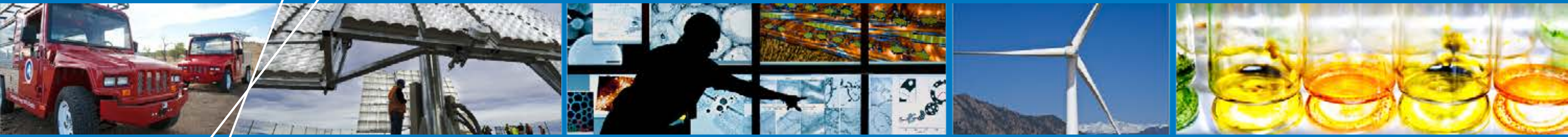
An Analytical Model for Real-Time Design Evaluations of Spline Couplings

"Gear SCouP"



Yi Guo,[1] Jon Keller,[1] Robert Errichello,[2] and Chris Halse[3]

[1]National Renewable Energy Laboratory
[2]GEARTECH
[3]Romax Technology

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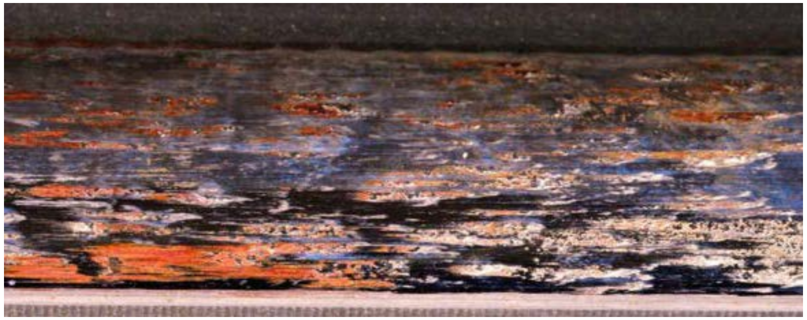
Research Motivation

- **Survey of gearbox designers pointed out the importance of spline connections**
  - What is a "good" spline design? How do I design it?
- **How can the Gearbox Reliability Collaborative (GRC) illuminate this subject?**
  - Damage to sun spline was evident from gearbox (GB) #1 tests believed to be mainly due to lubrication loss, but…
  - Poor load sharing & high frequency sun motion noted in GB #2 tests.
- **Fill gaps in standards by developing a new spline rating tool called "Gear SCouP"**
  - **Released and publicly available**

Photo by Robert Errichello, GEARTECH, NREL 19852



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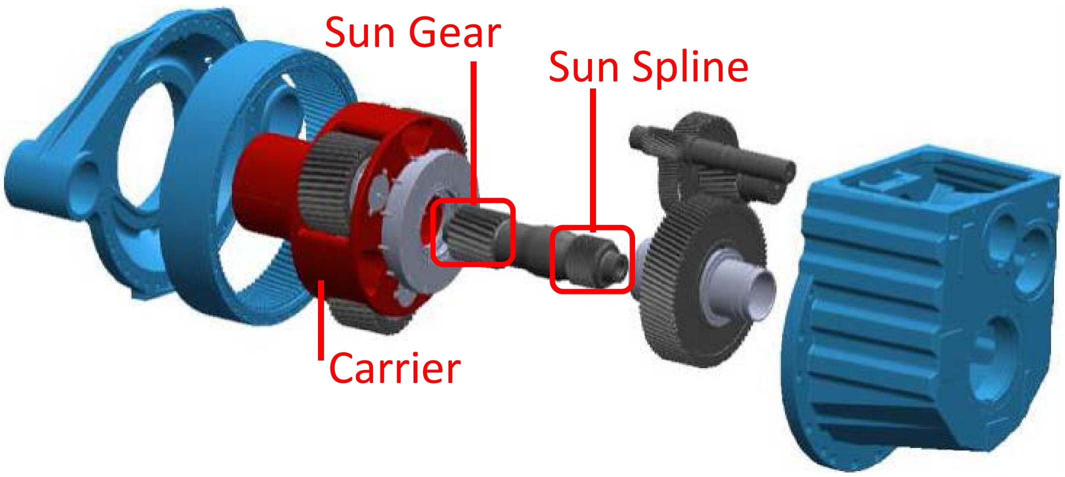
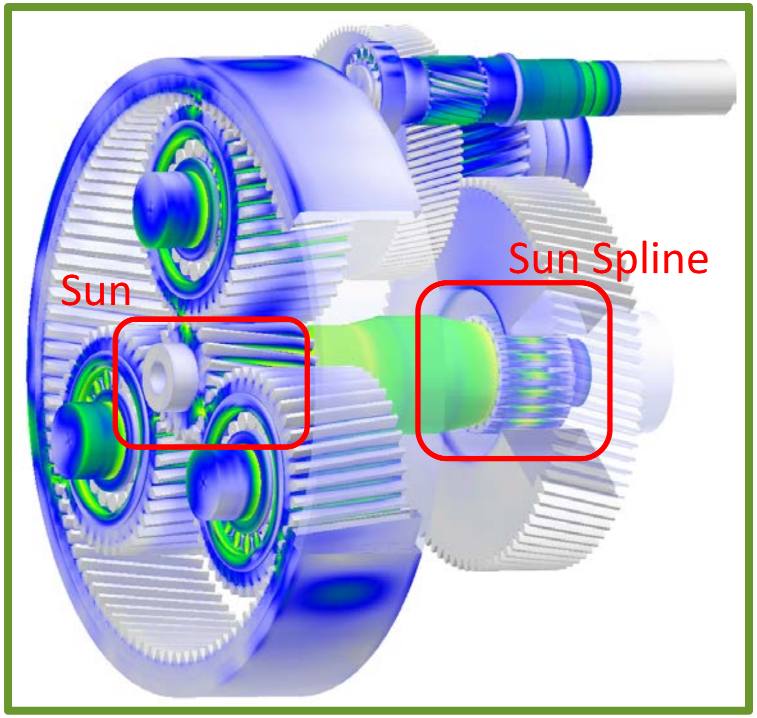
GRC Gearbox and Sun Spline





