Prediction of Helicopter Blade-Vortex Interaction Noise using Motion Data from Experiment

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1. Introduction
   • Background and Objectives

2. Methods and Results
   • Single Blade Calculation
   • Full CFD Calculation (Overlapped grid method)
   • Acoustic Analysis

3. Conclusion
Helicopter BVI Noise

Large impulsive noise caused by the blade and vortex interaction, inhibiting a flexible operation of helicopter.
CFD analysis for helicopter aerodynamics

**Single Grid Model**

- Euler/NS code
- + Wake capturing/coupling
- + Acoustics

**“MENTOR”**
- Multidisciplinary Euler/Navier-Stokes Tool for Rotorcrafts

**Full CFD Model (Overlapped Grid Model)**

- Euler (direct vortex capturing)
- + Acoustics

<table>
<thead>
<tr>
<th>Grid Type</th>
<th>Single grid</th>
<th>Overlapped grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid points</td>
<td>0.5~5 millions</td>
<td>20~60 millions</td>
</tr>
<tr>
<td>Computing time</td>
<td>1~10 hr/case</td>
<td>100~500 hr/case</td>
</tr>
<tr>
<td>Accuracy</td>
<td>moderate</td>
<td>excellent</td>
</tr>
<tr>
<td>Purpose</td>
<td>Design/Industry</td>
<td>Academic</td>
</tr>
</tbody>
</table>
Acoustic analysis for noise prediction

Using CFD Results

Kirchhoff Method

FW-H Method

Direct Calculation

Computational Aeroacoustics (CAA)

HSI Noise

BVI Noise

Blade

Shock Wave

Subsonic Region

Supersonic Region
Questions to be solved for correct prediction of BVI noise

Aero-elastic analysis (CFD/CSD)

Q1. Can accurate blade motion be simulated by using CFD/CSD coupling method?
Q2. If the blade motion is correctly simulated, can CFD capture the tip vortex trace and simulate the blade vortex interaction (BVI) accurately?
Q3. Can acoustic code predict BVI noise correctly from obtained pressure data?
As the middle step for full coupling aero-elastic analysis, primary focus on the second and third questions using elastic blade motion data captured from the experiment (HART II experiment).
International co-operative project on higher harmonic blade motion control

- BL: Baseline
- MN: Minimum Noise
- MV: Minimum Vibration

- Blade air-loading
- Blade elastic deformation
- Pressure distribution on blades
- Noise
- Wake
- etc.

Available for research use

by NASA Langley, US Army, DLR, DNW, ONERA

Noise contour

PIV
HART II Calculation

- Blade motion with elastic deformation
- HARTII Exp. Data
- Full CFD
- Aerodynamic/Acoustic Analysis
- Single blade 3D CFD + Beddoes model

Flap, Lead-lag (R)

Torsion (deg)

Flap, Lead-lag (R)

Torsion (deg)

$\psi$ (deg)
Numerical Scheme for rotor (Curvilinear Grid):

- **Governing Equation:** 3D unsteady Euler equation
- **Space:** Beam-Warming scheme + TVD scheme
  - 2nd Order Accuracy
  - MUSCL approach using minmod limiter
- **Time:** Euler Backward Implicit Time Integration
  - Newton iterative method in unsteady calculation
- **Solution algorithm:** Upwind Line Gauss-Seidal Relaxation Method

Blade grid: \((\text{chord} \times \text{normal} \times \text{span}) \times \text{blade} = (219 \times 42 \times 100) \times 1 = 919,800\)
Beddoes Generalized Wake Model

Swirl velocity
\[ v_\theta(r) = \frac{\Gamma}{2\pi r} \left( \frac{r^2}{r_a^2 + r^2} \right) \]

Translation by blade elastic deformation
\[ + X_e + Y_e + Z_e \]

\[ x_v = r_v \cos \psi_v + \mu_x \Delta \psi_v \]
\[ y_v = r_v \sin \psi_v \]
\[ z_v = -\mu_z \Delta \psi_v + \int_{\psi_b}^{\psi_v} (\nu / R\Omega) d\psi \]

Downwash
inside the disk
\[ v = v_0 \left( 1 + \frac{8E}{15\pi} - 2\mu_x y' - E\left| y'^3 \right| \right) \]
outside the disk
\[ v = 2v_0 \left( 1 + \frac{8E}{15\pi} - 2\mu_x y' - E\left| y'^3 \right| \right) \]

(van der Wall, 2000)
Ffowcs Williams & Hawkings (FW-H) equation

\[
p(x,t) = \frac{1}{4\pi} \left( \frac{\partial}{\partial t} \int \frac{\rho_0 v_n}{r\Lambda} d\Sigma + \frac{1}{c_0} \frac{\partial}{\partial t} \int \frac{p_b \cos \theta}{r\Lambda} d\Sigma + \int \frac{p_b \cos \theta}{r^2\Lambda} d\Sigma \right)
\]

- **Sound pressure**
- **Thickness noise**
- **Load noise (far)**
- **Load noise (near)**

\[
\Lambda = (1 + M_n^2 - 2M_n \cos \theta)^{1/2}
\]

