Background on GearLab

- GearLab was established nearly 30 years ago as an industrial consortium.
- It is the largest university research group in US focusing on gear research.
- Over 150 graduate degrees have been granted in the field of gear and power transmission technology.
- Two industrial short courses on gears have been offered to over 1500 engineers.
- Current sponsor base includes more than 50 companies and government agencies.
- Yearly research expenditures of GearLab exceed $1.5 million.
- GearLab staff consists of:
  - 2 Professors and an Adjunct Professor
  - 2 Full-time Research Engineers
  - 4 Post-doctoral Fellows
  - 15 Graduate Research Associates (7 Ph.D. and 8 MS)
  - 1 Visiting Scholar
## Research Goals

- **Increase Power Density**: Maximize the power transmitted by a gear system without penalizing other functional requirements such as QRD, noise and cost.

- **Improve Reliability**: Increase product life and minimize warranty incidents.

- **Reduce Noise**: Deliver quiet gear products.

- **Improve Efficiency**: Minimize the efficiency losses.

- **Reduce Cost**: Reduce product cost to deliver competitively priced products having exceptional value.
Funding Mechanisms

**Gear Research Consortium**
- 2 full-time staff engineers
- 7-10 Graduate assistants
- 55 Member companies

**Individual Research Projects**
- Several other professors
- Sponsored by a single company
- 1-3 year projects
- Performed by Graduate Students

**Consulting, Design and Test Projects**
- Sponsored by a single company
- Short term projects
- Performed by staff engineers

**P&W Center of Excellence in Gearbox Technology**
- Sponsored by Pratt & Whitney
- 5-year project portfolio
- Performed by staff engineers, post-docs and graduate assistants
## Current GearLab Sponsors (2009)

### Automotive
- Allison Transmission
- **American Axle & Mfg**
- ArvinMeritor
- Chrysler
- Cummins
- Dana
- Dymos
- Fiat (CRF)
- Ford
- **General Motors**
- Getrag-Ford
- GM Powertrain Europe
- Graziano Trasmissioni
- Hyundai Motor Company
- Magna Powertrain
- **Mazda**
- McLaren Performance Tech.
- Tremec
- Wia America

### Trucks / Agricultural
- AGCO
- Caterpillar
- Eaton
- John Deere
- **Komatsu**
- Mack Trucks
- Scania
- Volvo Powertrain
- Wind Turbines
- Cincinnati Gearing Systems
- GE Transportation
- GE Wind Energy
- Nat. Renewable Energy Lab
- Ricardo
- Romax
- Timken

### Aircraft
- Avio
- Honeywell
- Moog
- **Pratt & Whitney**
- Rolls Royce
- **Sikorsky Aircraft**

### Manufacturing
- Gleason Works
- Reishauer
- REM Chemical
- Rexnord
- Stackpole

### Others
- Emax
- Gleason Foundation
- Hmbtri Research Inst.
- Intec - Simpack
- LMS N. America
- Ontario Drive and Gear
- ProTek Engineering
- Tru-Die
- **Xerox**
Research Focus

Application Area:
- Power Transmission and Gearing

Disciplines:
- Geometry and Kinematics
- Design and Analysis
- Dynamics and Vibrations
- Acoustics and Noise Control
- Contact Mechanics and FEA
- Power Losses and Efficiency
- Material Fatigue and Engineered Surfaces
- Gear Tribology, Lubrication and Wear
- Scuffing/scoring
- Metrology and Test Methodologies
Research Focus

- Dynamics/Vibrations
- Friction/Efficiency
- Noise
- Lubrication
- Contact Mechanics
- Surface Wear
- Scuffing/Scoring
- Contact Fatigue Life
Example: Prediction of High-Speed Gear Scuffing
Example: Prediction of Mechanical Gear Efficiency
Prediction of Gear Surface Wear

- Dynamics/Vibrations
- Noise
- Friction/Efficiency
- Scuffing/Scoring
- Lubrication
- Contact Mechanics
- Surface Wear
- Contact Fatigue Life
Example: Modeling of Contact Fatigue Life of Gear Pairs
Current Consortium Projects

- Experimental and theoretical investigation into modulation side bands of planetary gear sets
- Dynamic modeling of planetary automatic transmissions
- An experimental and computational study of dynamic root stresses and bending fatigue lives of spur, helical and hypoid gears
- Loaded TCA models for face-milled and face-hobbed hypoid gears
- Experimental study of the dynamics of gear-shaft-bearing systems
- Development of a straight bevel gear load distribution model
Current Individually Sponsored Projects

