Experimental Investigation of Shrouding on Meshed Spur Gear Windage Power Loss

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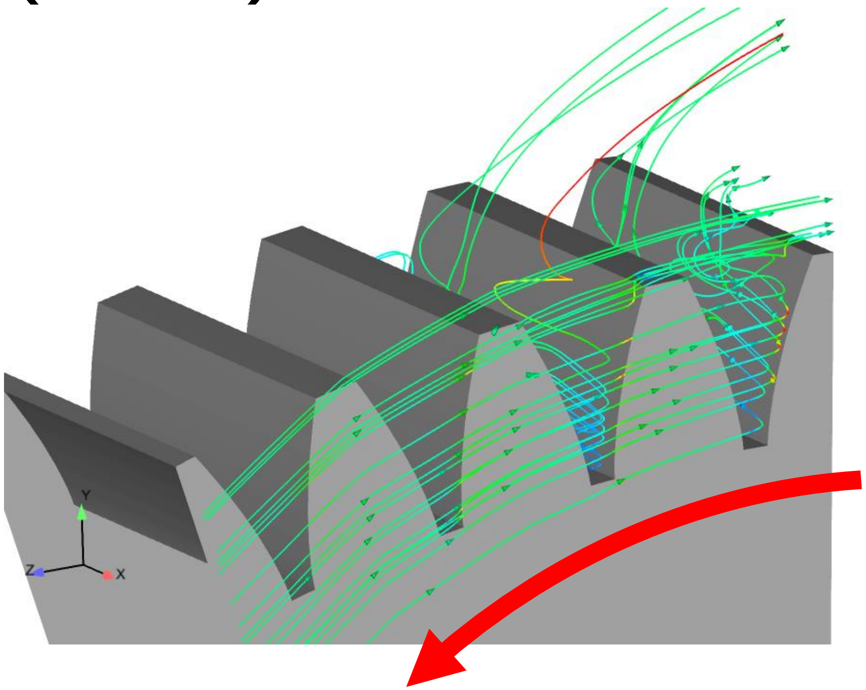
Windage power loss (WPL)

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



Ref:
Hill, Matthew J., et al. "CFD analysis of gear windage losses: Validation and parametric aerodynamic studies." Journal of Fluids Engineering 133.3 (2011): 031103.

Selected Spur Gear WPL Work

- (1984) Dawson: “Windage Loss in Larger High-Speed Gears”
  - single spur gears, air
  - reduction in WPL with shrouding
  - air flow patterns revealed through smoke experiment
- (1998) Lord: “An Experimental Investigation of Geometric and Oil Flow Effects on Gear Windage and Meshing Losses”
  - single and meshed spur gears, shrouding, air/oil
  - controlled lab experiments
  - decrease in WPL with increasing oil temp., increase in WPL with increasing oil flow
- (2011) Combined Analysis & Experimental Validation
  - single spur gear analyses, single phase, shrouding
  - Hill: “CFD Analysis of Gear Windage Losses….”
  - Handschuh: “Initial Expts. of High-Speed Drive Sys. Windage Losses”

Focus of this work

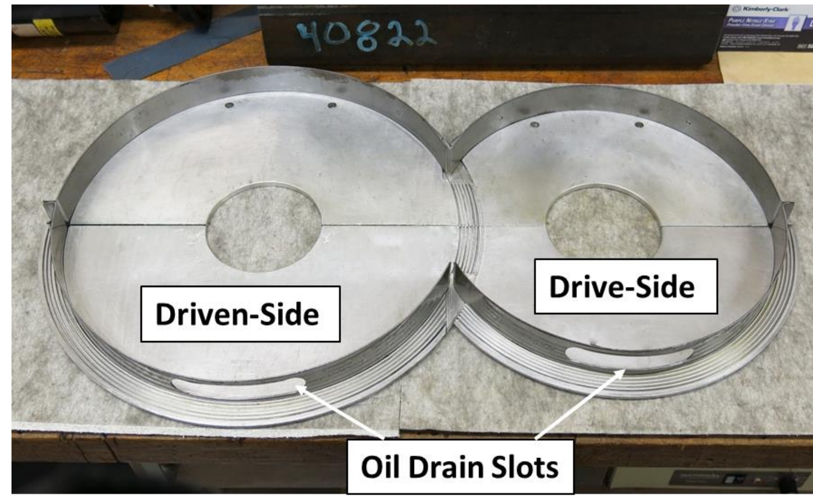
- Obtain baseline WPL experiments on <u>*meshed spur gears*</u>
  - Re-validate use of NASA rig
  - Provide a consistent experimental procedure for robust data
- Compare with literature
  - Single vs Meshed
  - Unshrouded vs Shrouded
- Identify WPL trends, if any
- Outline additional research