- **Connects planetary and parallel stages**
- **Articulated design allows the sun to float between the planets.**
    - **Equalizes load sharing among planets**
    - **Improves gearbox reliability.**

Sun spline design affects gearbox reliability

Sun Gear Motion Instrumentation

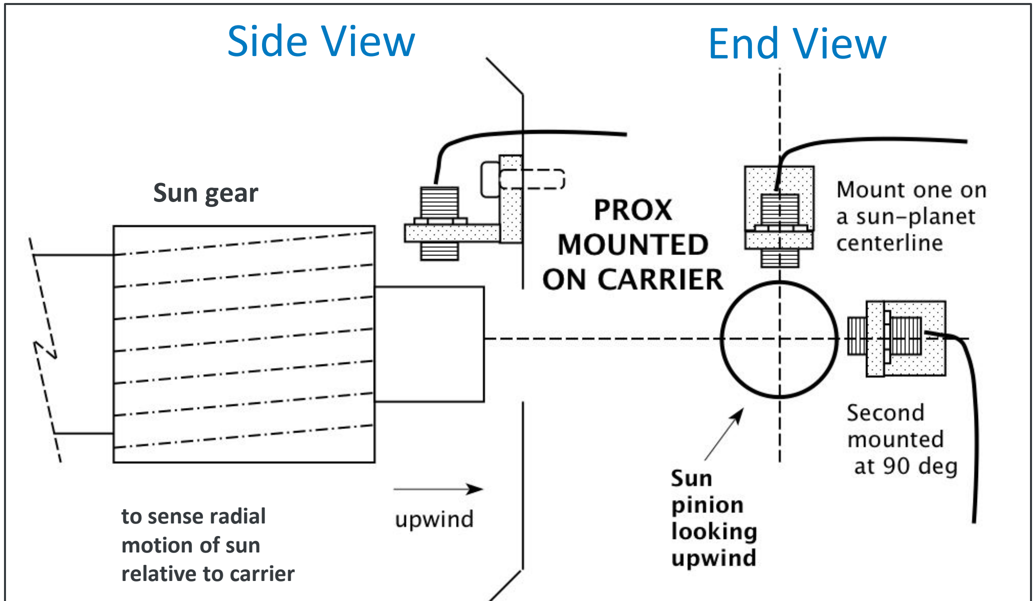
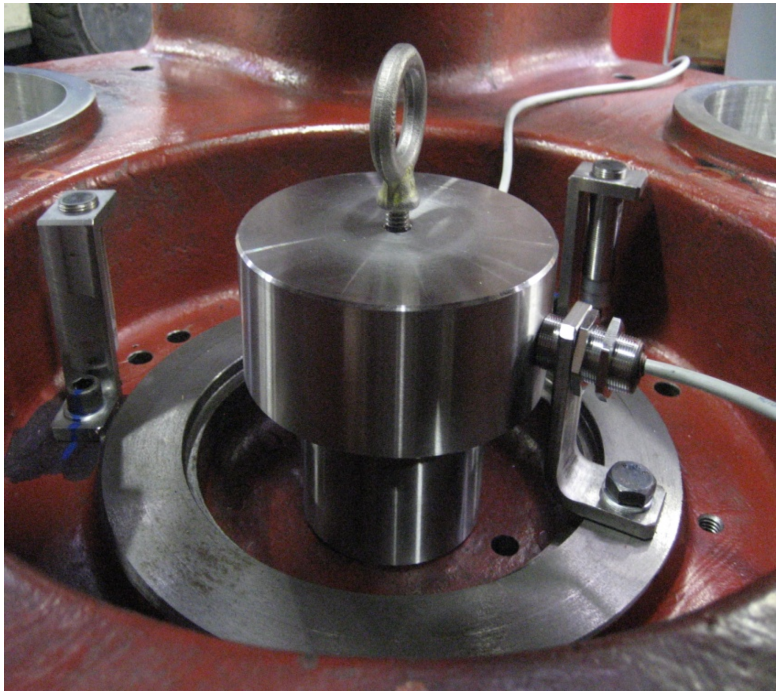


