In the Subsonics Rotary Wing (SRW) Project being funded for propulsion work at NASA Glenn Research Center, performance of the propulsion system is of high importance. In current rotorcraft drive systems many gearing components operate at high rotational speed (pitch line velocity > 24000 ft/ min). In our testing of high speed helical gear trains at NASA Glenn we have found that the work done on the air - oil mist within the gearbox can become a significant part of the power loss of the system. This loss mechanism is referred to as windage. The effort described in this presentation is to try to understand the variables that affect windage, develop a good experimental data base to validate, the analytical project being conducted at Penn State University by Dr. Rob Kunz under a NASA SRW NRA. The presentation provides an update to the status of these efforts.
Gear Windage Modeling Progress – Experimental Validation Status

Dr. Rob Kunz
Pennsylvania State University
Applied Research Laboratory

&

Dr. Robert F. Handschuh
U. S. Army Research Laboratory
NASA Glenn Research Center
Topics

• Background

• CFD modeling of high speed gearing

• Current analytical validation results

• Experimental testing build-up

• Status & plans
• High speed gearing tests at GRC have shown the importance of windage losses

• This topic has received very little attention in the open literature

• Analytical and experimental efforts are focusing on developing a proper aerospace database and a full 3-D modeling capability
Background

High-Speed Helical Gear Train Test Facility (NASA – GRC)
Background

High-Speed Helical Gear Train Test Facility
(15000 RPM)

- **Windage Loss**
- **Gear Meshing Losses**
- **Bearing Losses**

Power Loss (hp)

Input Torque (in*lb)
Gear Windage Results

High-Speed Helical Gear Train Prediction

\[ P_{\text{Windage}} = C_3 C' \rho N^{2.85} D^{4.7} v^{0.15} \lambda \]

Input Shaft Speed (RPM)

Windage Power Loss (hp)

- Dawson Model 1% Lube
- Dawson Model 0.75% Lube
- Dawson Model 0.5% Lube
- Dawson Model 0.25% Lube
- Dawson Model - No Lube
Technical Challenges

- Complex physics for CFD:
  - Geometries
  - High $M_{\text{tip}}$
  - High Re
  - Contact + relative motion
  - Multiphase flow (disperse [droplets], continuous [films])
  - Turbulence
  - Heat transfer
  - Viscous dissipation
- Little validation data
- Unknown relative importance of 1-phase and 2-phase physics
- Oil-out condition
Technical Approach: Overview

- Deploy five, modern components of CFD technology:
  1. unstructured, overset, moving meshes
  2. Multi-phase, multi-flow-regime (droplet+film)
  3. Thermal analysis
  4. Modern turbulence modeling
  5. Immersed Boundary Methods for gears.
• NPHASE-PSU Code:
  – Developed at Penn State ARL (Kunz).
  – Overset+unstructured+moving meshes
  – All modes of heat transfer
  – Full-n-fluid multiphase flow with deposition, atomization drag, dispersion and other relevant models
  – Parallel (MPI, matrix level)
  – Modern turbulence modeling (2, 4, 7-equation, DES)
  – High order discretization
  – Relevant application/validation basis
Technical Approach: Numerics/Code

- Scalar transport equation:
  - **Moving grid** in context of finite volume

\[
\frac{\partial}{\partial t} \int \rho \phi \, d\Omega + \int_{\partial \Omega} \rho \phi (V-W) \cdot dS = \text{sources of } \phi
\]

Absolute frame of reference velocity at control volume face

Velocity of control volume face

- Exact satisfaction of Geometric Conservation law (GCL)
• Critical enabler for multiple gear systems.
  – Quality meshes for gears required for accurate aero modeling
  – Each gear has its “own” high quality mesh
  – Efficient use of elements/computer resources
Overset Grid Technology

- Contact
- Contact enabler
• Supercomputing resources
  – 2,000,000 processor hours on Columbia
  – NPHASE-PSU up and running for large scale gear simulations

