Predicting Rotor BVI Loads Inclusive of the Fuselage Effect using an Unstructured Mesh Technique

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Viscous flow simulations of the HART II rotor were conducted using a flow solver based on unstructured meshes. To capture the blade-vortex interaction (BVI) phenomena accurately, a series of solution-adaptive mesh refinements was carried out. The blade deformation was considered using the HART II rotor measurement. Calculations were made for isolated-rotor and rotor-fuselage configurations, to investigate the fuselage effect on the blade loading and the rotor wake structure. The inclusion of fuselage significantly improves the trim control prediction, which results from the more accurate prediction of rotor inflow at the front and rear portions of the rotor disk. This improved trim control also leads to an improvement in the blade loading prediction for the rotor-fuselage configuration. From the solution-adaptive mesh refinement study, it was found that high-frequency blade loading caused by BVI can be obtained more accurately as the mesh is further refined, whereas the low-frequency loading is mostly independent to the mesh resolution. The predicted vortex core positions at the retreating side of the rotor were well matched with measurements, whereas a relatively large difference between the prediction and the measurement was observed at the advancing side.

Key Words: Blade-Vortex Interaction (BVI), Fuselage Effect, Unstructured Meshes, Adaptive Mesh Technique

Nomenclature

\( c \): chord length
\( r \): radial location
\( R \): rotor radius
\( \alpha_q \): shaft angle, positive aft
\( C_T \): rotor thrust coefficient
\( \theta_0 \): collective pitch angle
\( \theta_{lc} \): lateral cyclic pitch angle
\( \theta_{lc} \): longitudinal cyclic pitch angle
\( \beta_p \): precone angle
\( \psi \): rotor azimuth angle
\( \mu \): advancing ratio
\( w \): velocity component in \( z \)-direction
\( M \): Mach number
\( F_n \): sectional normal force
\( a_{\infty} \): speed of sound
\( \rho_{\infty} \): density
\( C_n M^2 \): sectional normal force coefficient \( F_{n}/(1/2 \rho_{\infty} a_{\infty}^2 c) \)

1. Introduction

Until recently, unsteady flow simulation of helicopter rotors remained one of the most challenging problems in the field of applied aerodynamics. For the prediction of rotor blade loading, unsteadiness of the flow field should be accurately simulated. At the same time, the simulation must account for the blade structural dynamic deformation, since rotor blades are not structurally stiff. In forward flight, rotor trim must also be achieved to satisfy the trim targets involving rotor thrust, pitching moment and rolling moment. In addition, the effect of rotor-fuselage interaction may be non-negligible in certain flight conditions. In this regard, for solving the rotor flow problems, a complete and comprehensive simulation is required, along with the ability of handling complex geometries and predicting rotor wake accurately.

In past decades, a series of experimental studies was conducted by the international collaboration between German DLR, French ONERA, NASA Langley, Netherlands DNW and the US Army Aeroflightdynamics Directorate, to investigate the influence of higher harmonic control (HHC) on blade-vortex interaction (BVI) in descending flight, which is known as the higher harmonic control aeroacoustics rotor test (HART) program. In 1994, the HART I tests\(^1\) were initiated with a 40% Mach-scaled model rotor of a BO105 main rotor. In the tests, blade loading, acoustic signature and blade deformation were measured, but little information was obtained regarding the rotor wake structure. As an extension of the HART I tests, the HART II tests\(^2,3\) were conducted later to focus more on investigating the wake structure. In the HART II tests, three different flight conditions were considered: a baseline (BL) case with conventional control inputs, and two additional cases with HHC inputs for minimum-vibration (MV) and minimum-noise (MN) cases. The measured data includes blade loading, acoustic signature, blade deformation and wake structure. Since blade loading and noise are closely related with the wake structure and blade deformation, this complete database is extremely useful for validating comprehensive analysis tools.