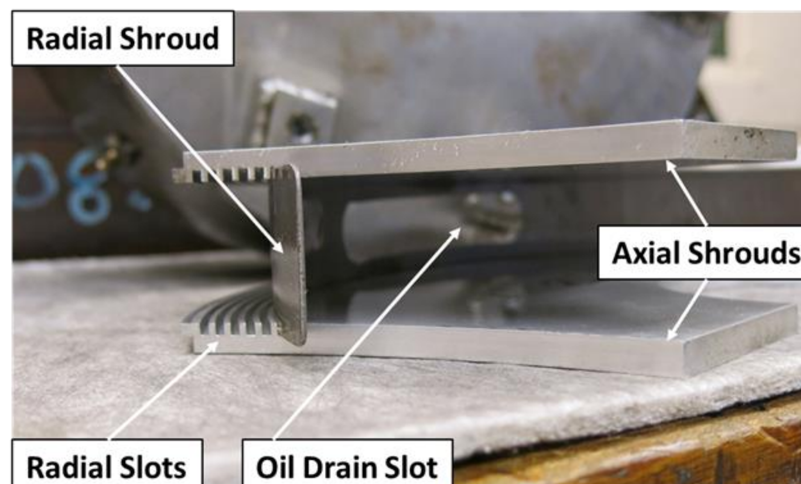
Gear Information

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

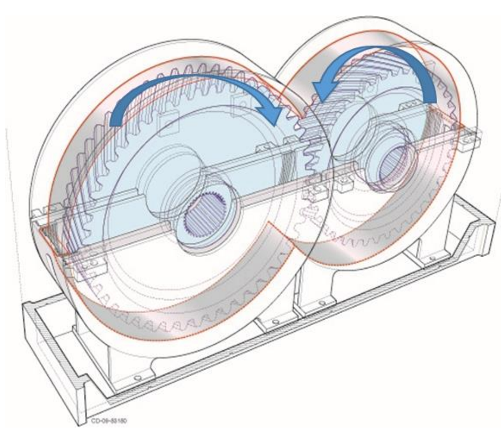
Shroud Information

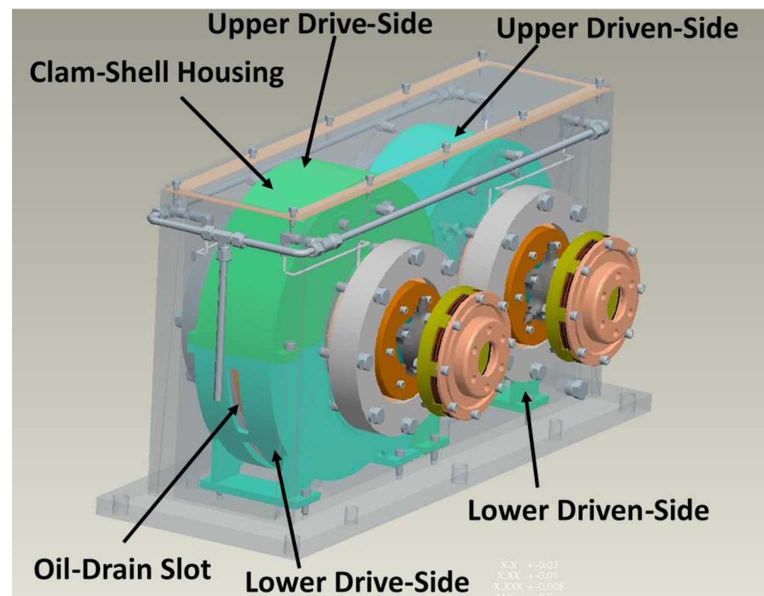
Shroud Config.	Axial Clearance	Radial Clearance	
	Per side [inches]	Drive-side [inches]	Driven-side [inches]
(U) Unshrouded w/o clam-shell housing	2.25	2.5	1.0
(CS) Unshrouded w/ clam-shell housing	1.5	0.82	0.82
(C1) shrouded	0.039	0.039	0.039





