National Aeronautics and Space Administration

HX5 SIERRA JOINT VENTURE

The Jetting Phenomena in Meshed Spur Gears

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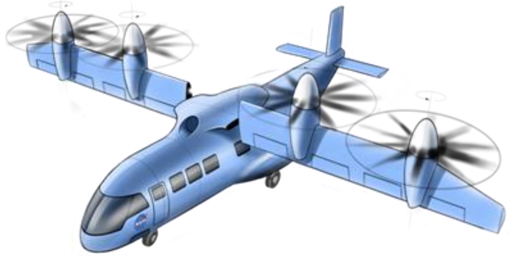


Acknowledgements

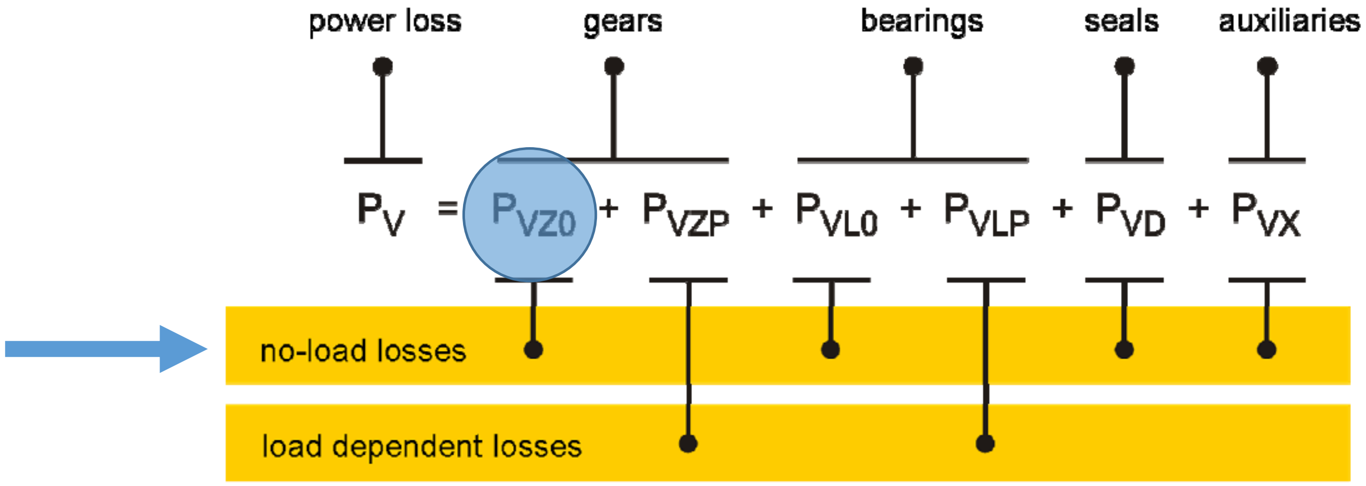
- NASA Revolutionary Vertical Lift Technology (RVLT) Project
- Dr. Robert F. Handschuh (NASA)
- Sig Lauge (HX5 Sierra, Technical Test Support)

Topics

- Gearbox Efficiency and Windage Power Loss (WPL)
- Summary of NASA shrouded WPL experiments
- Jetting phenomena in the literature
- Pocketing analysis
- An improved shrouded test configuration
- Conclusions

Gearbox Efficiency & Power Losses

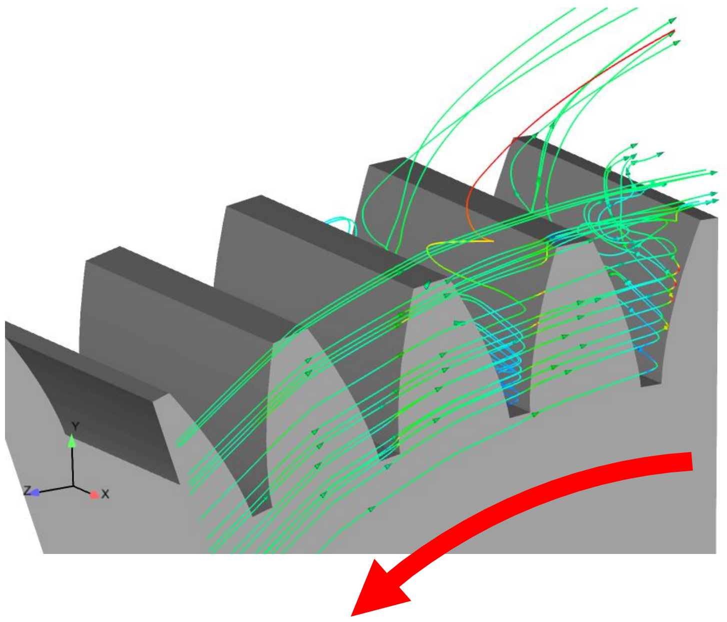
- Mechanical efficiency (load dependent)
- Bearing, shaft losses (load dependent)
- Current talk concerned with windage losses (load independent)



Hohn et. al, Optimization of gearbox efficiency, 2009.

Windage Power Loss (WPL)

- Definition
  - Drag on gear
  - Viscous drag on gear faces
  - Air/oil impingement on tooth surface (inertia effects)
- Category
  - Load-independent, spin-loss
- Significance
  - Pitch-line velocities greater than 10,000 ft./min. (51 m/s)
  - Gearbox efficiency losses
  - Reduced rotorcraft performance (i.e. payload, range)
- Shrouding may mitigate WPL



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

Highest Surface Speeds at the Input Shaft

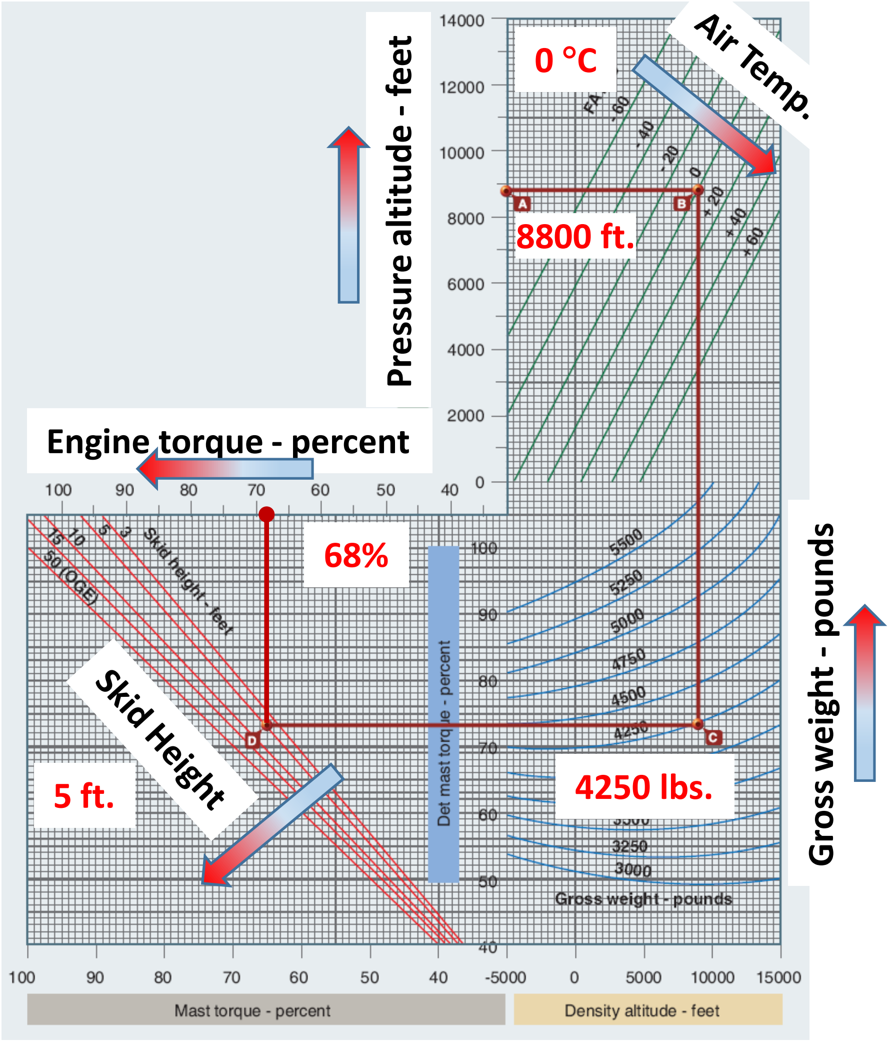
OH-58: ~35,000 rpm
~20,000 ft/min (pitch-line velocity)

UH-60: ~20,000 rpm

AH-64: ~20,000 rpm

Engine Torque versus Altitude

- Helicopter Performance Chart
  FAA Helicopter Flying Handbook
  Chapter 7, Fig. 7.3
- Torque required for cruise or level flight
- Available engine torque (e.g. 2-3%) can affect altitude, gross weight, skid height