Columbia system as NAS

Excellente parallel efficiency
• Hierarchal Approach:
  – Relevant verification
  – Non-moving gears
  – Free cylinders
  – Single gears
  – Enclosed cylinders
  – Multiple gears
  – NGRC test configuration
  – Industry configurations
3D flow near a rotating disc

\[
F = \frac{V}{r_0}, \text{ analytical solution}
\]

\[
G = \frac{V}{r_0}, \text{ analytical solution}
\]

\[
-H = -\frac{V}{\sqrt{\nu \omega}}, \text{ analytical solution}
\]

\[
F = \frac{V}{r_0}, \text{ NPHASE-PSU, stationary mesh}
\]

\[
G = \frac{V}{r_0}, \text{ NPHASE-PSU, stationary mesh}
\]

\[
-H = -\frac{V}{\sqrt{\nu \omega}}, \text{ NPHASE-PSU, stationary mesh}
\]

\[
F = \frac{V}{r_0}, \text{ NPHASE-PSU, rotating mesh}
\]

\[
G = \frac{V}{r_0}, \text{ NPHASE-PSU, rotating mesh}
\]

\[
-H = -\frac{V}{\sqrt{\nu \omega}}, \text{ NPHASE-PSU, rotating mesh}
\]
Hierarchal Approach: relevant verification ➔ non-moving gears ➔ free cylinders ➔ single gears ➔ enclosed cylinders ➔ multiple gears

Elements of NPHASE-PSU simulation of notional 2-gear system. Non-rotating, 1-phase, octree mesh.
### Diab Gear Validation

<table>
<thead>
<tr>
<th></th>
<th>Pitch diameter (mm)</th>
<th>Tooth width (mm)</th>
<th>Module (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gear 1</td>
<td>288</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>Gear 2</td>
<td>144</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>Gear 3</td>
<td>144</td>
<td>60</td>
<td>4</td>
</tr>
<tr>
<td>Gear 4</td>
<td>144</td>
<td>60</td>
<td>6</td>
</tr>
<tr>
<td>Disk</td>
<td>300</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

Geometry and predicted pressure distributions for 4 Diab gears
Diab Gear Validation

3D mesh topology

Secondary flows within gear teeth
Comparison of predicted and measured windage losses

Power (W) vs Speed (rad/s) graph showing a comparison between Experiment and NPHASE data. The graph indicates a linear relationship between power and speed, with Experiment data points consistently higher than NPHASE data points.

Diab Gear Validation

[Graph showing power vs speed with data points for Experiment and NPHASE]
- Low Re vs. high Re turbulence model, Diab disc
- Viscous vs. pressure losses, Diab gear 1
Selected visualizations

- Diab gear, pressure contours, 3D overset
- Overset grid, spur gear with shrouding
- Diab gear, relative streamlines and pressure isocontours
Current overset topology
• Test Plan
  – Phase I \(\rightarrow\) single gear windage.
    • Isolated gear spin down data \(\rightarrow\) only windage and bearing losses
    • No lubrication oil
    • Two spur gears
    • Evacuate test section to lower static pressures and vacuum
    • Variety of housing geometries
    • Oil mist and jet impingement lubrication
  – Phase II \(\rightarrow\) 2 gears
    • Run without lube oil ? (depending on spin down rate)
    • Shrouding for both gears
• Lots of data \(\rightarrow\) MUCH more than ever available
• Close coordination between
1-phase capability verified
1-phase capability validated for 3D rotating grid gears
  - Completed several verification cases
  - Very good comparisons with Diab data:
    • Dominant pressure effects
    • Possible underestimation of viscous work → turbulence modeling
  - Moving mesh approach converges well
  - Code scales well

Overset technology:
  - Fully established in context of moving meshes
  - New higher accuracy topology
  - New hybrid overset-immersed boundary method → enables contact
• 2-phase under way – hierarchy of approaches:
  – Mixture density and viscosity
  – Homogeneous 2-phase
  – Full n-fluid
• Working with Glenn to define validation test matrix