Continued - Shrouding





NASA WPL Test Rig

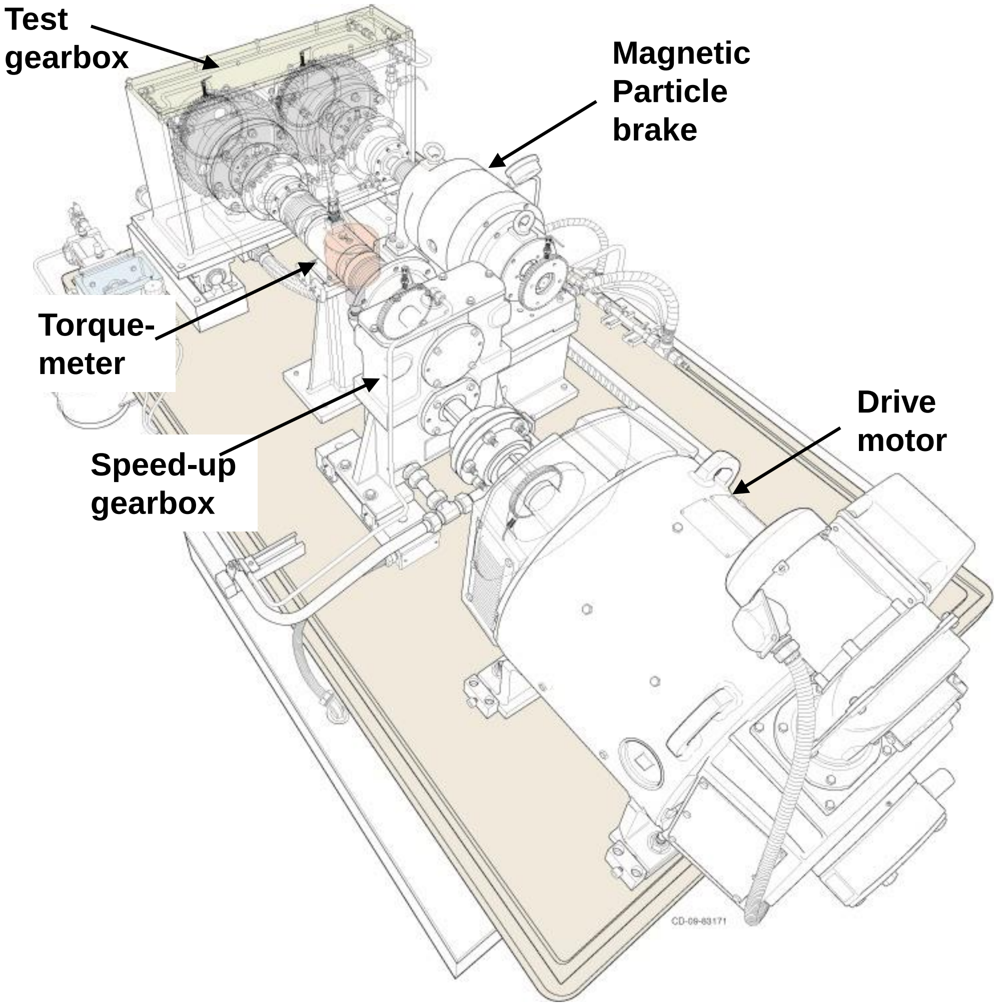
- dc motor: (112 kW (150 hp))
- speed-up gearbox: 5.17:1 ratio
- Eddy-Current Dyno: 100 N-m at 2865 rpm
- torque-meter: 2,000 in-lbs
- Into-mesh lubrication
- Measurements