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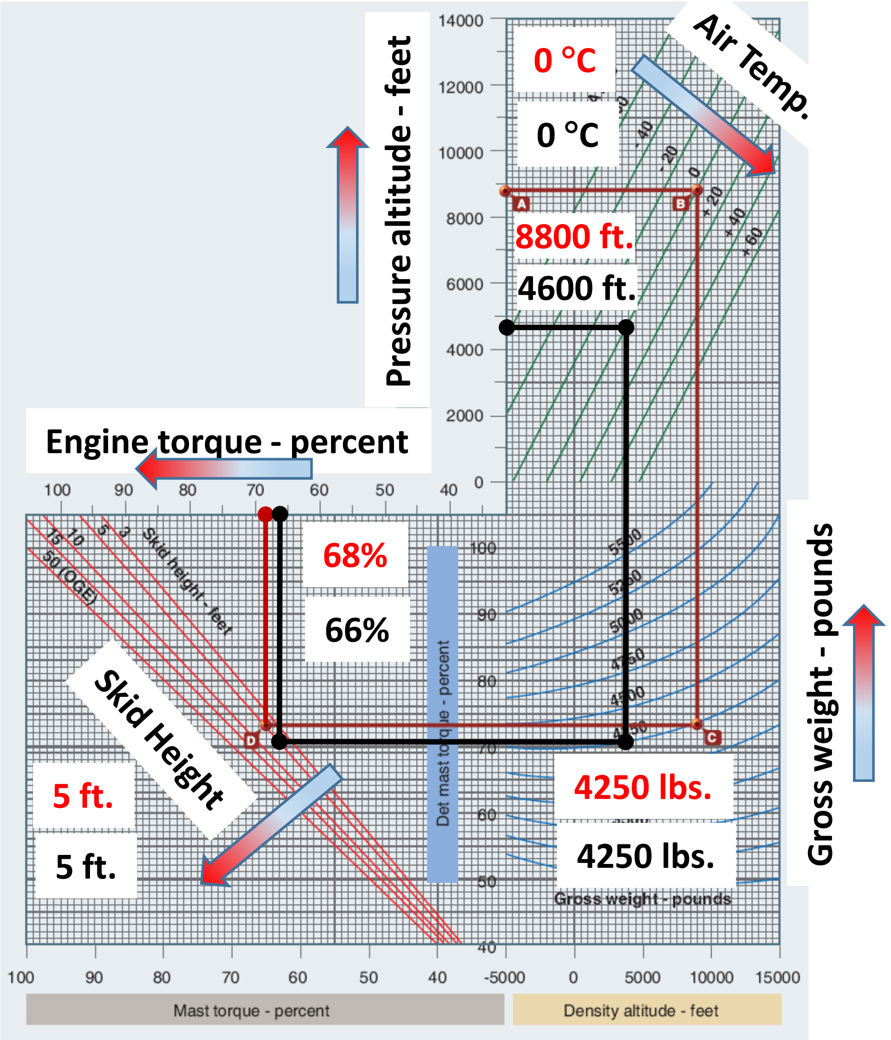

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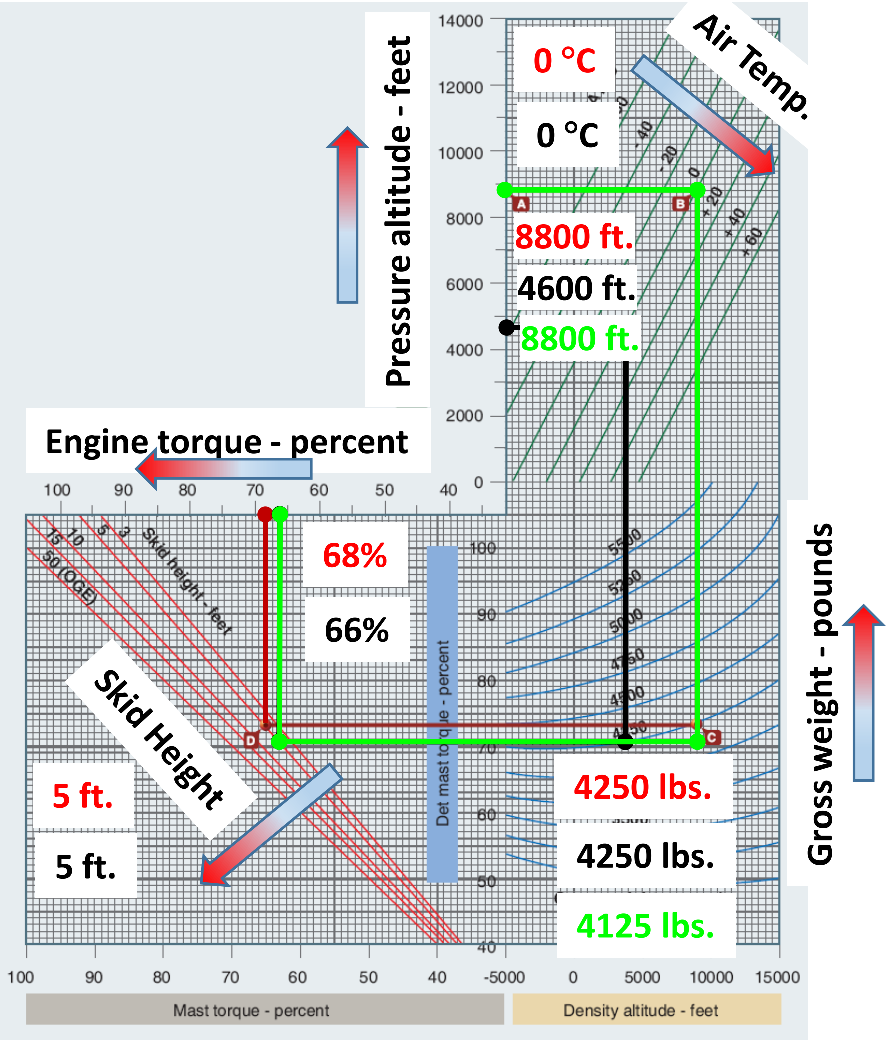

