Baseline Experimental Results on the Effect of Oil Temperature on Shrouded Meshed Spur Gear Windage Power Loss

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Windage power loss (WPL)

- Drag on gear tooth in transmitting load.
- Viscous drag on gear faces
- Air/Oil impingement on tooth surface (inertia effects)
- Significant at greater than 10,000 ft./min. (51 m/s)
- Gearbox efficiency losses
- Reduced rotorcraft performance (i.e. payload, range)

Ref:
Shrouded Spur Gear WPL Work

  - single spur gears, air
  - reduction in WPL with axial and radial shrouding
  - single and meshed spur gears, shrouding, air/oil
  - decrease in WPL with increasing oil temp., increase in WPL with increasing oil flow
- (2011) Combined Analysis & Experimental Validation
  - single spur gear analyses, shrouding
    - Hill: “CFD Analysis of Gear Windage Losses….”
    - Handschuh: “Initial Expts. of High-Speed Drive Sys. Windage Losses”
  - 7x to 12x increase in WPL for meshed spur gears compared to single spur gears
  - Explore WPL sensitivity to oil flow rate and oil temperature
Focus of this work

- Obtain WPL experimental on meshed spur gears
  - Oil inlet temperatures: 100°F (38°C), 125°F (52°C), 160°F (71°C), 180°F (82°C)
  - Constant oil pressure
  - 4 shroud configurations

- Compare with literature
  - Single vs Meshed
  - Unshrouded vs Shrouded

- Identify WPL trends, if any

- Outline additional research
# Gear Information

<table>
<thead>
<tr>
<th>Gear Parameter</th>
<th>Drive-side</th>
<th>Driven-side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of teeth</td>
<td>44</td>
<td>52</td>
</tr>
<tr>
<td>Pitch / module, 1/in. (mm)</td>
<td>4 (6.35)</td>
<td></td>
</tr>
<tr>
<td>Face Width in. (mm)</td>
<td>1.12 (28.4)</td>
<td>1.12 (28.4)</td>
</tr>
<tr>
<td>Pitch Diameter, in. (mm)</td>
<td>11.0 (279.4)</td>
<td>13.0 (330.2)</td>
</tr>
<tr>
<td>Pressure Angle, deg.</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Outside Diameter, in. (mm)</td>
<td>11.49 (291.85)</td>
<td>13.49 (342.65)</td>
</tr>
<tr>
<td>Material</td>
<td>Steel-SAE 5150H</td>
<td></td>
</tr>
</tbody>
</table>
## Shroud Information

<table>
<thead>
<tr>
<th>Shroud Config.</th>
<th>Axial Clearance</th>
<th>Radial Clearance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Per side</td>
<td>Drive</td>
</tr>
<tr>
<td></td>
<td>(inches)</td>
<td>(inches)</td>
</tr>
<tr>
<td></td>
<td>(mm)</td>
<td>(mm)</td>
</tr>
<tr>
<td>(U) Unshrouded w/o clam-shell housing</td>
<td>2.25 (57.15)</td>
<td>2.5 (63.5)</td>
</tr>
<tr>
<td>(CS) Unshrouded w/ clam-shell housing</td>
<td>1.5 (38.1)</td>
<td>0.82 (20.83)</td>
</tr>
<tr>
<td>(C36) shrouded</td>
<td>1.2 (30.5)</td>
<td>0.66 (16.76)</td>
</tr>
<tr>
<td>(C1) shrouded</td>
<td>0.039 (1.00)</td>
<td>0.039 (1.00)</td>
</tr>
</tbody>
</table>
Continued - Shrouding
NASA WPL Test Rig

- dc motor: 150 hp (112 kW)
- speed-up gearbox: 1:5.17 ratio
- Eddy-current brake: 73.8 ft.-lb. (100 N-m) at 2865 rpm (300 rad./sec.)
- torque-meter: 2,000 in-lbs (226 N-m)
- Into-mesh lubrication
- Measurements:
  - shaft speed
  - gear fling-off temperature
  - gear mesh oil flow
  - oil inlet/exit temperature
WPL Test

- Spin-down at 10,000 rpm (1047 rad/s)
  (i.e. disengage drive motor, clutches, dynamometer)
  10,000 rpm (1047 rad/s) in 2000 rpm increments every 100 seconds
  Record speed vs time
  Repeat 2x for 3 cycles total.