Illustration by McNiff Light Industry



Sun gear proximity sensor (one of two) mounted on the carrier

Photo by Edward Overly, NREL 26666

- **Sun motion only**
  - **Extremely difficult to make any measurement on the spline itself**

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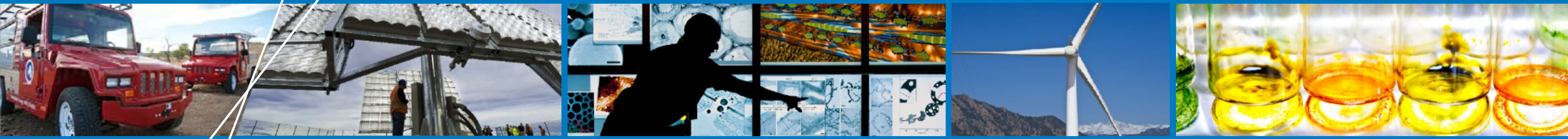

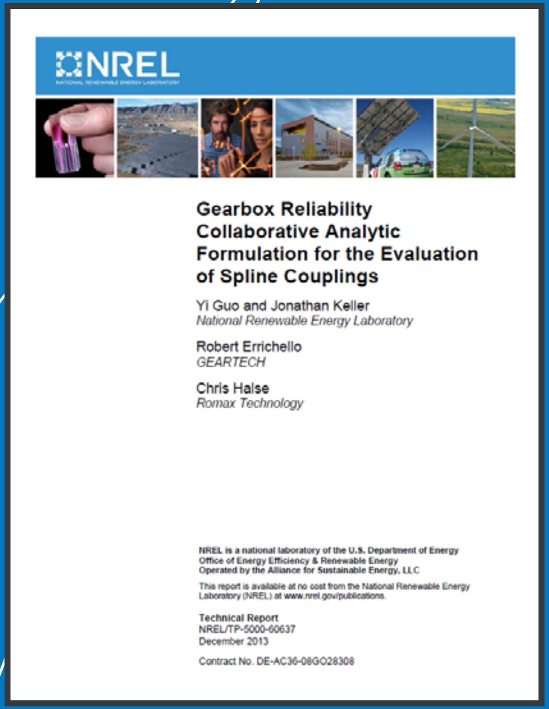
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Gearbox Reliability Collaborative Analytic Formulation for the Evaluation of Spline Couplings

Yi Guo and Jonathan Keller
National Renewable Energy Laboratory

Robert Errichello
GEARTECH

Chris Halse
Romax Technology

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Analytic Spline Rating Model

NREL/TP-5000-60637

www.nrel.gov/docs/fy14osti/60637.pdf

Model Assumptions

- Hub and sleeve shafts are considered rigid
- Only angular misalignment is considered
- Only torsional loading is considered
- Tooth contact occurs only on the drive side
- Tooth crowning leads to constant base pitch spacing in all planes
- The bending and contact stiffnesses are derived at a specified torque
- The spline teeth are equally spaced circumferentially