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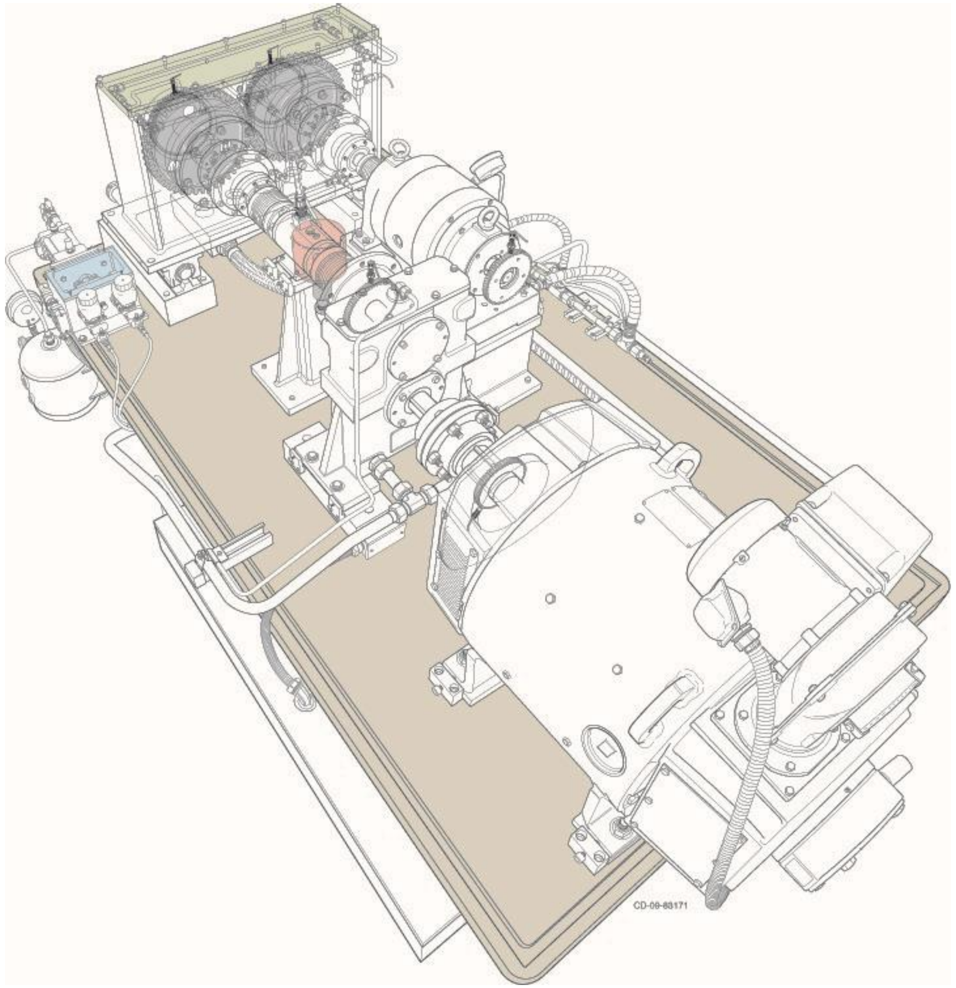
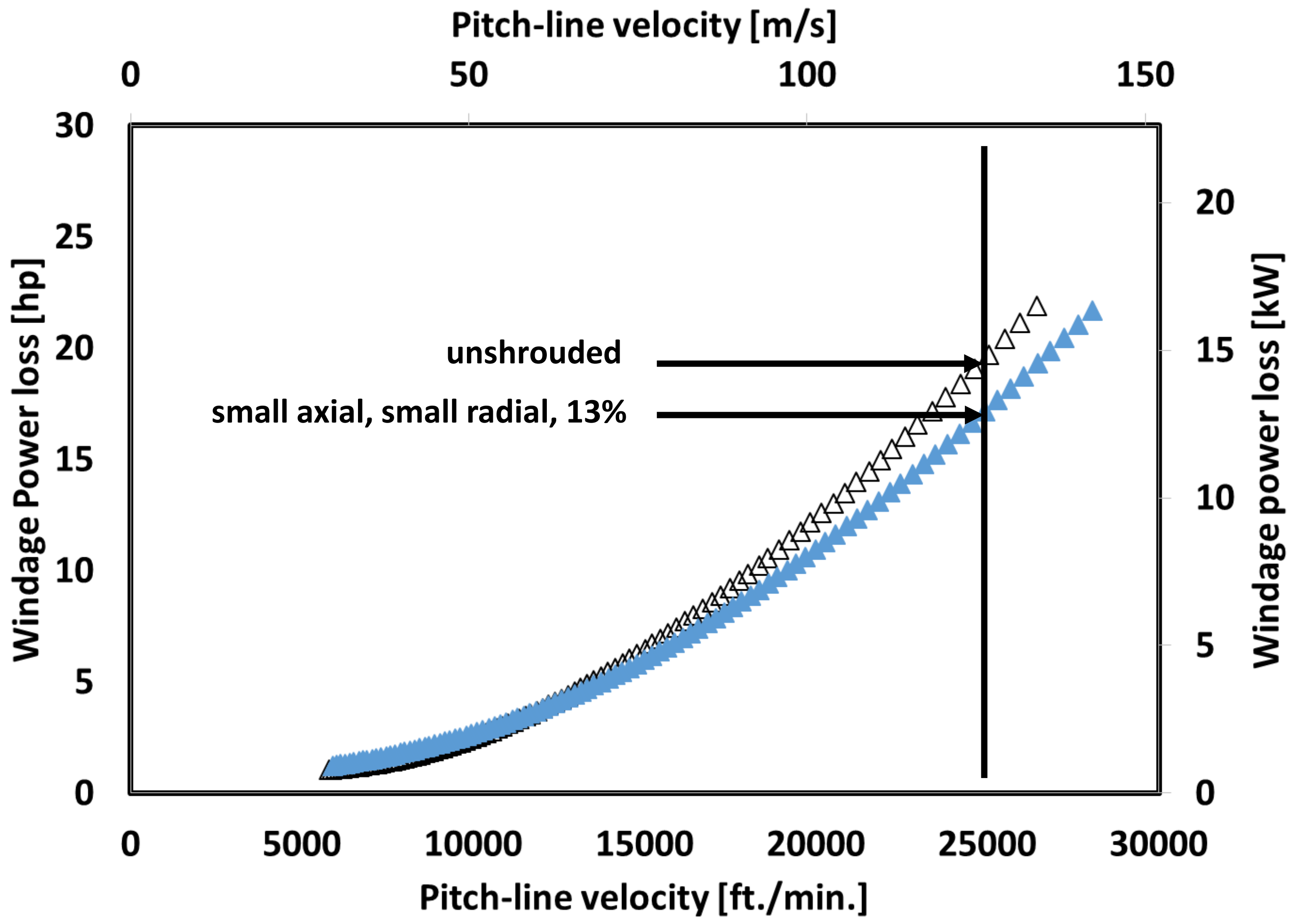
NASA Glenn Windage Power Loss Research





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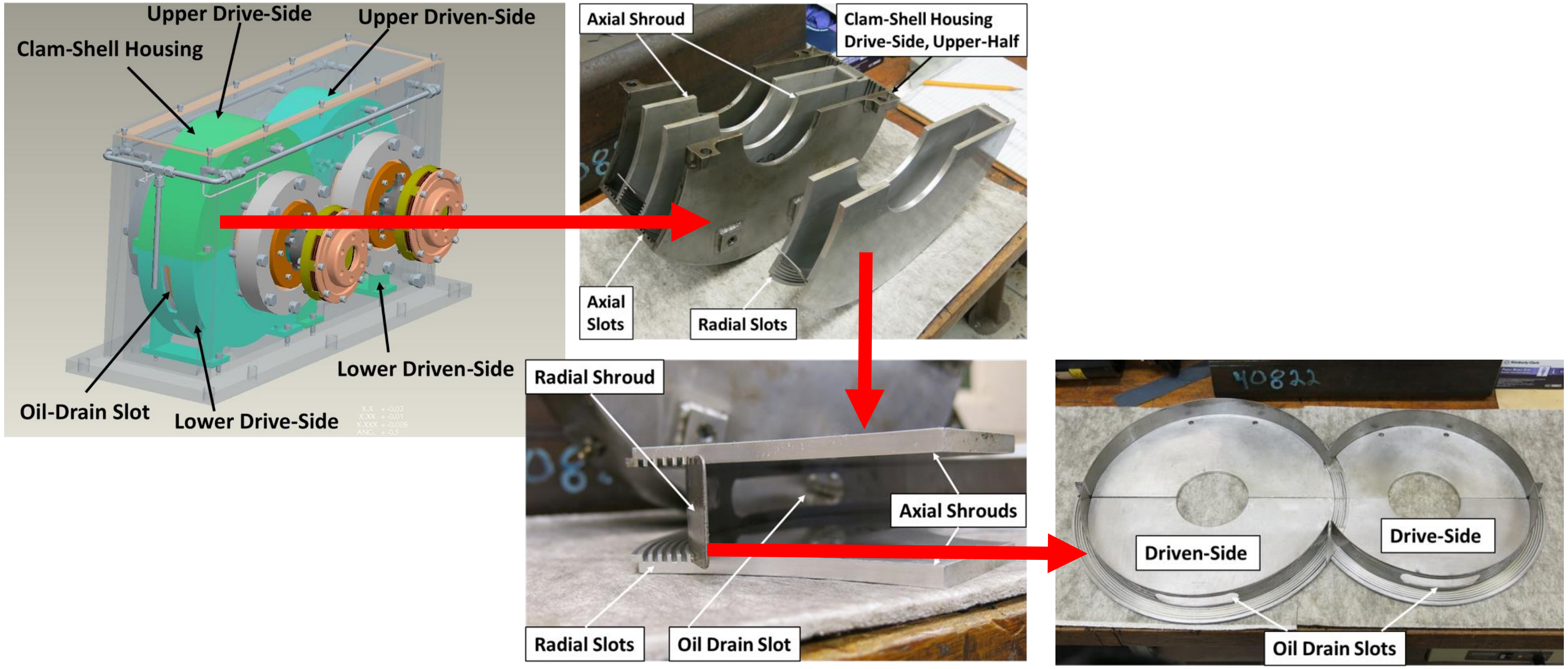

