotorcraft applications include: i) a hover model which treats the flow as a steady-state problem in a non-inertial frame of reference \(^2,15\) ii) a forward-flight formulation which solves the governing equations in a fixed inertial frame of reference accounting for isolated helicopter rotors with fully-articulated blades (i.e. the blades carry out periodic flap, lead-lag and pitch motions) iii) a mesh-deformation technique that deforms a multi-block structured mesh to account for these rotor blade deflections using a combination of rigid mesh motion (mesh blocks attached to a blade move with that blade) and grid deformation. The deformation method is based on the Trans-Finite Interpolation (TFI) method. Finally a trimming algorithm for forward-flight simulations is necessary. This is a basic trimming method based on blade element theory and approximate blade flapping equations.\(^13\) The method uses the loads on the blades from the CFD solution. The extensions for rotorcraft applications are included in a CFD solver previously used for various applications, including fixed-wing applications and aero-elastic analysis.\(^1\)

II. Description of numerical method

In order to solve problems in time dependent domains, including moving boundaries, the Navier-Stokes equations are used in the arbitrary Lagrangian Eulerian (ALE) formulation. For any control volume \( V \) with boundary \( \partial V \) and outward unit normal \( \vec{n} \), the conservation laws can be written in integral form as:

\[
\frac{d}{dt} \int_{\partial V(t)} \vec{\tilde{w}} \, d\vec{r} + \int_{V(t)} \left( \vec{F}(\vec{w}) - \vec{F}_v(\vec{w}) \right) \, d\vec{r} = \vec{S}
\]

where \( \vec{w} \) is the vector of conserved variables, \( \vec{F} \) and \( \vec{F}_v \) are the inviscid and viscous flux, respectively. In the absence of volume forces and in an integral frame of reference source \( \vec{S} = 0 \). A block-structured cell-centred finite-volume method based on curvilinear boundary-fitted meshes is used here. The spatial discretisation of Equation (1) leads to a set of ordinary differential equations in time,

\[
\frac{d}{dt} \left( \vec{w}_{i,j,k} V_{i,j,k} \right) = -\vec{R}_{i,j,k}(\vec{w})
\]

where \( \vec{w} \) and \( \vec{R} \) are the vectors of cell averaged conserved variables and residuals, respectively. Here, \( i, j, k \) are the cells indices in each of the grid blocks. In Equation (2), \( V_{i,j,k} \) is the cell volume. The convective terms are discretised using Osher’s upwind scheme.\(^16\) MUSCL variable interpolation is used to provide third-order accuracy with the Van Albada limiter to prevent spurious oscillations. Boundary conditions are set by using ghost cells on the exterior of the computational domain. In the far field, ghost cells are set at the free-stream conditions. For the present inviscid flow simulations, ghost values are extrapolated from the interior at solid boundaries ensuring the normal component of the velocity on the solid wall is zero.

For the present time-accurate simulations, temporal integration is performed using an implicit dual-time stepping method. Following the pseudo-time formulation,\(^17\) the updated mean flow solution is calculated by solving the steady state problems

\[
\vec{R}_{i,j,k}^* = \frac{3V_{n+1}^{i,j,k} \vec{w}_{n+1}^{i,j,k} - 4V_n^{i,j,k} \vec{w}_n^{i,j,k} + V_{n-1}^{i,j,k} \vec{w}_{n-1}^{i,j,k}}{2V_{n+1}^{i,j,k} \Delta t} + \frac{\vec{R}_{n+1}^{i,j,k}(\vec{w}_{n+1}^{i,j,k})}{V_{n+1}^{i,j,k}} = 0
\]
where the terms $V_{i,j,k}^{n-1}$, $V_{i,j,k}^n$ and $V_{i,j,k}^{n+1}$ represent the cell volume at different (real) time steps. Equation (3) represents a nonlinear system of equations. This system can be solved by introducing an iteration through pseudo time $\tau$ to the steady state, as given by