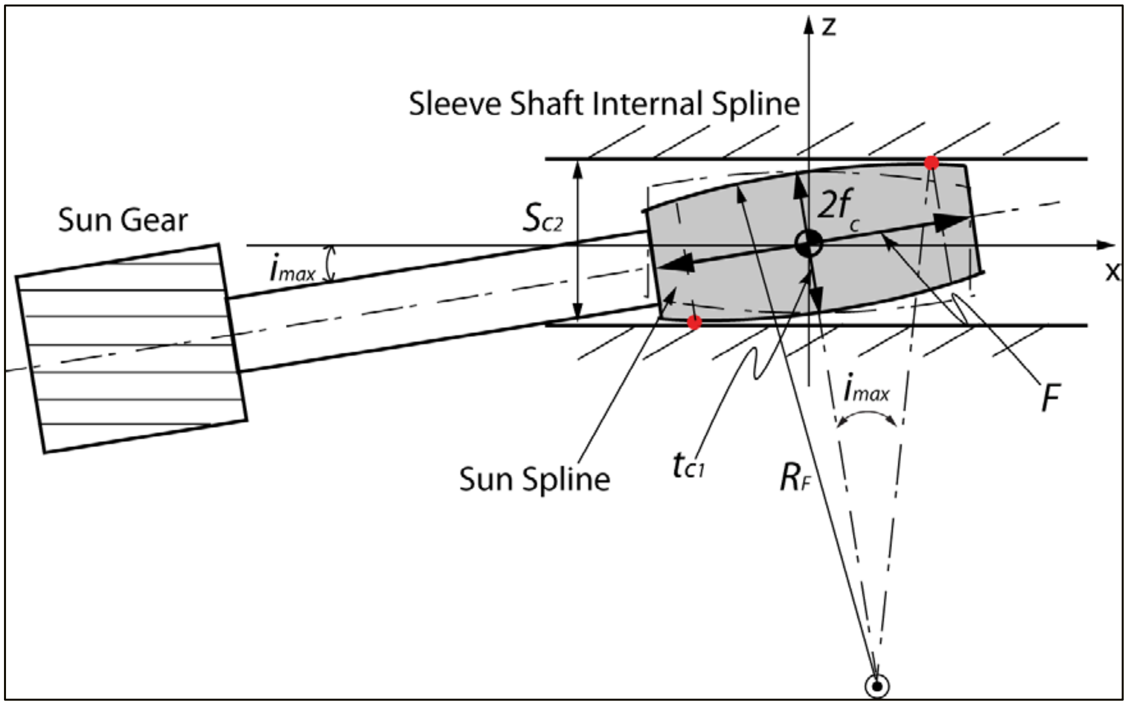
Reasonable for wind applications

Investigation of various tooth contact models underway

Future work to include tooth spacing error

Analytical Model: Jam Angle

- **Jam angle is an important design parameter**
  - Spline misalignment shall not exceed jam angle
- **Jam angle is defined by its geometry**



$$i_{\max} = \min\left\{ \operatorname{acos}\left(\frac{2R_F - S_{c2}}{2R_F - t_{c1}}\right),\ \operatorname{asin}\left(\frac{F}{2R_F}\right) \right\}$$

S_{c2} : sleeve circular space width

R_F : crown radius

t_{c1} : spline tooth thickness at pitch line

F : facewidth

	Analytical	2D FE	3D FE
Jam angle, degree	0.30	0.20	0.20

Tooth Contact Models

- **Single tooth torsional stiffness is based on Buckingham's experimental-based formula**

$$C = FE\frac{Z_1 Z_2}{Z_1 + Z_2}$$

Z_1, Z_2 : elasticity form factors

- **2D FE and 3D FE use different tooth contact models**
  - **2D FE: conformal contact & FE based bending stiffness**
    - **Local contact not considered**
  - **3D FE: line or conformal contact and computational surface integral of Green's function.**

Single tooth stiffness

	Analytical	2D FE	3D FE: Rigid Shaft	3D FE: 3D FE Shaft
Torsional stiffness, Nm/rad	13.4×10^6	8.62×10^6	13.8×10^6	12.5×10^6