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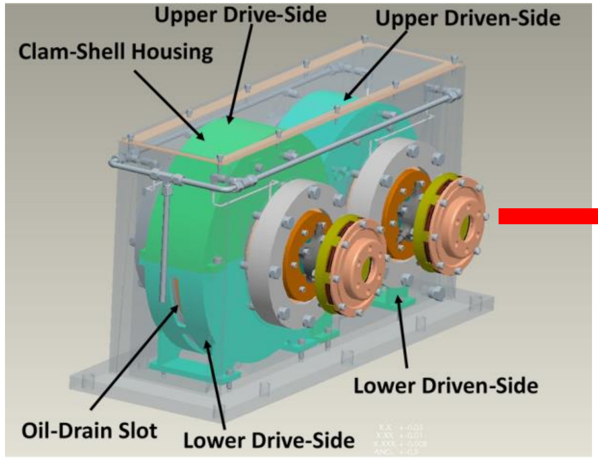
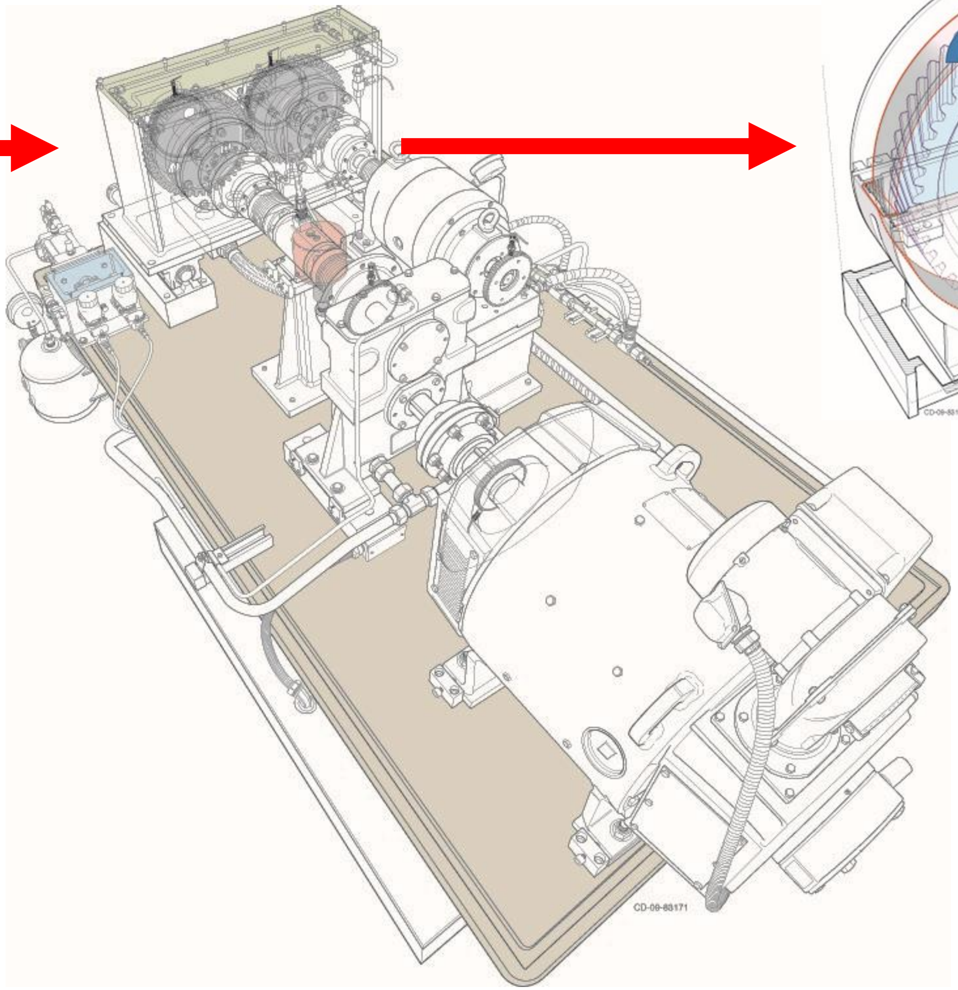
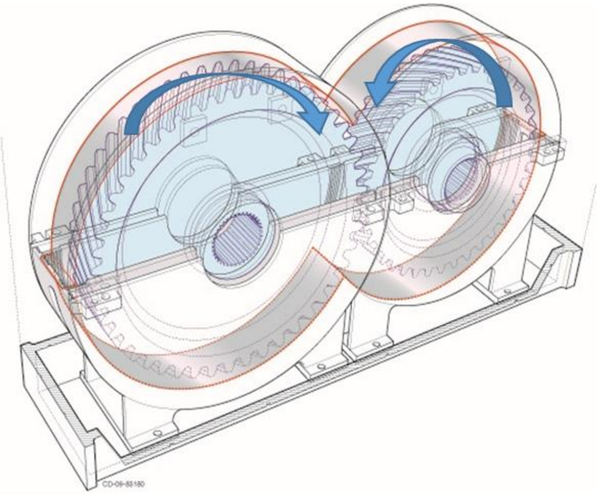
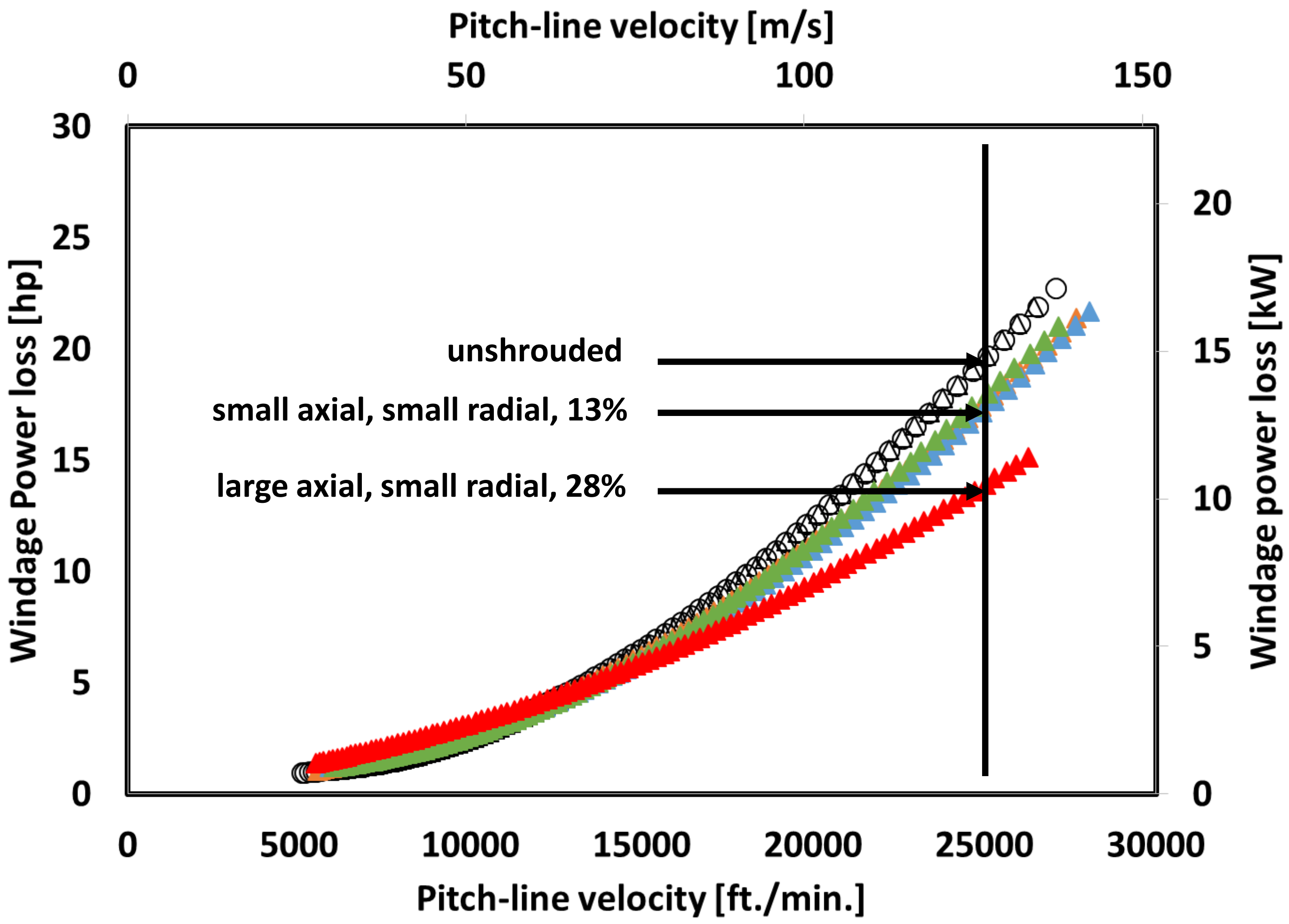






An Unexpected Result



Delgado, I., and Hurrell, M., 2017, "The Effectiveness of Shrouding on Reducing Meshed Spur Gear Power Loss – Test Results," AGMA Fall Technical Meeting, Columbus, Ohio

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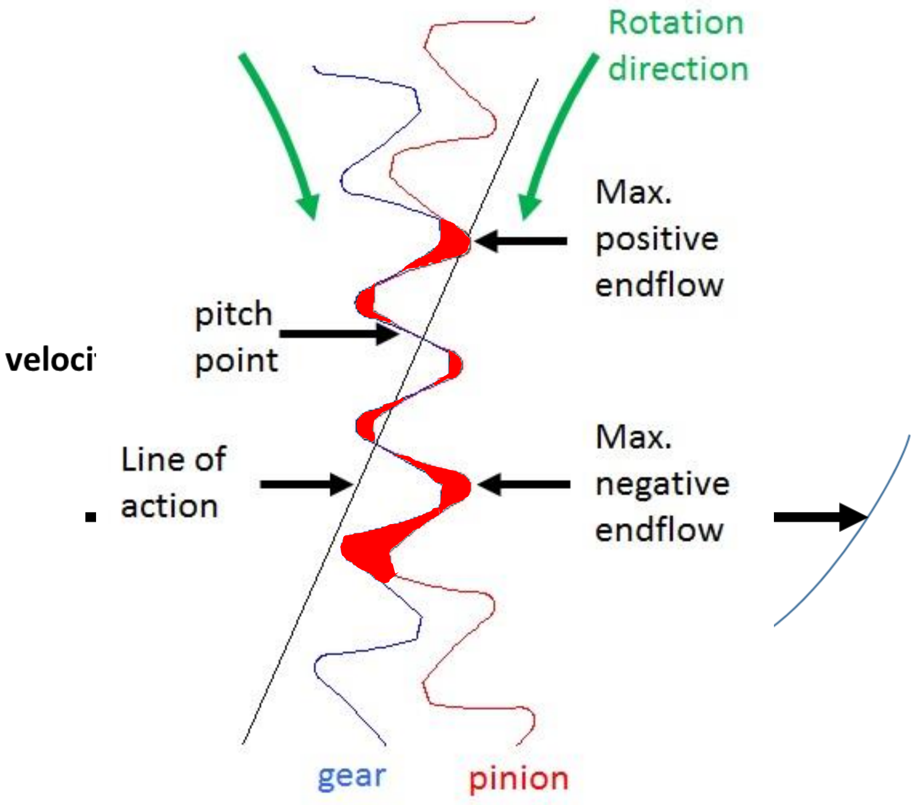
Literature on Jetting