- Oil In:
  100°F (38°C), 125°F (52°C), 160°F (71°C), 180°F (82°C)

- Shroud Config
  U, CS, C36, C1
WPL Calculation

- \( WPL = P_{\text{total}} - P_{\text{gear mesh}} - P_{\text{driveline losses}} \)
- \( P_{\text{total}} = \left( \tau_{\text{system}} [\text{ft-lbf}] \times N[\text{rpm}] \right) \div 5252 \)
  \( \tau_{\text{system}} = I_{\text{system}} \times \alpha_{\text{system}} \)
  \( I_{\text{system}} \) (equivalent inertia for meshed spur gears)
  \( \alpha_{\text{system}} \) via experiment
- \( P_{\text{gear mesh}} \) (estimated via NASA TP 1622, minimal, 1%)
- \( P_{\text{driveline losses}} = \left( \tau_{\text{driveline}} [\text{ft-lbf}] \times N[\text{rpm}] \right) \div 5252 \)
  \( \tau_{\text{driveline}} = I_{\text{driveline}} \times \alpha_{\text{driveline}} \)
  \( I_{\text{driveline}} \) (curved rail method by Genta)
  \( \alpha_{\text{driveline}} \) via experiment
WPL variation with increased oil temp.

- WPL unchanged with increased oil inlet temperature
- Oil flow increased with temperature: 0.73 gpm (2.76 lpm), 0.90 gpm (3.41 lpm), 0.97 gpm (3.67 lpm), 1.05 gpm (3.97 lpm)
- Indicative of WPL sensitivity to oil flow
- WPL unchanged for CS, C36, C1 configs.

![Graph showing windage power loss vs. surface speed]
Baseline Exp. Results on the Effect of Oil Temp. on Shrouded Meshed Spur Gear WPL

- Increase in WPL of ~10x (single vs. meshed)
- More than double
- Possible WPL insensitivity to shrouding (i.e. C36 vs C1) at surface speeds tested
Brg. temp. variation: U configuration

![Diagram showing bearing temperature variation with oil temp. for different configurations.]

<table>
<thead>
<tr>
<th>Input Inboard</th>
<th>Input Outboard</th>
<th>Output Inboard</th>
<th>Output Outboard</th>
</tr>
</thead>
<tbody>
<tr>
<td>T100:IPIB</td>
<td>T100:POB</td>
<td>T100:OPIB</td>
<td>T100:POPB</td>
</tr>
<tr>
<td>T125:IPIB</td>
<td>T125:POB</td>
<td>T125:OPIB</td>
<td>T125:POPB</td>
</tr>
<tr>
<td>T160:IPIB</td>
<td>T160:POB</td>
<td>T160:OPIB</td>
<td>T160:POPB</td>
</tr>
<tr>
<td>T180:IPIB</td>
<td>T180:POB</td>
<td>T180:OPIB</td>
<td>T180:POPB</td>
</tr>
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</table>
Brg. temp. variation: C1 configuration

![Diagram showing shrouded meshed spur gear configuration with oil temperature variation and output bearings](image)

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<td>T100:OPOB</td>
<td>T100:OPIB</td>
<td>T100:OPOB</td>
</tr>
<tr>
<td>T125:IPIB</td>
<td>T125:OPOB</td>
<td>T125:OPIB</td>
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</tr>
<tr>
<td>T160:IPIB</td>
<td>T160:OPOB</td>
<td>T160:OPIB</td>
<td>T160:OPOB</td>
</tr>
<tr>
<td>T180:IPIB</td>
<td>T180:OPOB</td>
<td>T180:OPIB</td>
<td>T180:OPOB</td>
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</tbody>
</table>

Surface speed [m/s] vs. Shaft bearing temperature [°C]

Shroud Configuration: C1
Gear fling-off (GFO) temp. variation

- GFO highest with C1 config.
- 40-50°F (20-30°C) difference at 28,000 ft./min. (142 m/s)
- Nearly identical GFO temps. for C36, CS, and U configurations
- Close clearance shrouds may increase local heating to gear
Summary Points

- At controlled oil pressure at tested oil inlet temperatures:
  - WPL data were identical for the U and CS shroud configurations.
  - WPL data were identical for the C36 and C1 shroud configurations.
  - WPL data (C36 & C1) less than (U & CS) shroud configurations.
  - Potential insensitivity of WPL to shrouding (C36 vs C1) for surface speeds tested.
- Shroud effectiveness may be reduced if oil temperatures and oil flows are not controlled.
- Shrouding appears to limit conductive and convective heat transfer to the surrounding structure:
  - could potentially be used to limit localized heating to the vicinity of the rotating gears.
  - Increased heating to gear (i.e. GFO results) needs to be accounted for.
- Estimates of power savings for optimal rotorcraft shrouding should always be stated, or qualified, for a given temperature and lube flow rate. The study presented herein highlights the importance of these parameters on the effectiveness of a given shroud configuration in reducing gearbox windage losses.
Acknowledgements

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• Robert F. Handschuh
• Sig Lauge
  
  HX5 Sierra, Technical Test Support
APPENDIX
• Helicopter Performance Chart
• Ref: FAA Helicopter Flying Handbook, Chapter 7.
• Torque required for cruise or level flight, Figure 7.3