Previously, several numerical studies were conducted to simulate the BVI phenomena and the wake structure of
the HART II rotor tests. Lim41 performed a comprehensive
analysis using a coupled OVERFLOW-2/CAMRADII
code. For the wake prediction, a high-order WENO
scheme was used with 35.5 M grid points. In this study,
blade loading and blade deformation were also calculated,
including the effect of fuselage. The results showed that
the blade loading is largely affected by the rotational flow
behind the rotor hub. Boyd6) also used the same OVER-
FLOW-2/CAMRADII code, but the number of grid points
was increased to about 69 M. This study was focused more
on acoustic problems related to BVI, as well as blade load-
ing. Biedron and Lee-Rausch6) used a coupled FUN3D/
CAMRADII approach. The FUN3D code is based on un-
structured meshes, and preserves a second order of accuracy
in space. The simulation was made with 13.6 M grid points
that were clustered in the near wake region. The blade load-
ing was predicted reasonably well, but the peak-to-peak var-
ation of the BVI loading was relatively small compared to
the previous OVERFLOW-2 results. Yang and Aoyama7)
used an Euler flow solver with a fourth-order compact
MUSCL TVD scheme. The number of grid points used
was nearly 41 M grid points, and the blade deformation
was taken from the HART II measurement. Although vis-
cosity was not included, the results of blade loading were
reasonably good. The effect of fuselage on the blade loading
was also considered, but was not discussed in detail.

In the present study, viscous flow simulations of the
HART II rotor baseline (BL) case are conducted. The test
configurations and the computational domain are modeled
using unstructured meshes so that complex geometries can
be easily handled. A solution-adaptive mesh refinement
technique is also adopted to resolve the tip vortex better
and to capture the BVI loading more accurately. The blade
deformation is prescribed from the HART II measured data.
Calculations are made for both isolated-rotor and rotor-fuse-
lage configurations to investigate the effect of fuselage on
the rotor blade loading and the wake structure. The effect
of mesh refinement is also examined. For validation, the
results are compared with the experimental data.

2. Numerical Method

In the present study, an unstructured mesh CFD flow
solver8,9) is used for the simulation of unsteady time-accu-
rate viscous flows around the HART II rotor. The governing
Reynolds-averaged Navier-Stokes equations are discretized
using a vertex-centered finite-volume method. The flow
domain is divided into a finite number of control volumes
composed of median duals surrounding each vertex. The
inviscid flux terms are computed using Roe’s flux-difference
splitting scheme. The flow variables at each dual face are
computed using a linear reconstruction approach to achieve
second-order spatial accuracy. The second-order derivatives
of the viscous terms are evaluated using the Green-Gauss
theorem, and the viscous flux terms are computed by adopt-
ing modified central differencing. An implicit time integra-
tion algorithm based on a linearized second-order Euler
backward difference is used to advance the solution in time.
The linear system of equations is solved at each time-step
using a point Gauss-Seidel method. The Spalart-Allmaras
one-equation turbulence model is adopted to estimate the
eddy viscosity. To reduce the large computational time, a
parallel algorithm based on a domain decomposition strat-
ey is adopted. The load balancing between processors is
achieved by partitioning the global computational domain
into local subdomains using the MeTiS libraries. The Message
Passing Interface is used to transfer the flow variables
across the subdomain boundaries.

3. HART II Model

The HART II experiments2) use a 40% Mach-scaled,
four-bladed, hingeless BO105 model rotor. The rotor blades
are rectangular with −8° linear twist and a precone angle of
2.5°. The blade featured a modified NACA23012 airfoil
with a trailing-edge tab of 5.4 mm length and 0.8 mm thick-
ness. The rotor was installed with the rotor shaft angle of
5.3° (nose-up) that was designed to simulate descending
flight. In the present calculations, the rotor shaft angle of
4.5° is used for the correction of the wind tunnel wall
effects. The test conditions are summarized in Table 1.

In the present study, two computational configurations are
considered. The first one is the isolated-rotor configuration,
and the second one is the rotor-fuselage configuration used
to investigate the effect of fuselage on the blade loading and
the rotor wake. In the case of the isolated-rotor, the blade
root was cut at the radial location of 0.44 m from the hub
center. For the rotor-fuselage configuration, the blade root
was extended further inboard to 0.198 m from the hub
center to realistically model the HART II experimental con-
figuration. The solid modeling of the two configurations is
presented in Fig. 1.