\(\Sigma\) : Influential surface
## Blade motion parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor radius, $R$ (m)</td>
<td>2.0</td>
</tr>
<tr>
<td>Blade chord length, $c$ (m)</td>
<td>0.121</td>
</tr>
<tr>
<td>Twist angle ($/R$)</td>
<td>-8.0°</td>
</tr>
<tr>
<td>Precone angle, $b_0$</td>
<td>2.5°</td>
</tr>
<tr>
<td>Thrust Coefficient, $C_T$</td>
<td>0.0044</td>
</tr>
<tr>
<td>Tip Mach number, $M_{tip}$</td>
<td>0.6387</td>
</tr>
<tr>
<td>Inflow ratio, $\mu$</td>
<td>0.15</td>
</tr>
<tr>
<td>Angle of tip path plane, $\alpha_{TPP}$</td>
<td>4.5° or 5.3°</td>
</tr>
<tr>
<td>Blade motion data</td>
<td>BL</td>
</tr>
<tr>
<td>Collective pitch angle, $\theta_0$</td>
<td>3.2°</td>
</tr>
<tr>
<td>Lateral cyclic pitch angle, $\theta_{1C}$</td>
<td>2.0°</td>
</tr>
<tr>
<td>Longitudinal cyclic pitch angle, $\theta_{1S}$</td>
<td>-1.1°</td>
</tr>
<tr>
<td>HHC lateral cyclic pitch angle, $\theta_{3C}$</td>
<td>0°</td>
</tr>
<tr>
<td>HHC long. cyclic pitch angle, $\theta_{3S}$</td>
<td>0°</td>
</tr>
</tbody>
</table>
Leading edge differential pressure distribution

Blade vortex interactions (BVI) are occurring.

HART II Experiment
Cal. with blade elasticity
Cal. without blade elasticity

Blade vortex interactions (BVI) are occurring.
Blade air-loading and acoustic results

Blade air-loading

without elasticity

with elasticity

Acoustics

Sound Pressure Level (Pa)

-100
-50
0
50
100

experiment
no-elasticity

experiment
with-elasticity

Sound Pressure Level (Pa)

-100
-50
0
50
100

experiment
no-elasticity

experiment
with-elasticity

Japan Korea CFD Seminar 2007.12.21
## Specifications of grid system

<table>
<thead>
<tr>
<th>Grid type</th>
<th>(X × Y × Z) = number of grid points</th>
<th>with fuselage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>rotor only</td>
<td>fine</td>
</tr>
<tr>
<td></td>
<td>coarse</td>
<td>medium</td>
</tr>
<tr>
<td>Inner background grid</td>
<td>290 × 230 × 50 = 3,335,000</td>
<td>450 × 400 × 80 = 14,400,000</td>
</tr>
<tr>
<td>Outer background grid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blade grid</td>
<td>(chord × normal × span) × blade (141 × 25 × 131) × 4 = 1,899,500</td>
<td></td>
</tr>
<tr>
<td>Fuselage grid</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>~5,560,000 points</td>
<td>~16,600,000 points</td>
</tr>
<tr>
<td>Inner background spacing</td>
<td>0.17c (=0.0105R)</td>
<td>0.099c (=0.006R)</td>
</tr>
</tbody>
</table>
Numerical Scheme for rotor and fuselage (Curvilinear Grid):

- Governing Equation: 3D unsteady Euler equation
- Space: Beam-Warming scheme + TVD scheme
  - 2nd Order Accuracy
  - MUSCL approach using minmod limiter
- Time: Euler Backward Implicit Time Integration
  Newton iterative method in unsteady calculation
- Solution algorithm: Upwind Line Gauss-Seidal Relaxation Method

Numerical Scheme for background grid (Cartesian Grid):

- Governing Equation: 3D unsteady Euler equation
- Space: Compact TVD scheme (4th Order Accuracy)
  Simple High-resolution Upwind Scheme (SHUS)
  - Advection Upstream Splitting Method (AUSM)
- Time: Explicit Time integration
  Four stage Runge-Kutta method (4th Order)
Effect of blade elasticity consideration

Measured and calculated coefficient of blade loading at 87% spanwise position with/without elastic deformation for BL case
## Results (Full CFD Cal.)

### Effect of grid size

<table>
<thead>
<tr>
<th>Grid Size</th>
<th>Coarse</th>
<th>Medium</th>
<th>Fine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
<td>(290 \times 230 \times 50 = 3,335,000)</td>
<td>(450 \times 400 \times 80 = 14,400,000)</td>
<td>(750 \times 580 \times 140 = 60,900,000)</td>
</tr>
<tr>
<td>Spanwise</td>
<td>0.17c (=0.0105R)</td>
<td>0.099c (=0.006R)</td>
<td>0.066c (=0.004R)</td>
</tr>
</tbody>
</table>

### Effect of Grid Dependency

<table>
<thead>
<tr>
<th>Grid Size</th>
<th>Coarse</th>
<th>Medium</th>
<th>Fine</th>
</tr>
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<tbody>
<tr>
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</tr>
<tr>
<td>Spanwise</td>
<td>0.17c (=0.0105R)</td>
<td>0.099c (=0.006R)</td>
<td>0.066c (=0.004R)</td>
</tr>
</tbody>
</table>

#### Measured and calculated coefficient of blade loading at 87% spanwise position with/without elastic deformation for BL case

![Graph showing coefficient of blade loading with different grid sizes.](image.png)
Effect of fuselage

Measured and calculated coefficient of blade loading at 87% spanwise position with/without elastic deformation for BL case
Acoustic results

Measure and calculated sound pressure for BL case using high pass filter at 4/rev.
For both single grid and full CFD calculation
Constitution of blade elastic deformation remarkably enhanced the calculation quality, thus indicating the necessity of CFD/CSD coupling in a future prediction system.

For single grid calculation
Beddoes generalized wake model successfully simulated the tip vortex trace in the wake, realizing the reasonable quality of calculation, but overestimation of air-loading and the BVI noise still remain.

For full CFD calculation
- The calculation quality is dependent on the inner-background grid size, proper grid size should be used to enhance the precision.
- Fairing effect also should be considered for high quality of calculation.
Thank you for attention