$$
\frac{w_{i,j,k}^{n+1,m+1} - w_{i,j,k}^{n+1,m}}{\Delta \tau} + 3V_{i,j,k}^{n+1} w_{i,j,k}^{n+1,m} - 4V_{i,j,k}^n w_{i,j,k}^n + V_{i,j,k}^{n-1} w_{i,j,k}^{n-1} + \mathbf{R}_{i,j,k}(w_{i,j,k}^{n+1,m}) V_{i,j,k}^{n+1} = 0
$$

where the $m$-th pseudo-time iterate at real time step $n + 1$ is denoted by $w_{i,j,k}^{n+1,m}$. The unknown $w_{i,j,k}^{n+1,1}$ is obtained when Equation (4) converges in pseudo-time to a specified tolerance. Typically the pseudo-time integration in Equation (4) is continued at each real time step until the residual has dropped three orders of magnitude. For the simulations presented here, this typically required $25 - 35$ pseudo-time steps. An implicit scheme is used for the pseudo-time integration. The resulting linear system of equations is solved using the Generalised Conjugate Gradient method.\(^{18}\)

A. Hover Modelling

Assuming that the shed wake from the rotor is steady, the hover problem can be re-cast in a steady state form. For a rotor-fixed frame of reference, the Navier-Stokes equations of Equation (1) can be used with the mesh velocity set to zero everywhere and a source term accounting for centripetal and Coriolis acceleration. In this non-inertial frame of reference, the energy equation needs to be modified to only account for the velocity contributions relative to the rigid-body rotation. This relative velocity field is $\vec{u}_r$. In the undisturbed situation, $\vec{u}_r = -\vec{\omega} \times \vec{r}$, where $\vec{r}$ is the position vector of the considered point and $\vec{\omega} = [0, 0, \omega_z]^T$ the rotation vector of the rotor. This creates difficulties in imposing boundary conditions, i.e. the ‘far-field’ has an undisturbed velocity field that depends on the position of the considered point relative to the rotation axis. In the present formulation, a non-inertial frame\(^{15}\) is used that resolves these problems. The frame of reference is created by introducing a grid velocity $-\vec{\omega} \times \vec{r}$. Relative to this frame of reference the velocity $\vec{u}_h = \vec{u}_r + \vec{\omega} \times \vec{r}$ is defined. Using this non-inertial frame of reference, the governing equations are given by Equation (1) with non-zero mesh velocities and source vector $\mathbf{S}$ defined as:

$$
\mathbf{S} = [0, -\omega \times \vec{u}_h, 0]^T
$$

This results in a small source term for the momentum equations, the energy equations is unchanged. Hover simulations typically involve only one rotor blade and periodic boundary conditions to model the presence of the remaining blades. In the present work, the rotor shaft coincides with the $z$-axis and the rotor spanwise direction corresponds to the $x$-axis, though all possible configurations can be treated. Two different approaches to impose far-field boundary conditions are used. The first is based on imposing unperturbed free-stream conditions at the far-field of the computational domain with extrapolation used in the vertical direction on the inflow and outflow boundaries for all variables. Experience shows that the far-field boundaries need to be at least 5 rotor radii away from the rotor when using this far-field boundary condition. A smaller domain leads to a significant re-circulation of the flow within the domain. The second approach is termed as ‘potential sink’ or ‘Froude’ boundary condition and is designed to suppress this re-circulation by placing a potential sink at the rotor origin.\(^2,4,6\) Furthermore, based on actuator-disk theory, a constant axial (outflow) velocity is prescribed on a circular part of the outflow boundary face. The magnitude of this velocity is determined by the rotor thrust (which gives the induced axial velocity through the rotor disk according to actuator-disk theory) and the outflow radius, for which the following empirical relation\(^4\) is used:

$$
\frac{R_{\text{outflow}}}{R} = 0.78 + 0.22 \exp(-d_{\text{outflow}}/R)
$$

where $d_{\text{outflow}}$ is the distance of the outflow boundary below the rotor disk. Actuator-disk theory predicts a wake contraction to $R/\sqrt{2}$ far from the disk, where the axial velocity is twice the induced axial velocity through the rotor disk. Here, $d_{\text{outflow}}/R \approx 4$ and $R_{\text{outflow}}/R \approx 0.783$. On the remainder of the far-field boundary, the velocity due to the potential sink is imposed. The strength of the sink is chosen to balance the mass flow into and out of the computational domain.