- Data from 1960s to present
  - Analytical closed form, CFD
  - Pressure measurements, PIV
- Pocketing Losses (aka trapping, squeezing)
  - Compression followed by acceleration of the fluid
  - Fluid discharge axially and via backlash
- Discharge velocity may reach sonic conditions
  - Occurs prior to the pitch point
  - Dependent on geometry and speed
- Axial discharge then suction during meshing cycle
  - Volumetric compression followed by expansion
  - Rosen (1961), Diab (2004), Seetharaman (2010)
- Jetting
  - Axial discharge due to air/oil compression
  - Possible sonic conditions
  - Narrow faced- gears



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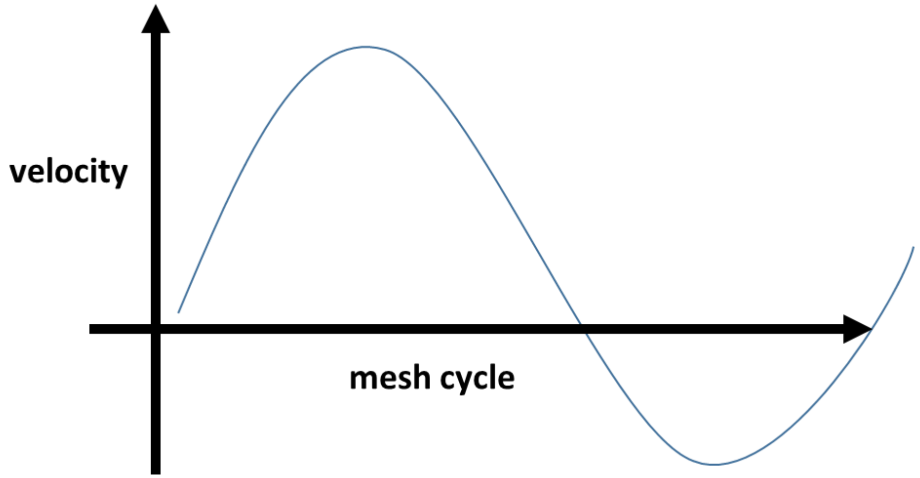

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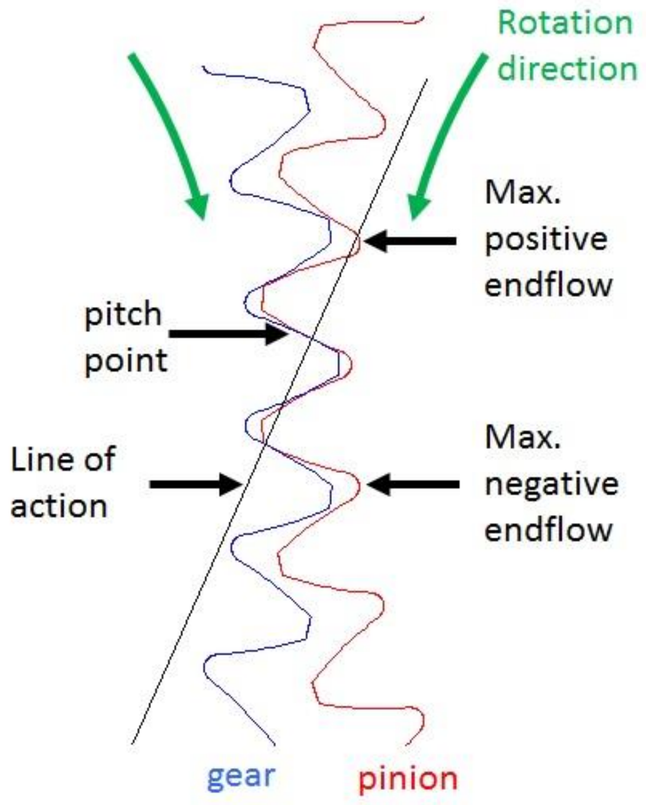

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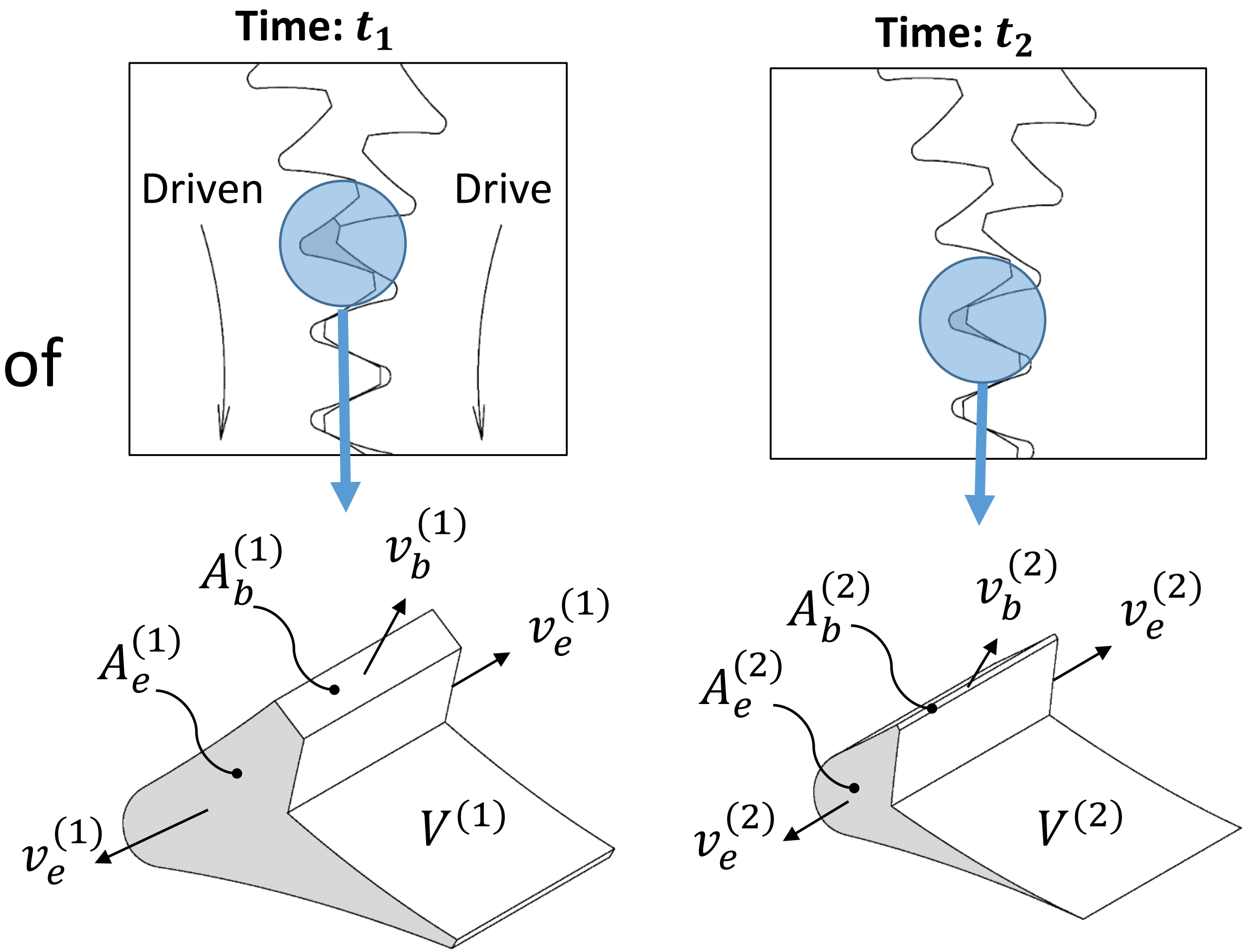
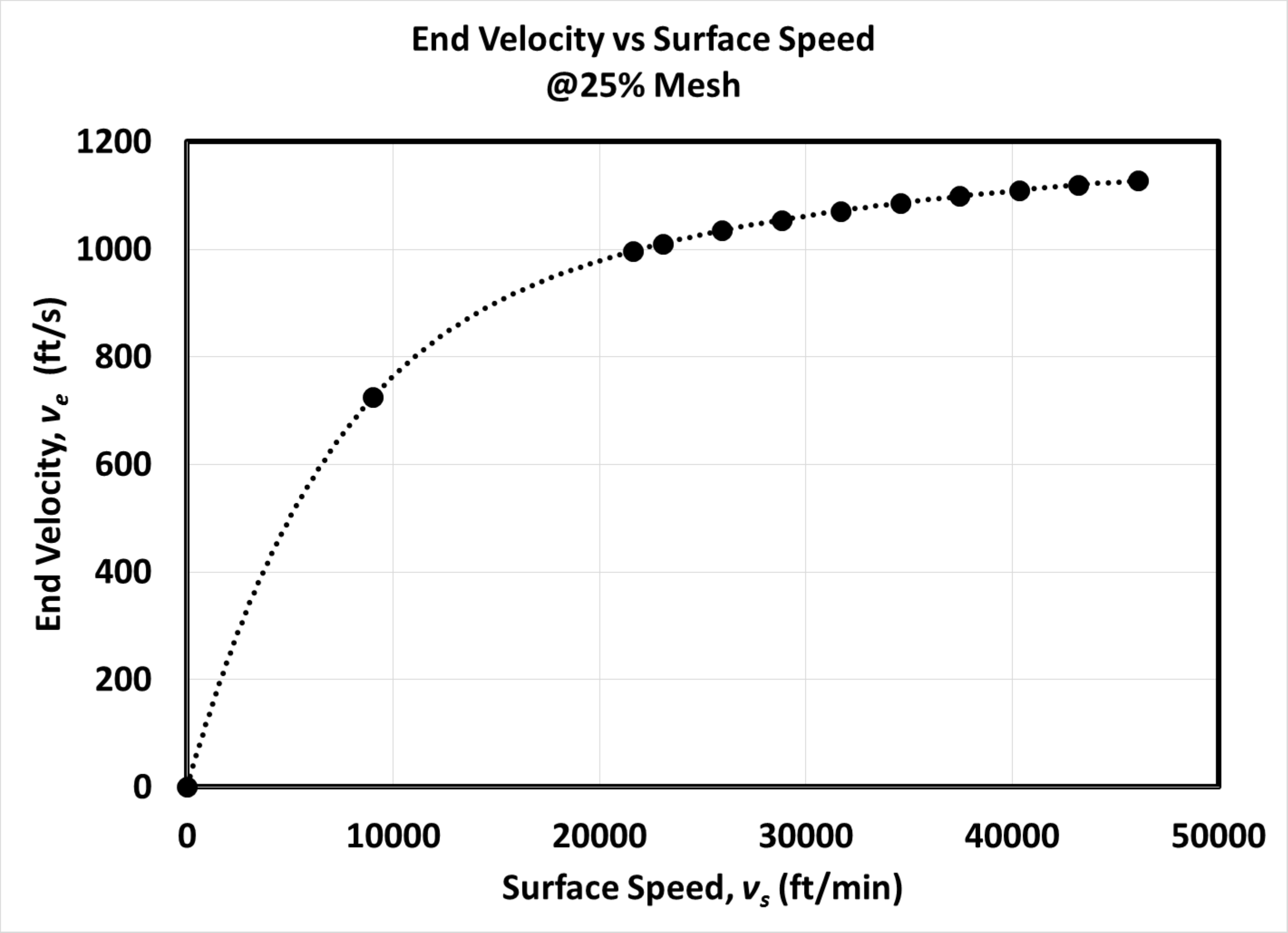
End Velocity Calculation