4. Blade Deformation

In the present study, the blade motion is prescribed based
on a variable-separable interpolation of the blade deflections
that are measured at discrete azimuthal and radial locations
of each blade. The deflection, D, can be reconstructed using
an interpolating function as

$$D(r, \psi) = \sum_{i=1}^{N_r} \sum_{j=1}^{N_p} a_{ij} R_i(r) P_j(\psi)$$  \hspace{1cm} (1)

<table>
<thead>
<tr>
<th>Table 1.</th>
<th>HART II test condition.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor radius, R</td>
<td>2.0 m</td>
</tr>
<tr>
<td>Blade chord length, c</td>
<td>0.121 m</td>
</tr>
<tr>
<td>Twist angle</td>
<td>−8.0°</td>
</tr>
<tr>
<td>Precone angle, βp</td>
<td>2.5°</td>
</tr>
<tr>
<td>Thrust coefficient, C_T</td>
<td>0.0044</td>
</tr>
<tr>
<td>Advance ratio, μ</td>
<td>0.15</td>
</tr>
<tr>
<td>Shaft angle</td>
<td>4.5° (aft)</td>
</tr>
<tr>
<td>Tip Mach number</td>
<td>0.6387</td>
</tr>
</tbody>
</table>
where \( r \) is the non-dimensional radial coordinate, and \( \psi \) is the azimuth angle. \( N_r \) and \( N_a \) are the number of radial and azimuthal interpolation functions, respectively, and \( R_i(r) \) and \( P_j(\psi) \) are used to describe the blade deflection. The radial interpolation functions are taken to be polynomials, and the azimuthal interpolation functions are taken to be the components of a Fourier series:

\[
R_i(r) = r^{(i-1)},
\]

\[
P_j(\psi) = \begin{cases} 
\cos \frac{j-1}{2} \psi & \text{if } j \in \{1, 3, 5 \ldots\} \\
\sin \frac{j}{2} \psi & \text{if } j \in \{2, 4, 6 \ldots\}
\end{cases}
\]

The coefficients \( a_{ij} \) of the interpolation function are obtained using simple least-squares fitting, and the set of coefficients are given in Ref. 10). In Fig. 2, the approximation of the blade torsion is compared with the measured data. The maximum differences between the approximation and measurement are 0.5 mm and 0.5 mm for the torsion and the flap/lag, respectively.

5. Computational Mesh

In the present study, an unstructured overset mesh technique\(^{11}\) is adopted to handle the relative motion between the blades and the fuselage. In this overset mesh scheme, the mesh topology is composed of multiple independent mesh blocks. The main background mesh represents the complete computational domain and contains the fuselage, and the sub-block meshes cover each individual blade. To resolve the boundary layer on the blade and fuselage surfaces, a hybrid mesh topology containing both prismatic and tetrahedral cells is used. The mesh deformation at every time-step due to blade deformation is taken care of using a spring analogy\(^{12}\) and an algebraic method,\(^{13}\) which are applied to tetrahedral elements in the far-field region and to the prismatic elements inside the boundary layer, respectively.

A solution-adaptive mesh refinement technique is adopted to effectively resolve the tip vortex. The mesh adaptation is applied in a quasi-steady manner to avoid excessive computational procedures typically required when the mesh adaptation is applied in a fully unsteady dynamic manner, particularly in 3D. In the present approach, cells carrying high vorticity level are tagged at every time-step as the blades rotate. Once the rotor completes one period of rotation, the calculation is paused and the tagged cells are refined. In the present study, two levels of mesh adaptation are made.

Figures 3 and 4 show computational meshes after each level of mesh adaptation for both isolated-rotor and rotor-fuselage configurations. As shown in these figures, the mesh refinement is mostly concentrated in the vicinity of the rotor disk, and the cell size in the wake region decreases as the mesh refinement proceeds. For both configurations, the typical cell size in the wake region corresponds to 0.25c for the initial meshes and 0.125c for the meshes after the first-level mesh adaptation, where \( c \) is chord length. After the second-level adaptation, the cell size is further reduced to approximately 0.0625c. The typical size of the computational cells and the mesh resolution for both configurations are kept very similar to each other to avoid the dependency of the predicted results on the cell size. Detailed information about the meshes used is summarized in Table 2. The additional number of nodes and cells after including the fuselage is due to the addition of prismatic cells surrounding the fuselage.