B. Forward Flight Modelling

The simulation of a helicopter rotor in forward flight requires a balance of moments and forces that is achieved by: i) tilting the rotor shaft forward and selecting a 'collective' blade pitch so that the rotor
forward thrust balances the drag and the vertical thrust the weight ii) introducing 'cyclic' pitch angles (i.e. harmonic pitch variations) that reduces the pitch on the advancing side where the blades experiences high velocities and increases the pitch on the retreating side iii) the flapping and lead-lag degrees of freedom will result in periodic flapping and lead-lag blade motions. The trimming problems consists of finding the rotor shaft angle, 'collective' pitch and 'cyclic' pitch angles that result in steady level flight. Modeling a trimmed helicopter rotor in forward flight therefore requires: i) a method to introduce the rotor blade settings and periodic motions ii) a method that adapts the grid to account for these blade motions iii) a trimming method that determines the harmonic coefficients of the blade motions. The present forward flight model is described in more detail elsewhere.\textsuperscript{19} In the present work, the rotor blade flapping, lead-lag and pitching are assumed to be described by the negative Fourier series commonly used in rotorcraft analysis:

\begin{align}
\psi &= \omega t \\
\beta(\psi) &= \beta_0 - \beta_{1s} \sin(\psi) - \beta_{1c} \cos(\psi) - \ldots \\
\delta(\psi) &= \delta_0 - \delta_{1s} \sin(\psi) - \delta_{1c} \cos(\psi) - \ldots \\
\theta(\psi) &= \theta_0 - \theta_{1s} \sin(\psi) - \theta_{1c} \cos(\psi) - \ldots
\end{align}

where \( \omega \) is the constant rate of rotation about the z-axis. The collective pitch is \( \theta_0 \) and the coning angle is \( \beta_0 \). In the present work, only the first harmonic is used. Assuming a constant rotation rate of the rotor, the temporal derivatives of the flap angle, lead-lag angle and pitch angle can be written as

\begin{align}
\frac{d\beta}{dt} &= \omega \frac{d\beta}{d\psi} ; \quad \frac{d\delta}{dt} = \omega \frac{d\delta}{d\psi} ; \quad \frac{d\theta}{dt} = \omega \frac{d\theta}{d\psi}.
\end{align}

In the present model, the flow is solved in the 'helicopter-fixed' frame of reference, i.e. the forward motion is modeled by introducing a free-stream velocity. Figure 1 defines the frame of reference for the rotor in forward flight and the linear transformations connecting the helicopter-fixed frame of reference to a blade fixed frame of reference. The coordinates of a point \( P \) in terms of the helicopter-fixed frame of reference after rotation (\( \psi \)), flapping (\( \beta \)), lead-lag (\( \delta \)) and pitching (\( \theta \)) become:

\begin{align}
\bar{x}_P &= C_{rot}C_{flap}C_{lag}C_{pitch}(\bar{x}_P - \bar{x}_{pitch}) + C_{rot}C_{flap}C_{lag}(\bar{x}_{pitch} - \bar{x}_{lag}) + \\
&\quad C_{rot}C_{flap}(\bar{x}_{lag} - \bar{x}_{flap}) + C_{rot}\bar{x}_{flap}
\end{align}