- Conservation of mass
- Control volumes described at times t_1 and t_2
- End velocity, v_e, as a function of volume, density, area, surface speed, gear radius



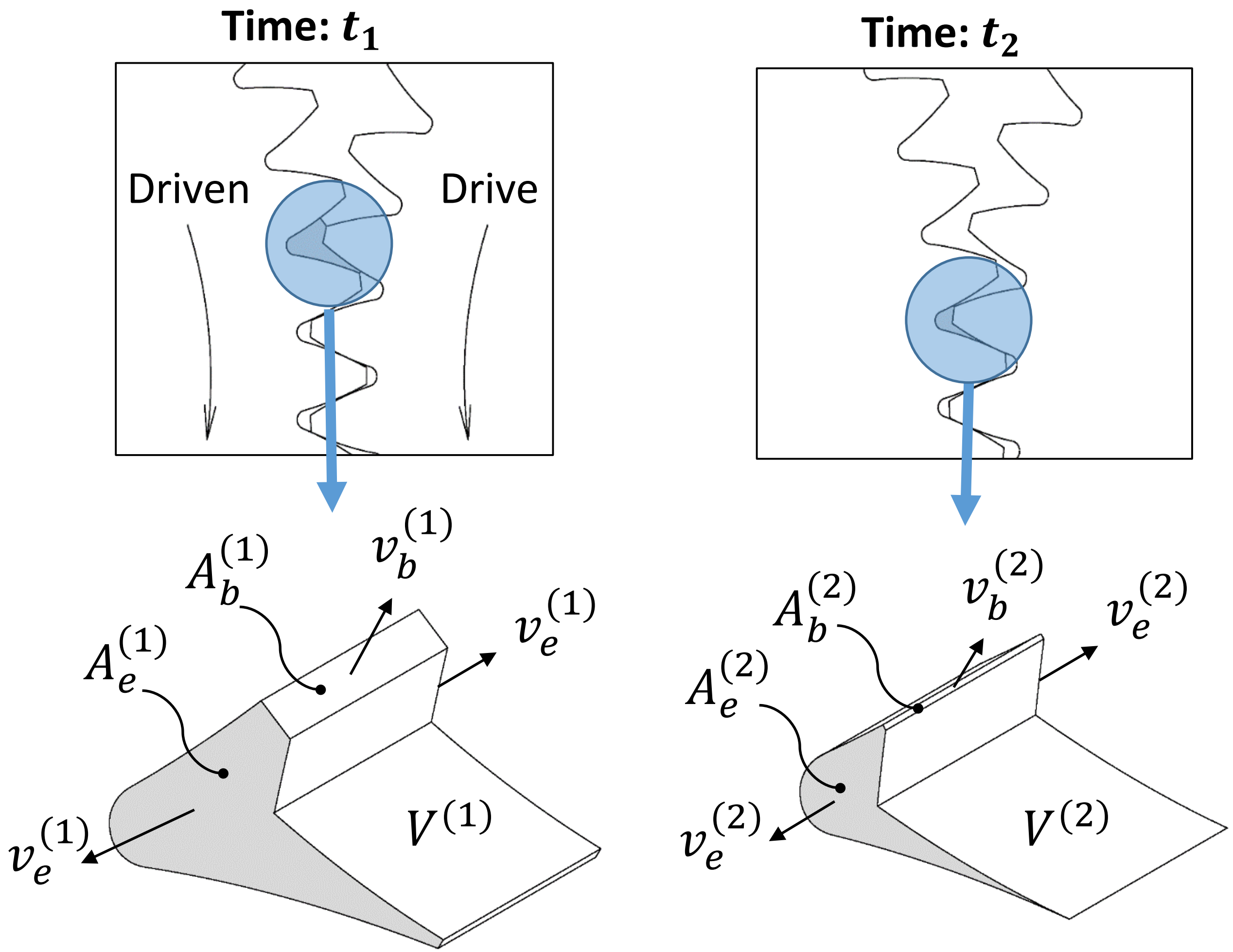
End Velocity vs Surface Speed



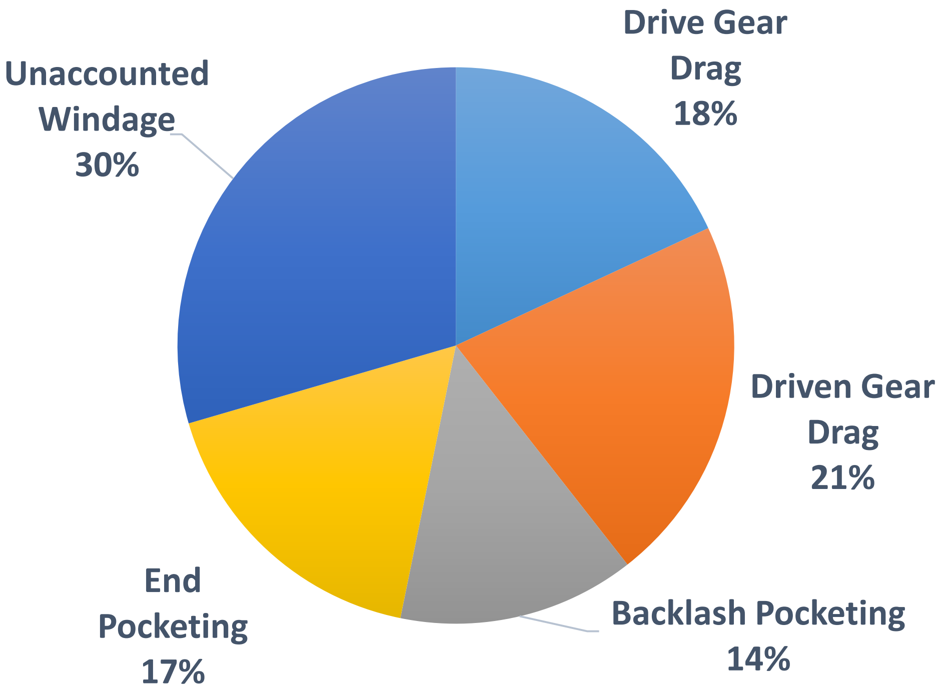
- The pocketing power loss due to axial jetting varies with the end velocity cubed and for high pitch line velocities, the end velocity can approach the speed of sound