For unsteady rotor flow calculations, the time-step size (azimuthal angle increment) is an important parameter affecting the solution accuracy. A convergence test study for the time-step size is conducted for each level of refined mesh, and azimuthal increments of 0.5°, 0.25° and 0.125° are used for the three different meshes, respectively.

All calculations are performed on a computer-based Linux cluster with 2.8 GHz CPU. A typical calculation for the isolated-rotor configuration on the second-level refined
mesh took approximately 5.7 CPU seconds per time-step using 186 processors.

6. Results and Discussion

6.1. Rotor trim

In order to retain the predicted thrust to a desired level and to eliminate rotor aerodynamic moments, a rotor trim procedure is applied to both isolated-rotor and rotor-fuselage configurations. These trim calculations are performed on the initial meshes to avoid the excessive computational time involved in the trim cycles. The trim controls consist of collective ($\theta_0$), lateral cyclic ($\theta_c$), and longitudinal cyclic ($\theta_s$) pitch angles, which are directly related to rotor thrust, pitching moment and rolling moment, respectively. The trim state is obtained by adjusting the trim controls iteratively using a Newton-Raphson method. One trim cycle consists of six rotor revolutions: three for calculating the derivatives of the force and moments with respect to the trim controls, and the remaining three for the solution iteration.

In Fig. 5, comparison of the trim controls between the prediction and the measured data is presented. As shown in the figure, a negligible difference is observed in the collective pitch angles between the isolated-rotor and rotor-fuselage configurations. In contrast, improved predictions of the cyclic pitch angles are obtained for the rotor-fuselage configuration over the isolated-rotor configuration, particularly for the lateral cyclic pitch angle $\theta_c$. 

Table 2. Meshes after each level of adaptation.

<table>
<thead>
<tr>
<th>Meshes after each level of adaptation</th>
<th>Isolated-rotor</th>
<th>Rotor-fuselage</th>
</tr>
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<tbody>
<tr>
<td>Initial mesh</td>
<td>2,897,615</td>
<td>3,030,066</td>
</tr>
<tr>
<td>Nodes</td>
<td>9,043,189</td>
<td>9,668,173</td>
</tr>
<tr>
<td>Cells</td>
<td>4,451,881</td>
<td>4,545,440</td>
</tr>
<tr>
<td>1st level adaptation</td>
<td>18,210,699</td>
<td>18,569,101</td>
</tr>
<tr>
<td>Nodes</td>
<td>8,042,165</td>
<td>8,660,890</td>
</tr>
<tr>
<td>Cells</td>
<td>39,416,933</td>
<td>42,928,170</td>
</tr>
</tbody>
</table>

Fig. 3. Computational meshes after each level of mesh adaptation for isolated-rotor configuration.

Fig. 4. Computational meshes after each level of mesh adaptation for rotor-fuselage configuration.

Fig. 5. Comparison of predicted and measured trim controls.
is presented. It is shown that a noticeable difference in
w-velocity component on the cutting plane located 1.5c below the rotor disk between isolated-rotor and rotor-fuselage configurations ($\Delta w_{vel} = w_{rotor-fuselage} - w_{isolated-rotor}$).

![Fig. 6. Difference of w-velocity component on the cutting plane located 1.5c below the rotor disk between isolated-rotor and rotor-fuselage configurations.](image)

To better understand the effect of fuselage on the trim controls, rotor downwash and the airload distributions on the rotor are examined. In Fig. 6, the difference of the w-velocity component between the isolated-rotor and rotor-fuselage configurations ($\Delta w_{vel} = w_{rotor-fuselage} - w_{isolated-rotor}$) on the cutting plane located 1.5c below the rotor disk plane is presented. It is shown that a noticeable difference in w-velocity exists near the azimuth angles of 0° and 180°, indicating that the fuselage induces non-negligible upwash and downwash flows near 0° and 180° azimuth angles, respectively. Figure 7 shows comparison of the predicted streamline traces around the rotor and the fuselage between the isolated-rotor and rotor-fuselage configurations. It is shown that due to the blockage of the fuselage, the flow is deflected upward in front of the rotor hub and in the downward direction behind. These upward and downward flows around the fuselage effectively change the local angle of attack of the rotor blades, and consequently influence the rotor blade loading.