where \( \bar{x}_{flap} \), \( \bar{x}_{lag} \) and \( \bar{x}_{pitch} \) defined the locations of the flap hinge, lead-lag hinge and the pitch centre and \( C_{rot, flap, lag, pitch} \) are the linear transformation matrices for the rotor rotation, blade flapping, blade lead-lag and blade pitching, respectively. The velocity of \( P \) in terms of the helicopter-fixed frame of reference is obtained by taking the derivative of Equation (9). In the present method, a novel method is used to account for the rotor blade motions.\textsuperscript{19} The multi-block grid is divided in blocks that are selected to move rigidly with one of the rotor blades and the remaining blocks that are deformed to account for the 'rigid' motion of the surrounding blocks. The method can be summarized as follows: i) Blocks connected to the rotor blade are tagged to move 'rigidly'. For each of these blocks the corresponding blade number is stored. ii) For the remaining blocks the number of connections to 'rigid' moving blocks is determined. iii) For the remaining blocks that have 2 connections to 'rigid' moving blocks, these are also tagged to move 'rigidly'. This will fill the remaining 'gaps' to form a layer of blocks around the rotor blades with a smooth bounding surface. iv) For the blocks tagged to move 'rigidly', the grid in the initial position (\( \psi = 0^\circ \)) is stored for reference. This block selection strategy is shown in Figure 2, which shows a close-up of the multiblock topology of the grid for one blade of the 4-bladed 7A\textsuperscript{20} model rotor. The shaded surface forms the bounding surface of the grid blocks that are automatically selected to move with the rotor blade. The grid outside of this shaded surface is deformed using the Transfinite Interpolation method. Equation (9) is used to update the grid from time level \( n \) to \( n + 1 \) for the blocks tagged for rigid-mesh motion. The method to update the grid for the blocks not moving with one of the rotor blades from time level \( n \) to \( n + 1 \) starts by selecting block faces connected to 'rigid' moving blocks and updating the mesh for these block faces using Equation (9). Then, the effect of rotor rotation is subtracted from the mesh updates and the block face updates are passed to the Transfinite Interpolation routine. After applying the Transfinite Interpolation method, the deformed mesh is rotated to the new azimuth.
C. Trimming method

In this work, the trimming method is based on blade-element theory. The trimming method consists of an initial trim-state computation and a number of subsequent re-trimming steps. Due to the simple nature of the method, the initial trim-state cannot be expected to be very accurate. In the re-trimming steps, the actual loads on the blade from the CFD solution are used to update the collective pitch in a Newton-Raphson process. In simulations of trimmed hovering rotors, the re-trimming is carried out after the steady flow solutions has converged to a prescribed level. The trimming is repeated every \( n_{\text{retrim}} \) steps. In simulations of trimmed forward flying rotors, revolution-averaged integrated loads from the CFD solution are used. The trimming method needs a target thrust as input and a model for the fuselage and its drag is necessary to compute the total drag as a function of the helicopter advance ratio \( \mu \). Table 1 summarizes the trimming method used in the present work for hovering rotors as well as rotors in forward flight. The sketches in Table 1 define the tip-path plane and the no-feathering plane within the rotor shaft frame of reference.

III. Results for hovering helicopter rotors

A. Model rotor test cases

The Caradonna and Tung\(^2\) and the HELISHAPE 7A/7AD1 rotors\(^20\) have been used as validation hover test cases. Results for these rotors are compared to wind tunnel data in this section. A summary of the hover cases is given in Table 2. Figure 3 presents the planform of the model rotors. The Caradonna and Tung model rotor employed two cantilever-mounted, manually adjustable blades. The blades have a NACA 0012 profile and are untwisted and untapered. The rotor aspect ratio, defined as the ratio of rotor radius and blade chord, is 6. The model rotor has a diameter of 2.286\(\text{m}\), and a chord length of 0.191\(\text{m}\). Two cases for this rotor are considered: 0° blade pitch incidence (non-lifting condition) and 8° blade pitch.

The 7A/7AD1 model rotors were tested in the DNW wind tunnel during the HELISHAPE research campaign.\(^20\) It is a 4-bladed rotor with 2.1 \(\text{m}\) radius, 0.14 \(\text{m}\) chord and has a non-constant geometric twist. The rotor has a rectangular planform and consists of ONERA OA213 and OA209 aerofoil sections. The rotor blade aspect ratio is 15. Figure 4 compares the computed chordwise surface pressure distribution for the Caradonna and Tung model rotor with the experimental data for 3 radial sections \((r/R = 0.68, r/R = 0.80\) and \(r/R = 0.89\)). The agreement is very good for both lifting and non-lifting cases.

