Development of a CFD Capability for Full Helicopter Engineering Analysis

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CFD Capability for Helicopter Analysis

Collective effort of more that 10 person-years

- Ken Badcock, René Steijl, Alan Brocklehurst, John Miller, Adriano Gagliardi, Agis Spentzos, Jeremy Beedy, Romy Morvant, Stefano Rolfo, Geoffrey-Alexis Hakkens
Outline of the presentation

Motivation and Objectives
CFD Method for Rotorcraft
Examples of Rotorcraft CFD
  Prediction of vortex locations
  Design optimisation of a flapped rotor
  Advancing side aerodynamics
  Dynamic stall on a rotating blade
  Combined Rotor/Fuselage Configuration

Summary and Future Steps

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Motivation – Helicopter flows are interesting!

- Unsteady, turbulent, vortical, compressible flow
- Stall on retreating side
- Shock hysteresis on advancing side
- Blade-vortex interactions
- Complex blade motion
- Complex wake structure
- Bluff-body flow around the fuselage
- Transition to turbulence
- Main rotor/ tail rotor interactions
- Tail rotor power limitations

The aerodynamic design of helicopters must account for and balance all the above!
Objectives

• Non linear aerodynamics of rotor flows calls for CFD
• Need for detailed analysis of rotorcraft flows for:
  • Design and Evaluation
  • Problem Solving
  • Understanding!

• Rotorcraft problem is different

• CFD methods need extensions

• Systematic approach is necessary to guarantee accuracy of results and efficiency of the method
Outline of the CFD Solver

- Control volume method
- Parallel
- Multi-block (complex geometry) structured grids
- Unsteady RANS - Variety of turbulence models inc. LES/DES
- Implicit time marching
- Osher's and Roe's schemes for convective fluxes
- MUSCL scheme for formally 3rd order accuracy
- Central differences for viscous fluxes
- Krylov subspace linear solver with pre-conditioning
- Moving grids, sliding planes
- Hover formulation, rotor trimming, blade actuation
- Documentation
- Validation database
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Parallel Computing

- Distributed and Shared Memory Machines
- MPI and OpenMP
- Linux Clusters
- CSAR, HPCX, NEC
Linux Cluster at Liverpool

- Jupiter 4
- Operational early 2006
- 130 Pentium 4 machines, 3.0 GHz CPUs
- 2 TB disk space
Example: Prediction of Vortex Locations

• Accurate representation of rotor wake is important
• Traditional wake methods predict vortex locations quite well for simple blade designs
• Few CFD investigations of wake locations exist
• Validation of CFD against data
• Typical grid size: 2-5 million points per blade
• Cost: 2 months using 36 P4 processors
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*Multi-block topologies for rotor cases*

2-4.5M grid points per blade, blade actuation requires special topologies
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CFD – Validation - UH-60A Model Tail Rotor Tests (Lorber)

UH60A - Hover $M_r = 0.626$, $10.5^\circ$ collective, $2.31^\circ$ coning
**CFD – Validation - UH-60A Model Tail Rotor Tests (Lorber)**

11.47° collective pitch, $M_{\text{tip}} = 0.628$, inviscid, 240-block grid, 4.5M grid points
Hover computations are not steady-state!

- To trim the rotor, several iterations are needed
- Initial estimate of the control angles
- Collective and coning are needed for hover
- Cyclic inputs for forward flight
- Computations must be repeated at several thrust settings

$M_{\text{tip}} = 0.6612$, target $C_T = 0.0050$
Comparison – Model Tail Rotor – Vortex Wake Trajectories

Comparison of CFD and Experiment
Vortex Locations - Vertical Displacement

TRB-0100  Rectangular Blade, Zero Twist, Mtip=0.263

Vortex locations around the azimuth
Four blade designs
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Iso-surfaces of Vorticity Magnitude

Rectangular Tip, Anhedral, 10 deg Pitch
Iso-surfaces of Vorticity Magnitude
Example: Flapped Rotor Design

- Blade twist can help with hover performance of rotors at high loading
- Blade twist could have adverse effects in forward flight
- Design a rotor with moderate twist and use a flap to recover performance during hover
- Typical grid size: 2-5 million points per blade
- Cost: 4 months using 36 P4 nodes
Optimum Flap Selections

Wind Tunnel Evaluation of a Helicopter Main-Rotor Blade with Slotted Airfoils at the Tips, Noonan et al., NASA TP 211260, December 2001
• Blocking for HIMARCS I Rotor
• Also used for varied twist blades

106 Blocks; 2mil+ grid points

• Pressure Contours at $\theta = 13.11^\circ$ and $\tau = 3.124^\circ$ ($M_\infty = 0.627$ and $Re = 9 \times 10^6$)
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Validation against NASA Experiments

