Drag Prediction of Two Production Rotor Hub Geometries

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Motivation

- Hub drag is a large fraction of total helicopter drag and can approach 30% of single rotor aircraft.
- Fairings can reduce hub drag, but generally not used because they inhibit inspection and maintenance.
- Prediction of total hub drag and the drag of individual components is desirable to design new hubs with reduced drag.
- Recent advances in gridding and computational power offer potential for design impact.
- Can we affordably use CFD today to predict hub drag?
Background

- Historically hub drag for a design is estimated from a component drag build-up process, then tested in WT:
  - Empirical drag from similar or nearly similar elemental shapes
  - Local velocities on components or assemblies
  - Interference effects on components or assemblies
  - Subjective process

- Gridding of very complex geometries has been a challenge in the past – weeks to months

- Modern unstructured flow solvers now providing enhanced gridding tools that overcome this bottleneck

- Computational resources are affordable to run lots of cores on a single problem

  => Evaluate a modern unstructured flow solver
      (CD-adapco STAR-CCM+)

- Others applying CFD to hub drag prediction (see paper)
Validation Data

- Two hub geometries tested at ½ scale as part of S-92A aircraft development in 1994 UTRC Main WT test
  - S-92A
  - UH-60A

- Drag data available for component build-up from WT testing of both hubs

- Drag is not corrected for tunnel effects (small)

- Hub geometry detail at the nuts and bolts level

- Tunnel and support pylon/splitter plate included in calculation

- Simulation performed for WT conditions
  - 150 knots
  - 500 rpm
  - $\mu=0.36$
  - ~SLS
S-92A Geometry

Surface representation of the $\frac{1}{2}$ scale S-92A hub
UH-60A Geometry

Surface representation of the ½ scale UH-60A hub
Model Details – S92A Hub

- Wind Tunnel & test pylon/splitter plate gridded
- Pylon/splitter plate support stand not included

- Shaft tilted 5 degrees forward
- Swashplate servos disconnected in WT model – swash plate was not functional
Grid Details – Surface Mesh

Surface wrapper in STAR-CCM+ used to “shrink wrap” geometry

- Water tight
- No surface repair
- No defeaturing

High geometric fidelity observed
Grid Details – Volume Grid

- 14.8M advanced hexahedral grid cells
- Boundary layer mesh had 8.2M cells
  - 4 layers of body fitted prismatic cells on all surfaces for boundary layers & for transition to hexahedral cells
  - 10 layers used on the beanie
  - Target of $y+ < 1.0$ for areas of attached flow
  - Average of $y+ = 19$ elsewhere
- Volumetric refinement behind hub to capture turbulent eddies
  - Established from a coarse grid test run
  - Courant number $< 1.0$
- Sliding grid around moving hub assembly
Solution Process

• Solution process was essentially the same for both hubs, but initial S-92A test case used a coarse grid to verify setup, hub motion, boundary conditions and to define the volumetric grid refinement region

• Simulation mimicked WT test conditions (1/2 scale Rn)

• No grid sensitivities performed

• Time step sensitivities performed for only the initial full S-92A configuration – to be discussed

=> Blind calculations for all solutions performed by 1st author using “best” practices
Initial S-92A Simulations

- Used full S-92A hub configuration
- Ran RANS model in a steady state Moving Reference Frame (MRF) on coarse grid
  - Effects of rotation in the flux calculation but geometry is static
  - Blade stubs aligned with coordinate axis (0°-indexing position)
- Fine mesh developed based on “best practices” and flow structure to resolve near wake
- Fine grid steady state MRF restarted from coarse grid solution
- URANS restarted from steady state MRF
- Detached Eddy Simulation (DES) restarted from URANS
- Case run beyond time necessary to achieve near-periodic solution
Initial S-92A Results

- Drag for steady state MRF ~ Maximum of DES for 5° time step
- Maximum unsteady drag occurs near 90° indexing position (largest frontal area)
- Minimum unsteady drag occurs near 45° indexing position (least frontal area)
- 4% change in drag from 5° to 0.5° for DES solutions
- 0.6% difference between URANS and DES
Hub Build-Ups

- CFD simulations mimicked WT test build-up in reverse
  - Started with full configuration
  - Removed components

6 S-92A Configurations

3 UH-60A Configurations
Key Simulation Parameters

Based on the initial test case, validation results for both hubs obtained with the following simulation parameters:

- Detached Eddy Simulation (DES)
- Time step = 5° of hub rotation (under-resolved for detailed unsteady flow structures, focus was drag)
- Sub-iterations used in each time step to converge time step solution
- Viscous boundary condition: “All y+ Wall treatment” - hybrid treatment that attempts to emulate the high y+ wall treatment for coarse meshes and the low y+ wall treatment for fine meshes. Formulated with the desirable characteristic of producing reasonable answers for meshes of intermediate resolution.
Validation – S-92A Hub

- Addition of components show very similar trends with WT test results
- Worst error between calculation and test is < 7%
- Generally over predicted test values

Normalized Drag of S-92A Hub Configurations

Calculation Error for S-92A Hub Configurations
Validation – UH-60A Hub

- Addition of components show very similar trends with WT test results
- Worst error between calculation and test is < 7%
- Generally under predicted test values
Flow Solutions

DES Solutions

Velocity Magnitude Contours

S-92A

Pressure Contours

S-92A

UH-60A

UH-60A
Unsteady Drag

S-92A hub has exposed scissors believed to cause 2p excitations in early aircraft flight development testing:

- Removing scissors component in calculations dramatically reduces 2p behavior.
- Residual 2p due to fittings on other components.

FFT of Unsteady Hub Drag

- Base + Swash Plate + Scissors & Servos + Pushrods
- Base + Swash Plate
- Base Hub

Magnitude vs. Per Hub Revolutions
Simulation Cost Breakdown

Experienced user can produce grid & results quickly

- CAD Model
- Surface Prep
- Surface Mesh
- Volume Mesh
- Simulation
- Post Process

- 4 man-hours
- 8 man-hours
- 12 CPU-hours
- 4 CPU-hours
- 2 man-hours

*Note: quoted CPU hours are on 24 processors

12 CPU-hours* – MRF
60 CPU-hours* – DES
Concluding Remarks

• Blind study of 9 configurations for two production hub geometries using a modern unstructured flow solver had worst error less than 7% compared with test.

• Grid refinement/time step studies may improve results.

• Harmonic content of unsteady drag is consistent with expectations associated with details of geometry.

• Accuracy and time to grid and run cases for complex geometries is acceptable for design studies.

• Development of CAD models may become a bottleneck.

• Temporal accuracy and grid resolution used in this drag study would not be adequate to calculate the spectral content in the flow field downstream of the hub.

• Results imply the possibility of taking on the challenge of predicting the downstream flow structures of complex hub geometries with a high degree of fidelity.