Figure 5 compares the computed chordwise surface pressure distribution for the HELISHAPE 7A/7AD1 model rotors with the experimental data for 3 radial sections \((r/R = 0.50, r/R = 0.915\) and \(r/R = 0.975\)) and for both tip geometries, the agreement with the experimental data is very good. The scatter in the experimental for the 7A rotor is due to the fact that measurements from multiple blades of the wind tunnel model were combined, showing differences from blade to blade. The results for the 7A/7AD1 rotors indicate that with the present CFD method, even on the relatively coarse meshes used here, the surface pressure on twisted blades at realistic tip Mach numbers can be predicted with a good level of accuracy. Furthermore, the results for the 7AD1 rotor show that the present multi-block topology can be used to mesh even complicated tip shapes (see Figure 3 for a description of the 7AD1 planform).

B. Trimmed Rotor Cases

For a hovering rotor, the trimming problem for a rigid rotor consists of finding a collective pitch that will produce the required rotor thrust \( T \) at a fixed rotor rotation rate (i.e. fixed tip Mach number). The thrust is normalized here as: \( C_T = T/(\rho u_{\text{tip}}^2\pi R^2) \), where \( C_T \) is the thrust coefficient and \( R \) the rotor radius. As a result of the flapping degree of freedom, the rotor blade settle at a constant flapping deflection, giving the rotor a coning angle at which the moments are balanced about the flap hinges.

Figure 6 shows sample results for the ONERA 7A model rotor in hover. The plots compare results based on the initial trim approximation and results obtained using a re-trimming after every 250 iterations. The grid used in the simulations has a built-in collective pitch of 7.5° at 0.7 of the rotor radius and 0° built-in coning.

Figure 6(a) shows the result for a target \( C_T = 0.0050 \), which requires a reduction of the collective pitch relative to the built-in collective pitch. The initial trimming over-predicts the collective pitch, i.e. the result without subsequent re-trimming converges to a \( C_T \) value above 0.0050. The re-trimming leads to a step-wise reduction in the collective pitch, until converging to a value 1.5° lower than the built-in collective pitch.
Table 1. Trimming approach for forward flight and hover

<table>
<thead>
<tr>
<th>1) tip-path plane orientation</th>
<th>Forward flight</th>
<th>Hover</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{tpp} = -D/W$</td>
<td>$\theta_{tpp} = 0$</td>
<td></td>
</tr>
</tbody>
</table>

| 2) determine inflow factor | $\lambda = \mu \theta_{tpp} + \lambda_i$ | $\lambda = \lambda_i$ |

<table>
<thead>
<tr>
<th>3) determine induced inflow</th>
<th>$\lambda_i$ from iteration:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_i = -\frac{C_T}{2} \sqrt{\mu^2 + \left(1 - \frac{1}{\lambda} \sin \theta_{tpp} + \lambda \right)^2}$</td>
<td>$\lambda_i = -\frac{C_T}{2}$</td>
</tr>
</tbody>
</table>

| 4) estimate for collective | $\frac{C_T}{\sigma} = \frac{\mu}{\pi} \left( \frac{1}{\mu} + \frac{1}{\lambda} \right)$ |

<table>
<thead>
<tr>
<th>5) approximate flapping equation</th>
<th>$\beta_0 = \frac{2}{3} \left( \theta_0 + \frac{4}{3} \lambda \right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(relative to no-feathering plane)</td>
<td>$\beta_{1c} = 0$</td>
</tr>
<tr>
<td>$\beta_{1s} = 0$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6) assume blade flapping</th>
<th>$\beta_{1c} = \theta_{tpp} - \theta_{shaft}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_{1s} = 0$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>7) determine cyclics</th>
<th>$\theta_{1c} = \beta_{1c}^{(nfp)} - \beta_{1c}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{1s} = -\beta_{1s}^{(nfp)} + \beta_{1s}$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>8) rotor loads from CFD</th>
<th>compute $\delta\theta_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>repeat steps 1-8</td>
<td>repeat step 2-5, 8</td>
</tr>
</tbody>
</table>

$C_T = \frac{T}{(\rho u_{tip}^2 \pi R^2)}$, $\sigma = \frac{N_{Radian}}{2\pi}$, $\gamma = \frac{\alpha a c R^2}{I}$, $a$ (lift-slope factor), $I$ (moment of inertia)

Table 2. Summary of conditions for the hovering Caradonna-Tung and HELISHAPE 7A/7AD1 rotors.