  shaft speed

  gear fling-off temperature

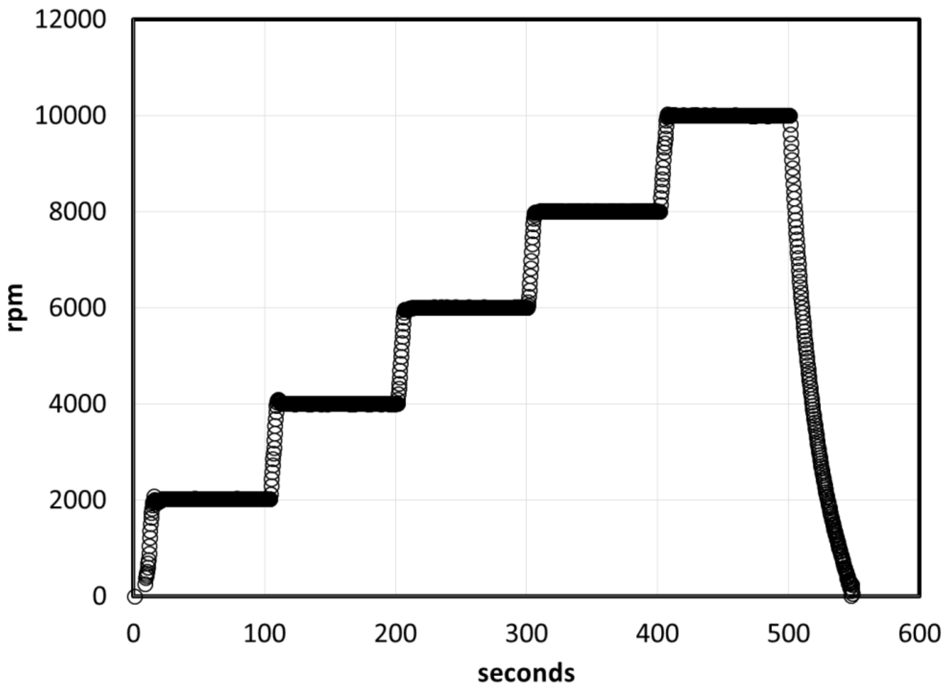
  gear mesh oil flow

  oil inlet/exit temperature



Typical WPL Test

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



Windage Power Loss Calculation

- Total Power Loss = Gear Mesh Loss + Driveline Losses + Windage Losses
- $\tau = I \times \propto$

  Equivalent inertia for meshed spur gear system

  Deceleration (α) calculated from velocity vs. time data

- $P(\text{hp}) = \dfrac{T\,\text{ft}\cdot\text{lbf} \times N\,\text{rpm}}{5252}$
- Subtract Gear Mesh Losses (Ref: Anderson, Loewenthal)

  Minimal

- Subtract Tare (Driveline) Losses

Tare (Driveline) Loss Calculation

- Determine inertia of shaft components minus test gear

  Use curved rail methodology (Ref: Genta)