![Fig. 7. Comparison of streamline traces around the rotor and fuselage between isolated-rotor and rotor-fuselage configurations.](image)

Figure 8 shows the difference of the sectional normal force coefficient ($\Delta C_n M^2 = C_n^{rotor-fuselage} - C_n^{isolated-rotor}$) between the isolated-rotor and rotor-fuselage configurations for one rotor revolution. To extract the pure fuselage effect, $C_n M^2$ from the rotor-fuselage configuration is computed with the same trim control settings as those of the isolated-rotor. It is shown that a noticeable difference of $C_n M^2$ exists near the azimuth angles of 0° and 180° where the rotor downwash is most influenced by the existence of the fuselage as indicated in Fig. 7. Some additional loading differences are also observed at the advancing side. As a result of this loading change, the rotor pitching and rolling moments increase, and thus, the cyclic pitch setting should also be increased in positive and negative directions, respectively, to further compensate for these additional pitching and rolling moments in the case of the rotor-fuselage configuration.

### 6.2. Effect of mesh adaptation

In the present study, a series of solution-adaptive mesh refinement is applied to capture the BVI loading accurately. In Fig. 9, the effect of adaptive mesh refinement on the blade loading at 87% radial location is presented for the rotor-fuselage configuration. The full signal of $C_n M^2$ in Fig. 9(a) shows that the loading below 3/rev variation is well predicted for all meshes, but the BVI loading at the 1st and 4th quadrants is strongly dependent on the level of mesh adaptation. To better understand the effect of mesh adaptation on the blade loading, the full signal of $C_n M^2$ is filtered to distinguish the high-frequency components (>7/rev) from the lower ones (0–7/rev). The high-frequency loading is exclusively associated with BVI, while the low-frequency loading is primarily associated with the control pitch angles and the blade structural deformation. In Fig. 9(b), comparison of the low-frequency loading is presented. It is shown that the low-frequency loading is mostly independent to mesh refinement. The predicted results compare very well with measurement at the 3rd and 4th quadrants, but slightly under/over-predicted at the remaining quadrants. In Fig. 9(c), the high-frequency loading is compared. For the initial mesh, the BVI loading at the 1st and 4th quadrants is not well captured due to the numerical dissipation for accurately capturing the rotor wake. In summary, as the computational mesh was further refined, the magnitude of high-frequency loading was also amplified, even though the refinement was not still dense enough for capturing the BVI loading at the 4th quadrant.

![Fig. 8. Difference of blade loading between isolated-rotor and rotor-fuselage configurations ($\Delta C_n M^2 = C_n^{rotor-fuselage} - C_n^{isolated-rotor}$).](image)

![Fig. 10. Comparison of vorticity fields at the cutting plane located 1.0c above the rotor disk plane.](image)
is highly dissipated, indicating high numerical dissipation. It is shown that as the mesh is further refined, the tip vortex is better preserved. It is also shown that the tip vortex in the advancing side (1st and 2nd quadrants) is less well-defined than that in the retreating side (3rd and 4th quadrants), causing poor prediction of the BVI loading as shown in Fig. 9. It is known that prediction of BVI loading in the advancing side is usually more difficult compared to the retreating side because the tip vortex in the advancing side is inherently weaker due to the relatively small angle of attack of the blade. In addition, the age of the vortex in the advancing side is much older than that in the retreating side. In contrast, the rotor blades entering the 4th quadrant encounter relatively young and strong vortices.

Figure 11 shows the effect of adaptive mesh refinement on the leading-edge pressure difference $\Delta P = P_{up} - P_{low}$ at 3% chordwise position of blade (rotor-fuselage configuration). The pressure difference is filtered to extract the components higher than 7/rev, and is plotted for one rotor revolution. Again, for the initial mesh, the stripe pattern at the 1st and 4th quadrants, which represents the BVI phenomena, is entirely missed. As the mesh is further refined, this stripe pattern becomes more distinctive.