<table>
<thead>
<tr>
<th>Flow Conditions</th>
<th>Caradonna-Tung$^{21}$</th>
<th>Caradonna-Tung$^{21}$</th>
<th>7A$^{20}$</th>
<th>7AD1$^{20}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tip Mach Number $M_{tip}$</td>
<td>0.520</td>
<td>0.439</td>
<td>0.6612</td>
<td>0.6612</td>
</tr>
<tr>
<td>Reynolds Number</td>
<td>$2.3 \cdot 10^6$</td>
<td>$1.9 \cdot 10^6$</td>
<td>$2.1 \cdot 10^6$</td>
<td>$2.1 \cdot 10^6$</td>
</tr>
<tr>
<td>Collective pitch $\theta_c$</td>
<td>$0^\circ$</td>
<td>$8^\circ$</td>
<td>$\theta_{0.7} = 7.5^\circ$</td>
<td>$\theta_{0.7} = 7.5^\circ$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Computation Details</th>
<th>Grid Size (periodic)</th>
<th>1.1 $\cdot 10^6$</th>
<th>2.0 $\cdot 10^6$</th>
<th>0.6 $\cdot 10^6$</th>
<th>0.6 $\cdot 10^6$ and 1.3 $\cdot 10^6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modelling</td>
<td>Inviscid</td>
<td>Inviscid</td>
<td>Inviscid</td>
<td>Inviscid</td>
<td></td>
</tr>
</tbody>
</table>

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while the coning angle converges to a value of 1.3°. Results for a target $C_T = 0.0068$, which is close to the experimental value obtained in the HELISHAPE campaign for the built-in collective and the tip Mach number 0.6612 used here, are shown in Figure 6(b). Again, the initial trimming over-predicts the collective pitch. The re-trimming leads to a $C_T$ that matches the target value at a collective pitch angle 0.35° larger than the built-in collective pitch. At convergence, the coning angle is 2.3°. The dashed line in Figure 6 shows the convergence of the thrust coefficient without any trimming. As can be seen, the overheat of the present trimming algorithm in comparison to a hover calculation without trimming at a given set of collective and coning angles is moderate. An increase between 50% and 70% in the number of iterations is observed.

IV. Results for helicopter rotors in forward flight

A. Non-lifting ONERA model rotor in high-speed forward flight

Figure 7 shows the geometrical definition of the non-lifting 2-bladed model rotor tested at ONERA. Two different rotor blade configurations are considered here. One has a nearly straight leading edge and a 75 cm radius, while a second configuration has a 30° leading edge sweep on the outer 15% and has a radius of 83.5 cm. The blades used here are different from the ONERA experiment in that the tapered root parts of the blades are removed. i.e. the blade up to 37% radius of the straight blade and 33% radius of the swept-tip blade. Both blades have symmetric NACA four-digit sections, varying in thickness-to-chord ratio from 17% at the root (widest chord, at 37% radius of the straight blade and 33% radius of the swept-tip blade) to 9% at the tip. Both blades have a linear taper, the tip chord is 70% of the widest chord. The increased blade radius of the swept-tip blade was achieved by adding a 85 mm part of 14% surface pressure is different at the root (widest chord, at 37% radius of the straight blade, i.e. between 71.9% and 82% radius of the swept-tip blade. The sweep starts at 85.7% radius, at which station the relative thickness is 13.5%. Bases on the widest chord, the rotor aspect ratio is 4.518 for the straight blade and 5.03 for the swept-tip blade. Figure 8 shows the surface pressure distribution for both rotors at an advance ratio of 0.45 for 5 azimuthal positions. Also shown is a comparison with experimental data for the chordwise pressure distribution at 95% rotor radius. For the straight blade $M_{tip} = 0.60$ and for the swept-tip blade, $M_{tip} = 0.628$. The inviscid simulations were carried out on a 236-block grid with 2.0·10⁶ grid points (straight blade) and a 344-block grid with 2.6·10⁶ grid points (swept-tip blade). For the straight blade, the agreement with the experimental data is very good. For the swept-tip blade, the comparison shows small differences, but the agreement is still good, considering the fact that the simulations were inviscid. Figure 8 clearly shows the hysteresis in the flow field, i.e. the surface pressure is different at $\psi = 60^\circ$ and $\psi = 120^\circ$ (when the blade normal Mach number is identical). This is an effect of the impulse effect of the unsteady flow field and a result of the three-dimensionality. For the swept-tip blade, this sweep introduces an additional hysteresis, since the highest blade normal Mach number occurs well after the $\psi = 90^\circ$ station.