Pocketing Power Loss Calculation

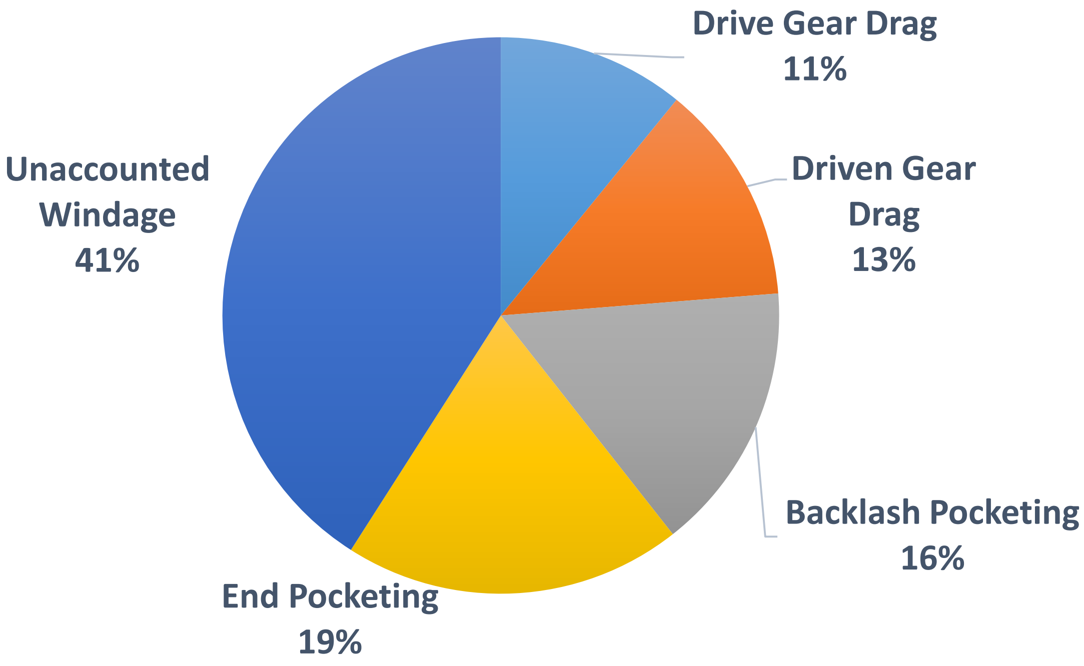
- Conservation of momentum
- $P_{\text{windage}} = P_{\text{pumping}} + P_{\text{drag}}$
- $P_{\text{drag}} \rightarrow \; P_{\text{drag1}}, P_{\text{drag2}}$
- $P_{\text{pumping}} \rightarrow \; P_{\text{ends}}, P_{\text{backlash}}$



Meshed Spur Gear Windage Losses at 25,000 ft./min. pitch-line velocity



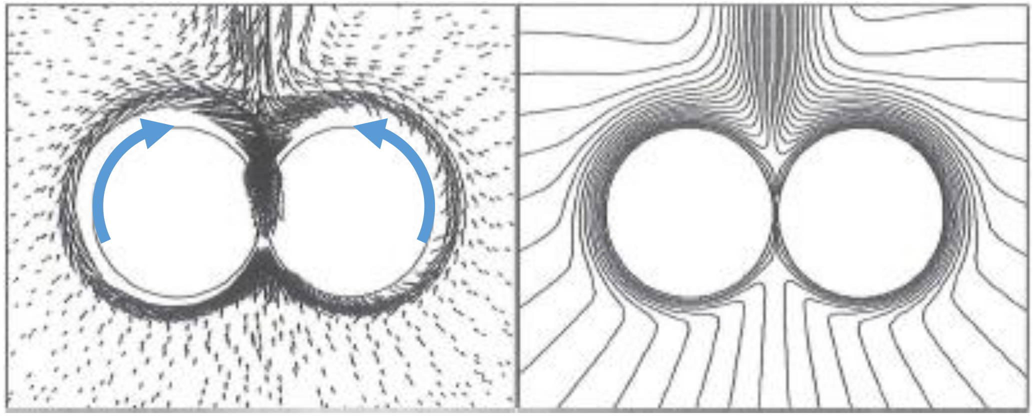
Unshrouded configuration



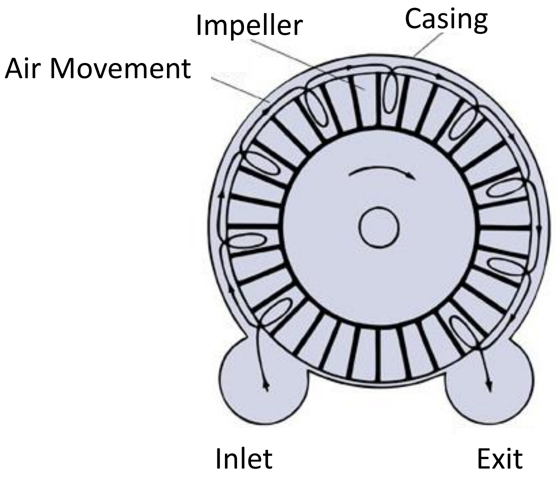
Min. axial, min. radial shroud configuration

Additional windage terms to investigate

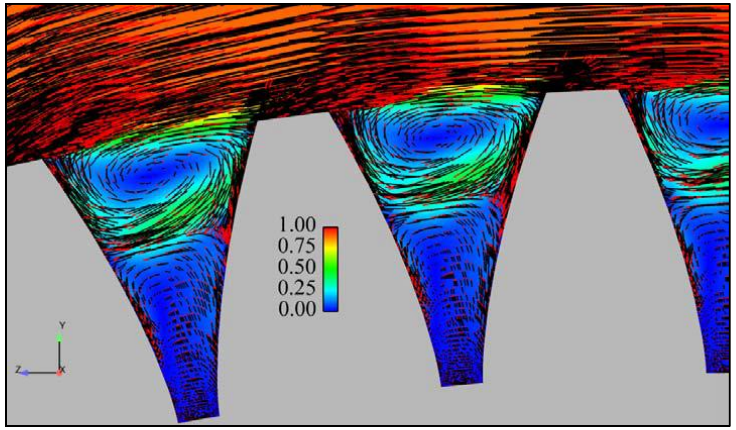
- $P_{windage} = P_{pumping} + P_{drag}$
- $P_{drag} \rightarrow P_{drag1}, P_{drag2}, P_{d12}$
- $P_{pumping} \rightarrow P_{ends}, P_{backlash}, P_{s}$



Wood, Graeme Brendon. "The quantification of airflows generated by rotating rollers in wool carding machines." (2001).



Engeda, A., and M. Raheel. "Theory and design of the regenerative flow compressor." Proc. International Gas Turbine Congress–TS050. 2003.



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Shroud Guidelines

- Applicable for pitch-line velocities greater than 10,000 ft/min.
- Avoid recirculation of the air/oil mixture in the meshing region.
- For spur gears, allow for a means of the fluid flow to exit the meshing region in the axial direction.
- Allow lubricant to cool, lubricate, and quickly exit the meshing region