6.3. Effect of fuselage
To investigate the effect of fuselage on the blade loading, comparison of $C_{nM}^2$ between the isolated-rotor and rotor-fuselage configurations is made in Fig. 12. The results are presented after the second-level mesh adaptation. It is shown that after the inclusion of the fuselage, the predicted low-frequency loading is significantly improved at most of the azimuthal stations. This improvement is directly related to the improved prediction of trim controls and rotor inflow.
as described in Figs. 5 and 7. For the high-frequency loading, local improvement in the blade loading near the azimuth angle of 360° is observed, which is mainly due to the different wake structures in that region between the two configurations.

In Fig. 13, the vorticity fields on the cutting plane 1.0c above the rotor disk plane are compared between the two configurations after the second-level mesh refinement when the reference blade is located at the azimuth angle of 0°. The figure shows that a strong and distinctive root vortex develops for the isolated-rotor configuration, while for the rotor-fuselage configuration, a wake flow develops behind the rotor hub without a distinctive root vortex.

In Fig. 14, comparison of the leading-edge pressure difference for the two configurations with the measurement is made for the results after the second-level mesh adaptation. It is shown that the overall accuracy of the prediction is improved by including the fuselage in the prediction, particularly near the azimuth angle of 0°. In the measurement, the stripe patterns from BVI at the 1st and 4th quadrants are clearly presented. These patterns are well predicted after the second-level mesh adaptation, even though the strength is slightly lower than the measurement. However, relatively poor prediction is observed in the first quadrant.

6.4. Tip vortex core position

Figure 15 shows the rotor wake structure represented by the iso-surface of \( A_2 \)-criterion for the rotor-fuselage configuration after the second-level mesh adaptation. The figure is presented when the reference blade is located at the azimuth angles of 20° and 70°. In the figure, the selected vortex core positions on the longitudinal cutting planes located at \( y = 1.4 \text{ m} \) and \( y = -1.4 \text{ m} \) are labeled consistently with the measurement. The position labeled with 22 in the 1st quadrant is not well defined in the present prediction.

In Fig. 16, the predicted tip vortex core positions for the isolated-rotor and rotor-fuselage configurations are compared with the measurement. The core positions correspond to the labeled numbers in Fig. 15. It is shown that both configurations provide reasonable predictions at the retreating side. In contrast, a relatively large difference exists at the advancing side, especially in the 1st quadrant where the tip vortex is the oldest. It is also shown that the prediction at the labels 18 and 44 are slightly improved after including the fuselage due to the upwash in the front of the
Improved trim control led to an associated improvement in predictions for the trim controls and the rotor inflow. This was found that inclusion of fuselage provides improved both isolated-rotor and rotor-fuselage configurations. It HART II measured data. Calculations were performed for mesh techniques was used to handle the blade motion. effectively. A combination of overset mesh and deforming steady manner to capture the rotor wake accurately and of solution-adaptive mesh refinement was applied in a quasi- using a viscous flow solver on unstructured meshes. A series around the HART II rotor were numerically investigated loading more difficult at the advancing side. 

In the present study, the blade loading and flow fields around the HART II rotor were numerically investigated using a viscous flow solver on unstructured meshes. A series of solution-adaptive mesh refinement was applied in a quasi-steady manner to capture the rotor wake accurately and effectively. A combination of overset mesh and deforming mesh techniques was used to handle the blade motion. The elastic blade deformation was prescribed from the HART II measured data. Calculations were performed for both isolated-rotor and rotor-fuselage configurations. It was found that inclusion of fuselage provides improved predictions for the trim controls and the rotor inflow. This improved trim control led to an associated improvement in the prediction of low-frequency loading. It was also found that the magnitude of high-frequency blade loading caused by BVI becomes clearer as the mesh is further refined, whereas the low-frequency loading is mostly independent to mesh adaptation. At the retreating side of the rotor, the predicted BVI loading and the wake positions were well matched with the measured data, whereas relatively large discrepancy existed at the advancing side due to the numerical dissipation of the rotor wake.

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