3D CFD Validation - $C_T$ versus $C_Q$

3D CFD Validation - Figure of Merit

3D viscous computations at all thrust settings
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Optimum Inboard Flap

- Pressure Contours at $\theta = 13.7925^\circ$ and $\tau = 3.304^\circ$ ($M_\infty = 0.627$ and $Re = 9 \times 10^6$)

446 Blocks; 2.7mil+ grid points
Test Cases Evaluated

- Both the clean and flapped rotor blades were evaluated at $C_T$ settings ranging from 0.0007 to 0.01

<table>
<thead>
<tr>
<th>Flap Location</th>
<th>Flap Span</th>
<th>Flap Chord</th>
<th>Flap Deflection</th>
<th>Number of Designs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inboard</td>
<td>4.5%R-31.81%R</td>
<td>4.5%R-31.81%R</td>
<td>32%c, 22%c, 11%c</td>
<td>3°, 10°</td>
</tr>
<tr>
<td></td>
<td>88.6%R-95.45%R</td>
<td>2.27%R-11.36%R</td>
<td>32%c, 22%c, 11%c</td>
<td>3°, 10°</td>
</tr>
</tbody>
</table>
CFD Results - Blade twist study

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CFD Results - Blade performance

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Wake Structure

Iso-Surface of V-velocity

Tip and Flap Vortex Interaction
Example:
Advancing and Retreating Side Aerodynamics
Example: Study of Advancing Side Aerodynamics

- Advancing blade lift phase delay: minimum lift 40° beyond $\psi = 90°$ at high $\mu$
- Pitch-link load shows similar phasing
- Predictive methods based on reduced-order aerodynamics fail to predict this
- 3D unsteady transonic flow conditions on advancing side
- Grid size: 6-16 million points (four blades must be computed)
- Cost: 6 months using 36 P4 processors

$\mu=0.37$, 86.5% radius (NASA TM-110396)

UH-60A: $\mu=0.355$ and Puma: $\mu=0.362$ (NASA TM-104006)
Untwisted blade with cyclic pitch

10 deg collective, 10 deg cyclics, turbulent flow
Advancing Side Aerodynamics

UH-60A rotor
High-speed forward flight
$\mu = 0.35$, $M_{\text{tip}} = 0.625$

$\theta_0 = 6.809 \text{ deg.}$
$\theta_{1s} = 4.928 \text{ deg.}$
$\theta_{1c} = -1.747 \text{ deg.}$
$\beta_0 = 1 \text{ deg.}$

$C_T = 0.005$
Advancing Side Aerodynamics

• Contributions from:
  – Cyclics: up to 10 degrees of delay
  – Impulsive Effects: up to 10 degrees of delay (at high tip Mach number)
  – dM/dt Effects: up to 10 degrees of delay (dominant effect)
  – Yawed Flow Effects: 5-6 degrees of delay (combined with 3D tip effects)
  – 3D Effects: 5-8 degrees of delay
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3D Dynamic Stall – Validation Study – Wing cases

Comparison with oscillatory data from LABM

Pitching motion, \( k = 0.048 \)

\[ \text{AoA} = 18 + 6 \sin(\omega t) \]

\( x/c = 0.4 \)

\( z/c = 0.5 \)

AoA = 18 deg downstroke

AoA = 12 deg
3D Dynamic Stall – Validation

Ramping motion
\[ \alpha^+ = 0.027 \]
-5° -> 40°
Re=1.45x10^6
M=0.16
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Retreating Side – 3D Dynamic Stall

- Vortex cores for a retreating side computation
- Untwisted blade
- 10 degrees of collective 10 degrees of cyclic
- Re=4 million
- M=0.3
- 4 days on 36 CPUs
Demonstration: Combined Rotor/Fuselage Configuration

- CFD capability for rotor body
- Validation against data
- Derive some method for assessing rotor designs
- Typical grid size: 4-12 million points for fuselage + 3-4 million points per blade
- Cost: estimated 25-30 months using 36 P4 CPUs
Isolated Fuselage – Validation – ROBIN Body at -5 degrees

Comparison with Published Data:
Mineck and Althoff, NASA TM-210286
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Isolated Fuselage – Validation – ROBIN Body at -10 degrees

Detailed Flow Features Captured

Vortex around the pylon

Recirculation after the pylon
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Combined Rotor/Fuselage Configuration – Demonstration Case
Combined Rotor/Fuselage Configuration – Demonstration Case

Fast forward flight: $\mu=0.25$, fixed cyclic

1.5 million grid points (1.1 rotor + 0.4 fuselage)
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GOAHEAD (F6 project) - Fuselage in wind tunnel section
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Summary and future steps

- Rotor Wake
- Rotor Design
- Advancing & Retreating Side Aerodynamics
- Fuselage Flow
- Interactions

Cost (CPU months) vs. Case complexity

- 25-30
- 2
- 4
- 6
- 10

HPC New Methods

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