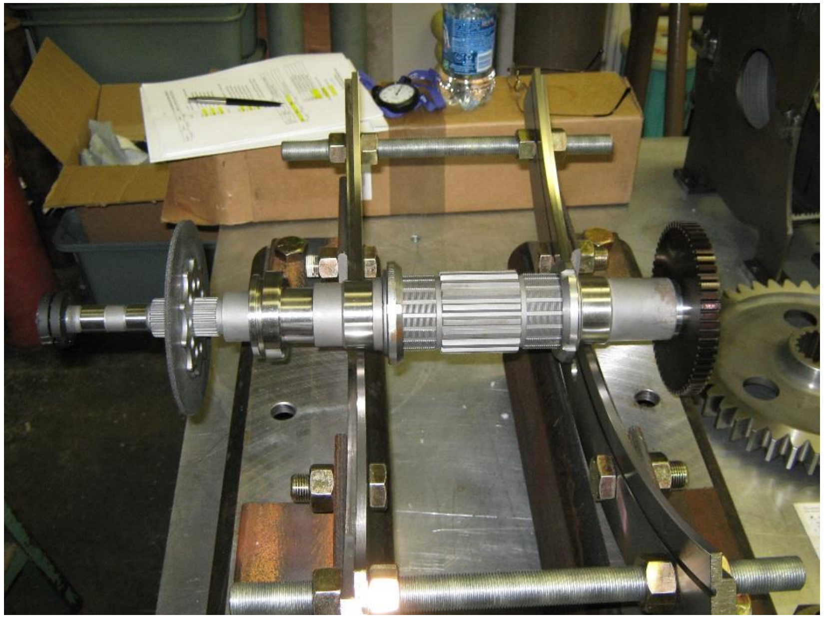
- Conduct shaft only wind-down tests

  Velocity vs. Time curves

- Calculate power loss

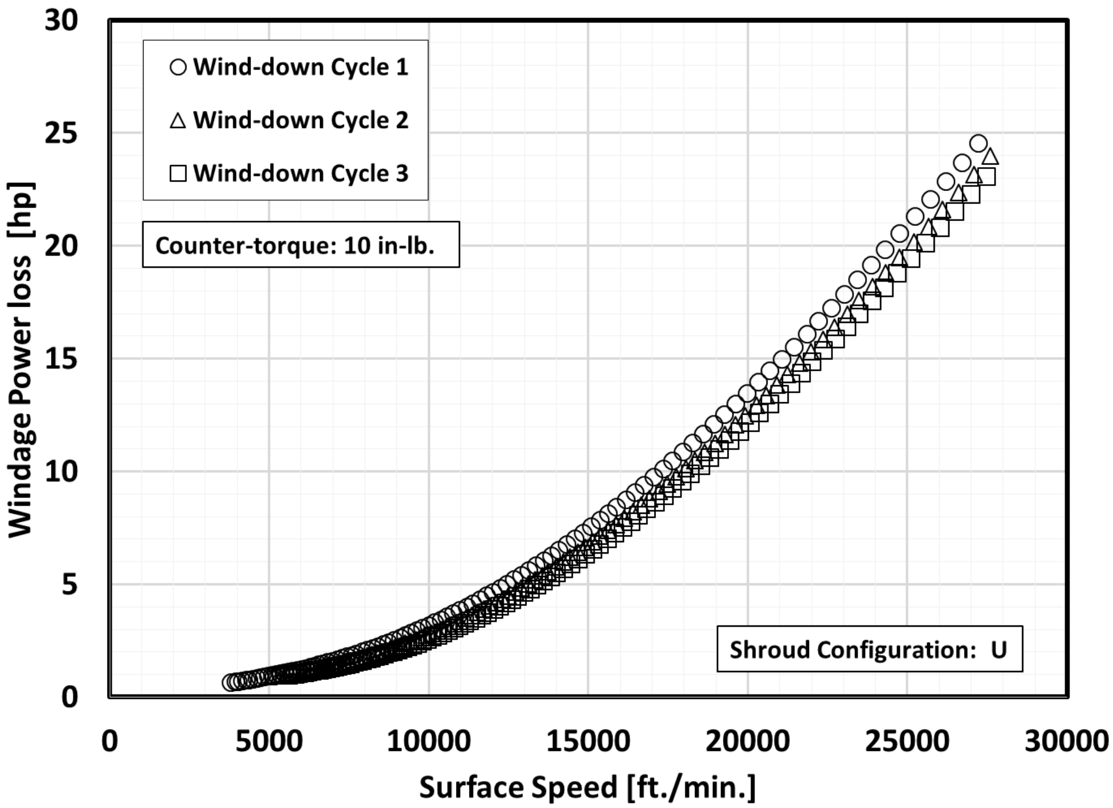
$$\tau = I \times \propto$$

$$P(\mathrm{hp}) = \frac{T\ \mathrm{ft} \cdot \mathrm{lbf} \times N\ \mathrm{rpm}}{5252}$$



WPL Variation – Cycle 1 to Cycle 3

- Unshrouded (U) configuration
- Slight decrease in WPL with increasing cycles



Gear fling off & oil inlet temps. U vs. CS vs. C1 configs.