- Pratt & Whitney Center of Excellence in Gearbox Technology. **Pratt & Whitney**
- Development and Validation of a Gear Pitting Life and Scuffing Models. **GM Powertrain**
- Development of New Design and Analysis Tools for Rotorcraft Gearing. **Sikorsky Aircraft**
- An Experimental Study of the Transmission Error and Root Stresses of Loaded Hypoid Gear Pairs. **Mazda**
- An Experimental Study of the Planet Load Sharing and Planet Phasing of Planetary Gear Sets. **Mazda**
- Development of New Heavy Truck Automatic Transmission Configurations. **Komatsu**
- An Experimental and Theoretical Investigation of Planetary Gear Efficiency. **GM Powertrain**
- An Experimental Study of Thermal Mapping and Efficiency of Automotive Rear Axles. **GM Powertrain**
- Development of Plastic Gear Design Tools. **Xerox**
Research Issues: Gear Contact Modeling

- Gear contact analysis is critical to prediction of (i) vibration and noise excitations, (ii) contact and root stresses, and (iii) optimal micro-geometry.
- Use of the conventional Finite Element (FE) tools to model gear contacts is not feasible.
- Gear-specific, FE-based contact models are available, but require significant computation time.
- Semi-analytical methods are very effective to predict gear load distribution with minimal computational effort. Our LDP model for spur and helical gears falls in this category.
- These contact models do not include the dynamic effects. They are quasi-static in nature. Dynamic behavior needs to be included in these models.
- They are mostly limited to gears having simpler geometries. Models for spiral bevel, straight bevel, worm and hypoid gear pairs are needed.
Research Issues: Gear Contact Modeling

Loaded TCA Models for Face-milled and Face-hobbed Hypoid Gears

- Develop a methodology that simulates the face hobbing and face milling processes to define surface geometries of hypoid gears including the coordinates, normal vectors and radii of curvature.

- Develop a novel formulation for unloaded tooth contact analysis by using the ease-off topography, surface of action to predict unloaded transmission error and unloaded contact pattern in addition to potential contact lines/curves to be used for loaded tooth contact analysis.

- Develop an analytical tooth compliance model tailored for FH and FM hypoid gears and spiral bevel gears and verify its accuracy through comparison to FE models.

- Develop a loaded tooth contact analysis model for FH and FM hypoid gears to predict pressure distribution and loaded transmission error with or without misalignments and mounting errors of various types.
Research Issues: Gear Contact Modeling

Gear Surface (Formate)

Pinion Surface (Generate)
Research Issues: Gear Contact Modeling

Ease-off Surface:

- Ease-off surface
- Pinion surface
- Conjugate gear surface
- Surface of action
- Real gear surface
Research Issues: Gear Contact Modeling

Hypoid Gear Test Machine
Research Issues: Gear Dynamics and Vibrations

- Gears exhibit complex dynamic behavior that is highly **nonlinear** and **parametrically excited**.
- They are capable of producing characteristically different motions that lead to **gear whine** or **gear rattle**.
- Gear dynamic behavior influences and is influenced by surface wear and manufacturing errors.
- Deformable-body effects of thin gear rims, flexible shafts and bearings all contribute the dynamic behavior of a gear pair.
- Torque dependence of dynamic behavior and the tooth surface corrections to minimize the gear vibrations are critical issues.
- Dynamic response of a gear system acts as the input of gear and transmission noise.
- Gear dynamics is influenced by lubrication conditions through friction-induced off-line-of-action motions.
Research Issues: Gear Dynamics and Vibrations

Gear Dynamics Test Machine
Research Issues: Gear Dynamics and Vibrations

Gear Dynamics Measurements

\[ DF = \frac{(\sigma_{dyn})_{\text{max}}}{(\sigma_{static})_{\text{max}}} \]

- Static
- Dynamic

\[ \mu \]

\[ \theta_p \quad \theta_g \]

Accelerometer

pinion

gear
Research Issues: Gear Dynamics and Vibrations

Measured Strains and Accelerations:

<table>
<thead>
<tr>
<th>Gear pair</th>
<th>Gear A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque</td>
<td>$T = 200 \text{ Nm}$</td>
</tr>
<tr>
<td>Speed</td>
<td>800 rpm, UP</td>
</tr>
<tr>
<td>$K$</td>
<td>1.05</td>
</tr>
<tr>
<td>DTE</td>
<td>1.5 µm</td>
</tr>
</tbody>
</table>

![Graph showing measured strains and accelerations over mesh cycles and frequency.](image)
Research Issues: Gear Dynamics and Vibrations

Measured Strains and Accelerations:

<table>
<thead>
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<th>Gear A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque</td>
<td>$T = 200$ Nm</td>
</tr>
<tr>
<td>Speed</td>
<td>1150 rpm, UP</td>
</tr>
<tr>
<td>K</td>
<td>1.4</td>
</tr>
<tr>
<td>DTE</td>
<td>5 $\mu$m</td>
</tr>
</tbody>
</table>
**Research Issues: Gear Dynamics and Vibrations**

Measured Strains and Accelerations:

<table>
<thead>
<tr>
<th>Gear pair</th>
<th>Gear A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque</td>
<td>$T = 200$ Nm</td>
</tr>
<tr>
<td>Speed</td>
<td>1700 rpm, UP</td>
</tr>
<tr>
<td>$K$</td>
<td>1.6</td>
</tr>
<tr>
<td>DTE</td>
<td>6.75 $\mu$m</td>
</tr>
</tbody>
</table>

---

![Graphs showing measured strains and accelerations](image)
**Research Issues: Gear Dynamics and Vibrations**

Measured Strains and Accelerations:

<table>
<thead>
<tr>
<th>Gear pair</th>
<th>Gear A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque</td>
<td>$T = 200$ Nm</td>
</tr>
<tr>
<td>Speed</td>
<td>2150 rpm, UP</td>
</tr>
<tr>
<td>$K$</td>
<td>1.05</td>
</tr>
<tr>
<td>DTE</td>
<td>1.5 $\mu$m</td>
</tr>
</tbody>
</table>

![Graph showing measured strains and accelerations](image)
Research Issues: Gear Dynamics and Vibrations

Measured Strains and Accelerations:

<table>
<thead>
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<th>Gear A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque</td>
<td>$T = 200$ Nm</td>
</tr>
<tr>
<td>Speed</td>
<td>3150 rpm, UP</td>
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<tr>
<td>$K$</td>
<td>1.9</td>
</tr>
<tr>
<td>DTE</td>
<td>9 $\mu$m</td>
</tr>
</tbody>
</table>

![Graph showing measured strains and accelerations](image)
Research Issues: Gear Lubrication

- Gear lubrication modeling is a **complex** and truly **transient** phenomenon:
  - Most of the key lubricated contact parameters vary as gears rotate:
    - rolling velocity, sliding velocities, load, surface roughness, radii of curvature, temperature
- Present elastohydrodynamic lubrication (EHL) models cannot handle such transient effects.
- In most gear applications, speed, surface roughness and lubricant parameters are such that a full fluid film is not possible. Conditions are often **mixed** or **boundary-EHL** type with excessive **asperity-to-asperity contacts**.
- Lubrication conditions dictate surface stresses (normal and shear) and the resultant contact fatigue and mechanical power loss behavior.
- Friction-induced vibrations originating at the gear mesh are also dictated by the lubrication characteristics.
Research Issues: Gear Lubrication

![Graphs showing research issues related to gear lubrication.](image)
Research Issues: Gear Lubrication
Gear contact fatigue is influenced by a host of contact, lubrication, load, speed, and surface parameters.

Dynamic effects, often undesirable lubrication conditions, heat treatment, and finishing and surface engineering processes all impact contact fatigue.

Stress conditions are truly **multi-axial** and no multi-axial fatigue theory is readily available to gears.

No published basic or stress-life data is available for common gear materials.

Most of these limitations are valid for tooth bending fatigue problems as well.
Research Issues: Gear Fatigue

\[ \sigma_{xx} \]

\[
\begin{array}{c}
\begin{array}{c}
\text{Roll Angle (deg)} \\
20 \quad 25 \quad 30 \quad 35 \quad 40
\end{array}
\end{array}
\]

\[
\begin{array}{c}
\begin{array}{c}
\text{Tooth Force (kN)} \\
0 \quad 1 \quad 2 \quad 3 \quad 4
\end{array}
\end{array}
\]

\[
\begin{array}{c}
\begin{array}{c}
z \text{ (mm)} \\
-0.1 \quad -0.08 \quad -0.06 \quad -0.04 \quad -0.02 \quad 0
\end{array}
\end{array}
\]

\[
\begin{array}{c}
\begin{array}{c}
x \text{ (mm)} \\
-0.4 \quad -0.3 \quad -0.2 \quad -0.1 \quad 0 \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4
\end{array}
\end{array}
\]

\[
\begin{array}{c}
\begin{array}{c}
\sigma_{xx} \text{ (MPa)} \\
0 \quad -0.5 \quad -1 \quad -1.5 \quad -2
\end{array}
\end{array}
\]
Research Issues: Gear Fatigue
Research Issues: Gear Fatigue

\[ \sigma_{xz} \]

\[ \sigma_{xz} \text{ (MPa)} \]

- Graph showing the distribution of stress \( \sigma_{xz} \) with axes for \( x \) (mm) and \( z \) (mm).
- Graph showing the variation of tooth force with roll angle (deg).
Research Issues: Gear Fatigue

Smooth Surfaces

Rough Surfaces
Research Issues: Gear Fatigue

Twin-Disk Contact Fatigue Tests
Research Issues: Gear Fatigue

Gear Contact Fatigue Tests
Research Issues: Gear Efficiency

- Power losses from gear systems and transmissions can be classified in two groups: (i) load-dependent (mechanical) losses and (ii) load independent (spin) losses.