B. Fully articulated 2-bladed rotor in high-speed forward flight

This test case involves the lifting forward flight of a fully articulated 2-bladed rotor. The rotor blades are untapered, non-twisted with an aspect ratio of 6 and have a symmetric NACA0012 profile. For this case, $M_{tip} = 0.60$ and $\mu = 0.35$. The control angles are: $\theta_{shaft} = 2.0^\circ$ (forward), $\theta_0 = 4.0^\circ$, $\theta_{1s} = 3.0^\circ$, $\theta_{1c} = -1.5^\circ$. The flapping angles are: $\beta_0 = 2.0^\circ$, $\beta_{1s} = 1.0^\circ$ and $\beta_{1c} = 1.0^\circ$. Blade lead-lag was neglected. Inviscid simulation on 236-block grid with 1.5·10⁶ points. Figure 9 shows the integrated blade loads from the 4th revolution of the simulation. The non-dimensional aerodynamic blade pitching moment and non-dimensional aerodynamic moment about the flapping hinge are shown for both blades as a function of the rotor azimuth. The pitching moment curve shows the characteristic nose-up (positive) moment at the rear of the rotor disk. As the blade moves through the advancing side (i.e. $0^\circ < \psi < 180^\circ$) the pitching moment shows a drastic change to a nose-down moment beyond the $\psi = 90^\circ$ position (where the largest blade normal velocity occurs). The moment about the flapping hinge corresponds qualitatively with the integrated blade normal force. It can be seen that the maximum of the normal force occurs well beyond the $\psi = 90^\circ$ position. This variation of the blade loadings is typical of helicopter rotors in (high-speed) forward flight. Figure 10 shows the rotor blades relative to a rotor without periodic blade motions. The coning of the rotor and the flapping motions are apparent, as is the cyclic pitch. For a radial station at 89% rotor radius the chordwise $C_p$ distribution is shown, based on the local blade normal Mach number. It is apparent that the rotor carries the loads mainly at the front and aft of the rotor disk. The cyclic pitch clearly reduces...
the load on the advancing side of the rotor disk. The high blade pitch on the retreating side leads to large values of $C_p$ on that side of the rotor disk.

V. Summary and future work

The present framework for rotorcraft CFD is capable of routine simulations of helicopter rotors in hover. The simulation of a realistic helicopter rotor in forward flight, i.e. including the blade pitching, flapping and lead-lag motions, is tractable, but remains demanding. A CFD framework has been presented and validated which allows the efficient and accurate computation of helicopter rotor flows. Key ingredients are: i) the full Navier-Stokes equations which permit for non-linear, unsteady aerodynamic phenomena to be captured, ii) the hover formulation which can simplify computations by transforming an unsteady problem to a steady-state one, iii) a novel grid-deformation strategy that allows all blade motions to be taken into account separately and preserves the quality of the CFD grids and finally iv) a simple trimming algorithm that allows computations to be performed for standard non-maneuvering rotor conditions. Results have been obtained both for hovering and forward flying rotors and comparisons against experimental data are encouraging. The validation cases covered a wide range of Mach numbers and angles and for all cases the proposed method resulted in high quality grids and efficient CPU times. This work is part of a wider effort undertaken by the authors in predicting unsteady rotor flows. Separate from validation efforts future research is now directed towards the coupled rotor/ fuselage problem. The elastic deformation of the blades has not been considered by the present paper, however, a coupled aeroelastic analysis of the rotor is possible within the present framework. In addition, the periodic nature of the flow is to be exploited for the efficient computation of rotor flows. These results will be reported in future papers.