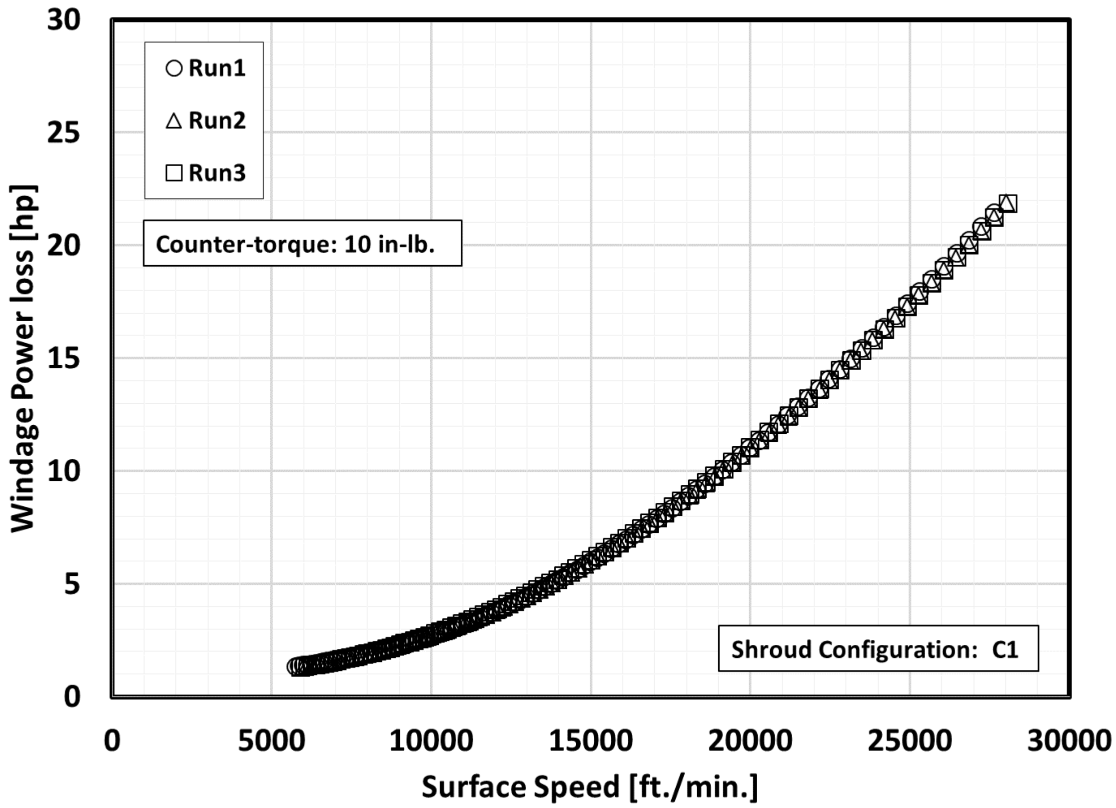
Configuration →	U Run 1	CS Run 1	C1 Run 1	C1 Run 2	C1 Run 3

Wind-down Cycle	instantaneous gear fling-off temperature [°F]				
1	165	171	192	191	194
2	184	187	208	206	210
3	196	199	218	219	222

	oil inlet temperature [°F]				
start of wind-down cycle 1	86	86	92	91	95
end of wind-down cycle 3	101	104	108	106	109