- Spin losses are mostly due to windage and/or oil churning. No analytical model has been published on such losses. CFD tools are too computational to be applied to gear pair problems.

- The prediction of mechanical gear losses relies upon linking a contact model with a gear lubrication model. Hence, limitations in predicting gear lubrication conditions hinder the efficiency predictions as well.

- Experimental data on spin and mechanical losses are spotty and without details. New databases are needed for model validation purposes.
Research Issues: Gear Efficiency

Gear Pair Efficiency Tests
Research Issues: Gear Efficiency

Transmission/ Gearbox Efficiency
Research Issues: Gear Efficiency

Rear Axle Efficiency
Research Issues: Gear Surface Wear

- Gear surface wear is impacted by a large number of contact, lubrication, surface and material parameters.

- Use of simplified wear criteria such as Archard’s wear formula has been proven to be effective for gear wear modeling. This, however, requires an experimentally determined wear coefficient.

- The wear of gear surfaces impacts gear dynamics significantly. Likewise, dynamic conditions alter loading to change wear rates significantly.

- As other failure modes are eliminated through proper design, long-cycle behavior and wear of gears are becoming more critical.

- Most gear wear models are limited to spur and helical gears. Wear models for other gear types are needed.
Research Issues: Gear Surface Wear

Influence of Lubricants on Contact Fatigue and Wear

NASA Glenn Gear Fatigue Test Program

- Seven different gear lubricants were used for extensive contact fatigue tests.
Research Issues: Gear Surface Wear

Gear Surface Wear Measurement

[Image of gear surface wear measurement setup and graphs showing Roll Angle and Face dimensions.]
Research Issues: Gear Surface Wear

Measured Wear versus Lubricant Viscosity

- Average Wear Rate [µm/million cycles]
- Kinematic Viscosity [cSt]

Graph showing the relationship between average wear rate and kinematic viscosity.
Research Issues: Gear Surface Wear

Pitting Life versus Lubricant Viscosity

Kinematic Viscosity [cSt]

Pitting life [millions of cycles]
Research Issues: Gear Surface Wear

Pitting Life versus Wear Rate

![Graph showing the relationship between pitting life (millions of cycles) and average wear rate (µm/million cycles). The graph includes a line for 50% pitting life and another for 10%, with data points labeled A to G.]
Research Issues: Planetary Gear Sets

**Durability Issues**
- Gear bending/contact fatigue
- Scoring limits/lubrication
- Rim/hoop failures
- Ring support failures
- Gear tooth wear
- Bearing failures
- Complex duty cycles
- Planet load sharing
- Engineered surfaces

**Dynamics Issues**
- Dynamic design factors
- Noise
- Planet mesh phasing
- Rim deflection resonances
- Number of planets
- Carrier deflections
- Efficiency considerations

**Design Issues**
- Rim deflections
- Internal gear mounting
- Planet bearings/pins/washers
- Gear and carrier piloting
- Number of planets
- Tolerance Sensitivity
- Carrier deflections
- Efficiency considerations
- Profile optimization
Research Issues:
Planetary Gear Sets

Planetary Gear Set Measurement Set-up:
Research Issues:
Planetary Gear Sets

Frequency Spectra:

Measured

Predicted
Powder Metal Gear Research Issues

- Powder metal **gear fatigue** performance:
  - Bending fatigue (tooth breakage) stress-life data
  - Contact fatigue (pitting/micro-pitting) stress-life data
  - Influence of process and material parameters on fatigue life.

- Powder metal **gear efficiency** performance:
  - Surface roughness effects
  - Influence of process and material parameters on power losses

- Powder metal gear **process simulation**:
  - Die profile corrections via mathematical tools
  - Influence of typical powder metal profile deviations on transmission error and gear noise performance

- Powder metal **gear wear** performance:
  - Surface roughness effects
  - Influence of process and material parameters on surface wear
Any Questions?

Gleason Gear and Power Transmission Research Laboratory