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References


Figure 1. Frame of reference for forward-flight simulations and rotor blade motions: rotor rotation, blade flapping, blade lead-lag, blade pitch.
Figure 2. (a) Detail of the multi-block topology (140 blocks) used for one blade of the 4-bladed 7A rotor. Around the blade, a C-H topology is used with 'extruded' blocks towards far-field and 'hub' surface. (b) Shaded surface forms bounding surface of grid blocks selected to move as 'rigid' blocks with harmonic blade motion.

Figure 3. Definition of geometry of HELISHAPE 7A/7AD1 rotor blades and Caradonna and Tung rotor blade. For the 7A/7AD1 rotors, the non-linear geometric twist relative to the datum at 20% radius is shown. The 7AD1 planform shows the parabolic tip taper and anhedral. The Caradonna and Tung is untapered and untwisted.
Figure 4. Caradonna and Tung rotor in hover. Non-lifting case: $M_{tip} = 0.44$, $0^\circ$ collective pitch. Lifting case: $M_{tip} = 0.52$, $8^\circ$ collective pitch. Comparison of computed surface pressure with experimental data.

Figure 5. HELISHAPE 7A/7AD1 model rotors in hover, $M_{tip} = 0.6612$, $7.5^\circ$ collective (at 70% rotor radius). Comparison of computed surface pressure with experimental data.
Figure 6. HELISHAPE 7A\textsuperscript{20} model rotor in hover. Trimming simulations, $M_{\text{tip}} = 0.6612$. Inviscid simulations on 140-block grid with $0.6 \cdot 10^6$ grid points.

Figure 7. Geometrical definition of ONERA 2-bladed model rotors.\textsuperscript{22, 23}
Figure 8. Surface pressure distribution on advancing blade of non-lifting ONERA model rotor\textsuperscript{22,23} for both blade geometries at advance ratio $\mu = 0.45$. For the straight blade, $M_{tip} = 0.60$ (inviscid simulation on 236-block grid with $2.0 \cdot 10^6$ grid points). For the swept-tip blade, $M_{tip} = 0.628$ (inviscid simulation on 344-block grid with $2.6 \cdot 10^6$ grid points). Stepsize $\Delta \psi = 0.25^\circ$ used in simulations.

Figure 9. Integrated rotor blade loading for fully articulated 2-bladed rotor in forward flight. $M_{tip} = 0.60$, $\mu = 0.35$. The control angles are: $\theta_{shaft} = 2.0^\circ$ (forward), $\theta_0 = 4.0^\circ$, $\theta_1s = 3.0^\circ$, $\theta_{1c} = -1.5^\circ$. The flapping angles are: $\beta_0 = 2.0^\circ$, $\beta_1s = 1.0^\circ$ and $\beta_{1c} = 0.1^\circ$. Blade lead-lag was neglected. Non-dimensional aerodynamic blade pitching moment and non-dimensional aerodynamic moment on flapping hinge. Inviscid simulation on 236-block grid with $1.5 \cdot 10^6$ points. Stepsize $\Delta \psi = 0.25^\circ$ used in simulation.
Figure 10. Rotor blade motions and chordwise $C_p$ distribution ($r/R = 0.89$) for fully articulated 2-bladed rotor in forward flight. The dark shading shows the articulated blade surfaces compared to a rotor without articulation (light grey). $M_{tip} = 0.60, \mu = 0.35$. The control angles are: $\theta_{shaft} = 2.0^\circ$ (forward), $\theta_0 = 4.0^\circ$, $\theta_1s = 3.0^\circ$, $\theta_1c = -1.5^\circ$. The flapping angles are: $\beta_0 = 2.0^\circ$, $\beta_1s = 1.0^\circ$ and $\beta_1c = 1.0^\circ$. Blade lead-lag was neglected. Inviscid simulation on 236-block grid with $1.5 \cdot 10^6$ points. Stepsize $\Delta \psi = 0.25^\circ$ used in simulation.