WPL Variation – Run 1 to Run 3

- Test data on 3 consecutive days
- Little variation in WPL for 3rd cycle



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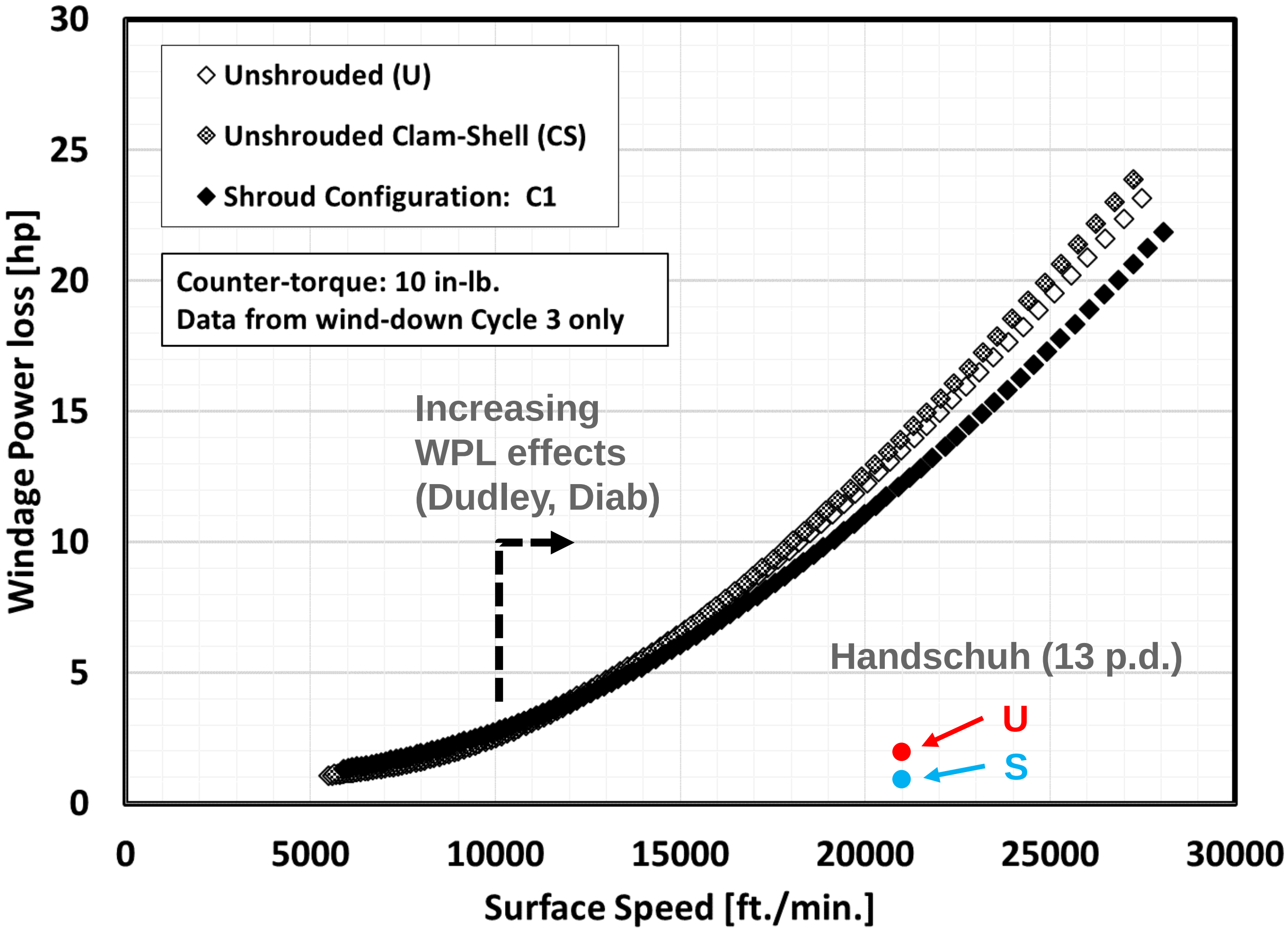
Gear mesh oil flows
U vs. CS vs. C1 configs.

Configuration →	**U**	**CS**	**C1**		
Run →	Run 1	Run 1	Run 1	Run 2	Run 3
	[GPM]				
Cycle 1	0.65	0.68	X	X	0.74
Cycle 2	0.69	0.78	X	X	0.81
Cycle 3	0.75	0.94	0.89	0.87	0.91

WPL - U vs. CS vs. C1 configs.



- 15,000 ft/min
  - No shroud benefit below
  - CS oil drain slots negatively affect WPL above
- Ref. Hill: slotting
- C1 vs U
  - 10% reduction in WPL @ 25,000 ft/min
  - Increasing shroud benefit above 15,000 ft/min
- Handschuh 13 p.d.
  - 7x difference (U)
  - 12X diff. (S)

WPL: Oil Flow vs Oil Temperature

- Sensitivity of oil flow rate and oil temp. w.r.t. WPL?
- Reported: Increased oil flow rate *increases* WPL (Ref. Lord)
- Reported: Increased oil temp. decreases oil viscosity, *decreasing* WPL (Ref. Lord)
- Need to separate effects in a future study

Summary Points

- Demonstrated experimental repeatability.
- Observed: Increased shrouding effectiveness above 15,000 ft./min.
  - Windage power loss more pronounced above 10,000 ft./min.
- Observed: C1 shrouding results in 10% drop in windage power loss at 25,000 ft./min. compared to U configuration
  - C1 drain holes offset WPL reduction at 25,000 ft./min.
  - In general: oil drain holes may offset gains in shrouding.
- 7x increase in WPL
  - Comparison to Literature: unshrouded single vs. unshrouded meshed
- 12x increase in WPL
  - Comparison to Literature: shrouded single vs shrouded meshed

Follow-up Studies

- Sensitivity of windage power loss on oil temperature and oil flow
- Axial vs. Radial shroud effectiveness
- Oil drain slot size, #, location vs. shrouding effectiveness
- Shroud effectiveness at higher surface speeds.
- Sources for more than doubling of windage power loss comparing single versus meshed spur gear in both unshrouded and shrouded configurations.

Acknowledgements

- NASA Revolutionary Vertical Lift Technology Project
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  HX5 Sierra, Technical Test Support