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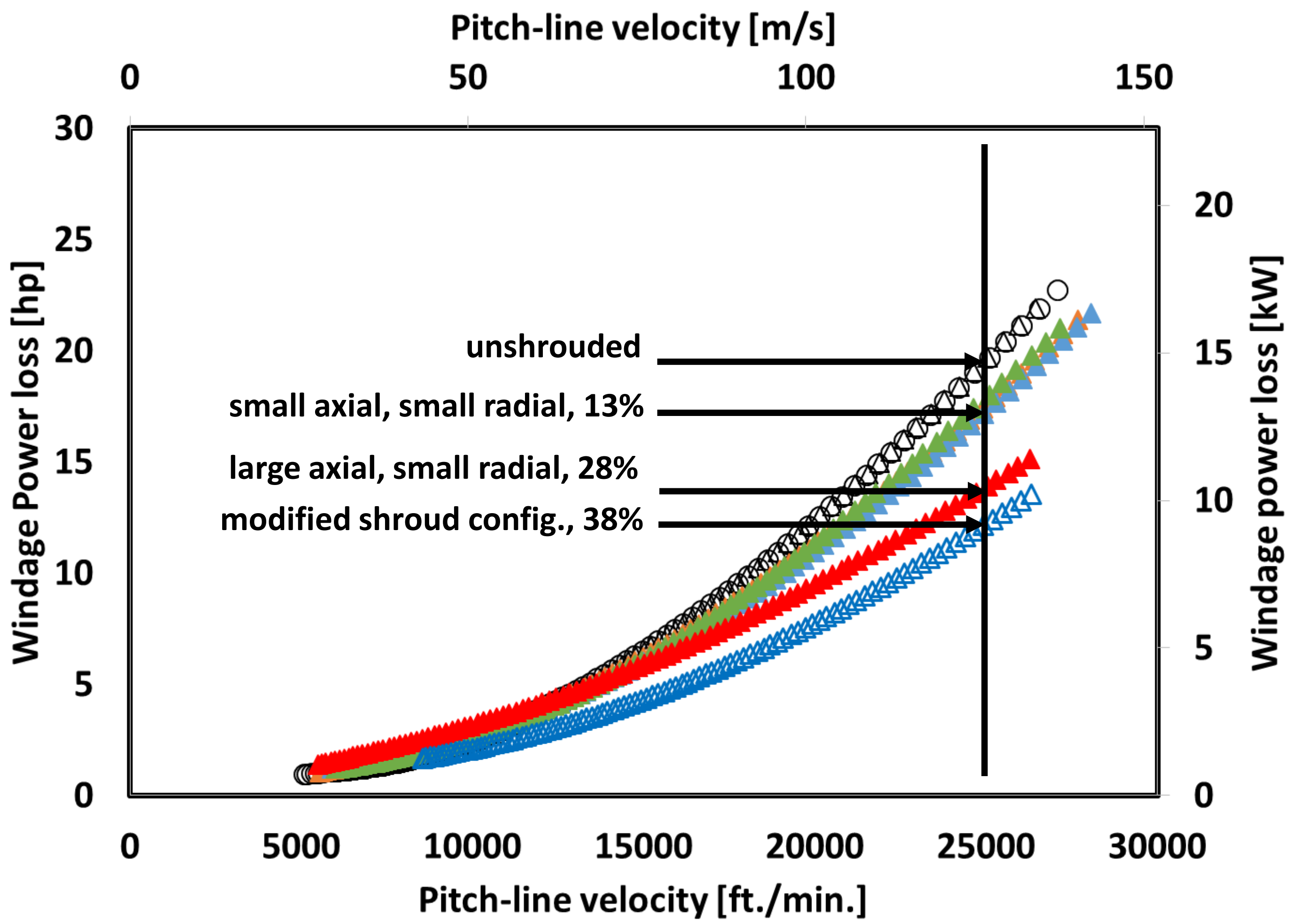
Results: Modified Shroud Test



Conclusions

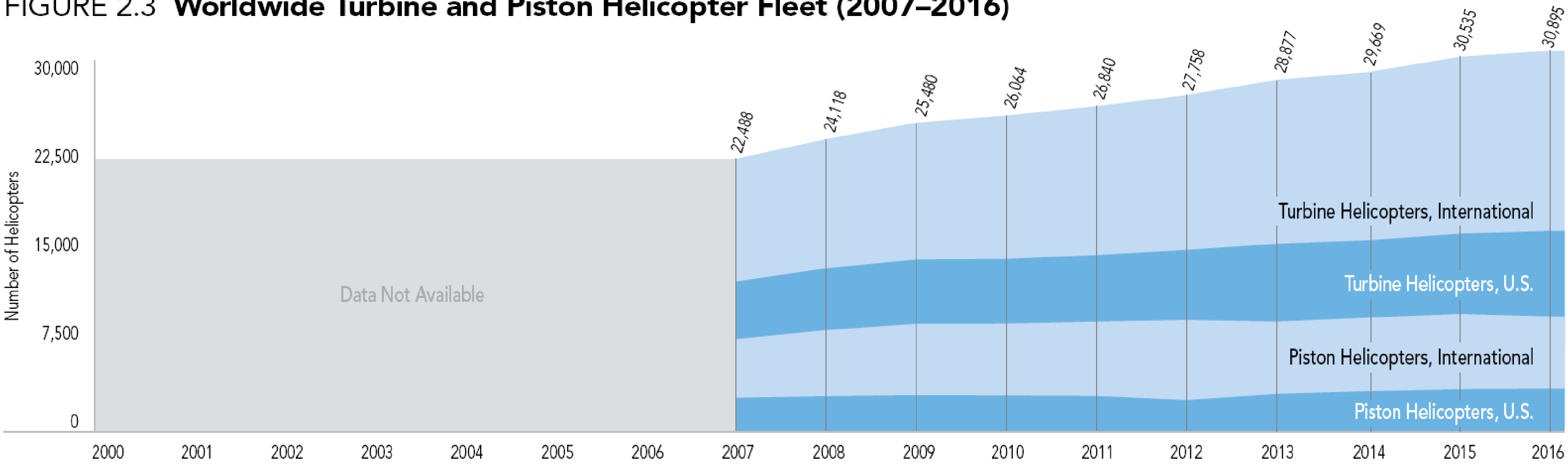
- Windage power losses (WPL) affect gearbox efficiency and rotorcraft performance
- Shrouding has been shown to reduce WPL
- Meshed spur gear axial jetting (near sonic conditions) are an additional source of WPL
- Analyses indicate additional secondary and drag interaction windage losses on meshed spur gears
- At 25,000 ft/min, the modified shroud test showed a 38% decrease in WPL relative to unshrouded conditions.
- Understanding the component mechanisms of windage power loss is critical for the high speed gear trains of modern rotorcraft applications

Questions?

Appendix

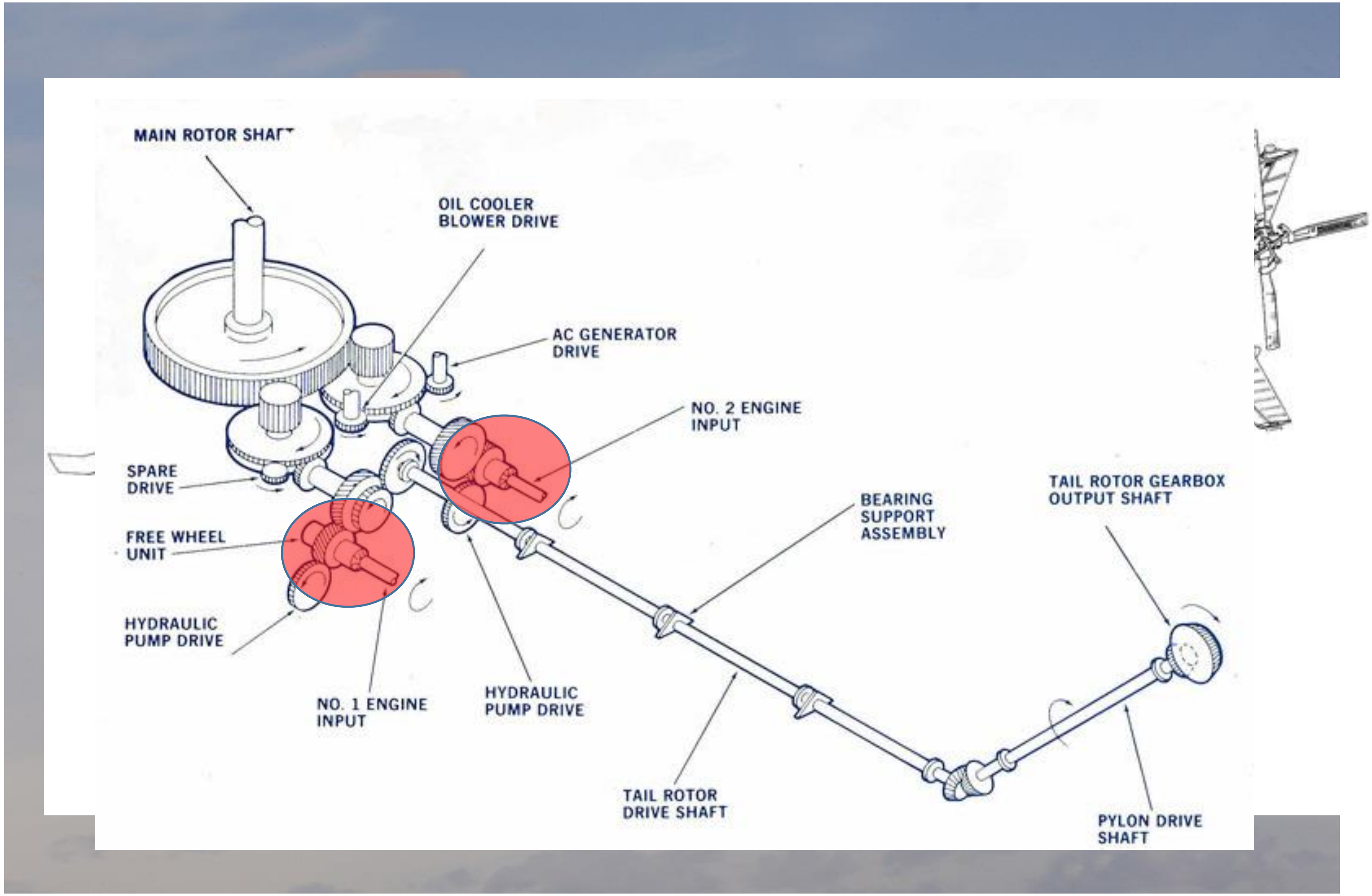
Turbine Helicopter Fleet

FIGURE 2.3 **Worldwide Turbine and Piston Helicopter Fleet (2007–2016)**



Source: JETNET LLC; www.JETNET.com

Input Shaft Location



Further Work

- Quantify pressure and velocity at mesh region
- Explore feasibility of CFD models
- Explore feasibility of flow visualization studies