Investigation on the effects of various tooth contact models is underway

Tooth Load Distribution and Global Stiffness

- **Load on individual tooth is distributed into N_S slices**

$$P_d^s\Big|_l = P_d \cos\left(\frac{\pi}{N_S} l\right)\Bigg|_{l=-\frac{N_S}{2}}^{l=\frac{N_S}{2}} = P_i\left[1-\frac{z_0 sin(\frac{2\pi}{N}j+\alpha)^2}{z_e}\right]\cos\left(\frac{\pi}{N_S} l\right)\Bigg|_{l=-\frac{N_S}{2}}^{l=\frac{N_S}{2}}$$

N : number of total teeth

N_s: number of slices along tooth flank

q : number of teeth in contact compared to N

- **Contact tooth length on each tooth varies**

$$\left[F_d - 0.5F_c,\quad F_d + 0.5F_c\right]$$

$$F_d = F_i \cos\left(\frac{2\pi}{N} j + \alpha\right) \qquad \alpha = \frac{qN - \mathrm{int}(qN)}{4} + \frac{\pi}{N}$$

$$F_c = 2\sqrt{R_f^2 - \left(R_f - \delta_d\right)^2} \qquad \delta_d = \frac{P_d}{C}$$

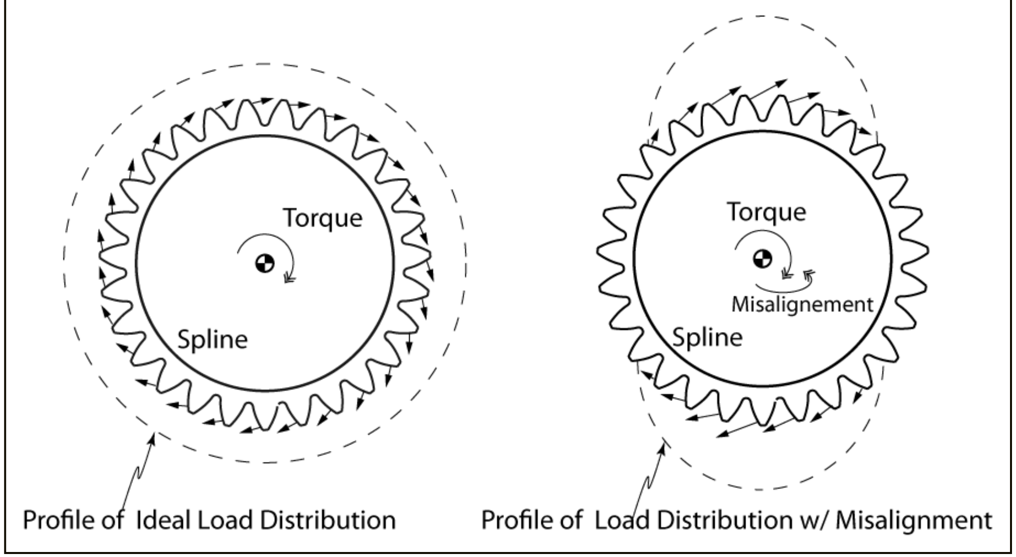
- **Global stiffness**

$$M(i) = \sum_{j=1}^{\mathrm{int}(qN)} M_j(i,j) = \sum_{j=1}^{\mathrm{int}(qN)} F_d(i,j) P_d^i(i,j)$$

$$F_d = F_i \cos\left(\frac{2\pi}{N} j + \alpha\right)$$

$$k_t = \frac{\delta M}{\delta i} \cong \frac{M(i+\Delta i) - M(i)}{\Delta i}$$

Load distribution profile



Analytical Model: Strength Calculation

Hertzian contact stress

$$\sigma_c = 0.418\left(\frac{P_i^{'}E}{R_F}\right)^{1/2}$$

$$P_i^{'} = \frac{P_i}{h_1}$$

h_1 : active tooth flank

P_i : tooth load

Bending stress

$$\sigma_b = \frac{W_t P}{K_v F J}$$

W_t : tangential force

K_v : velocity factor

P : diametral pitch

J : geometry factor

Shear stress (pitch line)

$$\tau = \frac{P_i \cos(\phi)}{t_{c1} F}$$

ϕ : pressure angle

+

Fatigue and yield strength

- Assumed surface-initiated fatigue
- Modified Goodman's fatigue failure criterion
- Used effective distortion energy stress for fatigue criteria
- Used the maximum shear theory for yield criteria
- Through hardened, carburized, nitrided, and induction hardening to heat treatment considered

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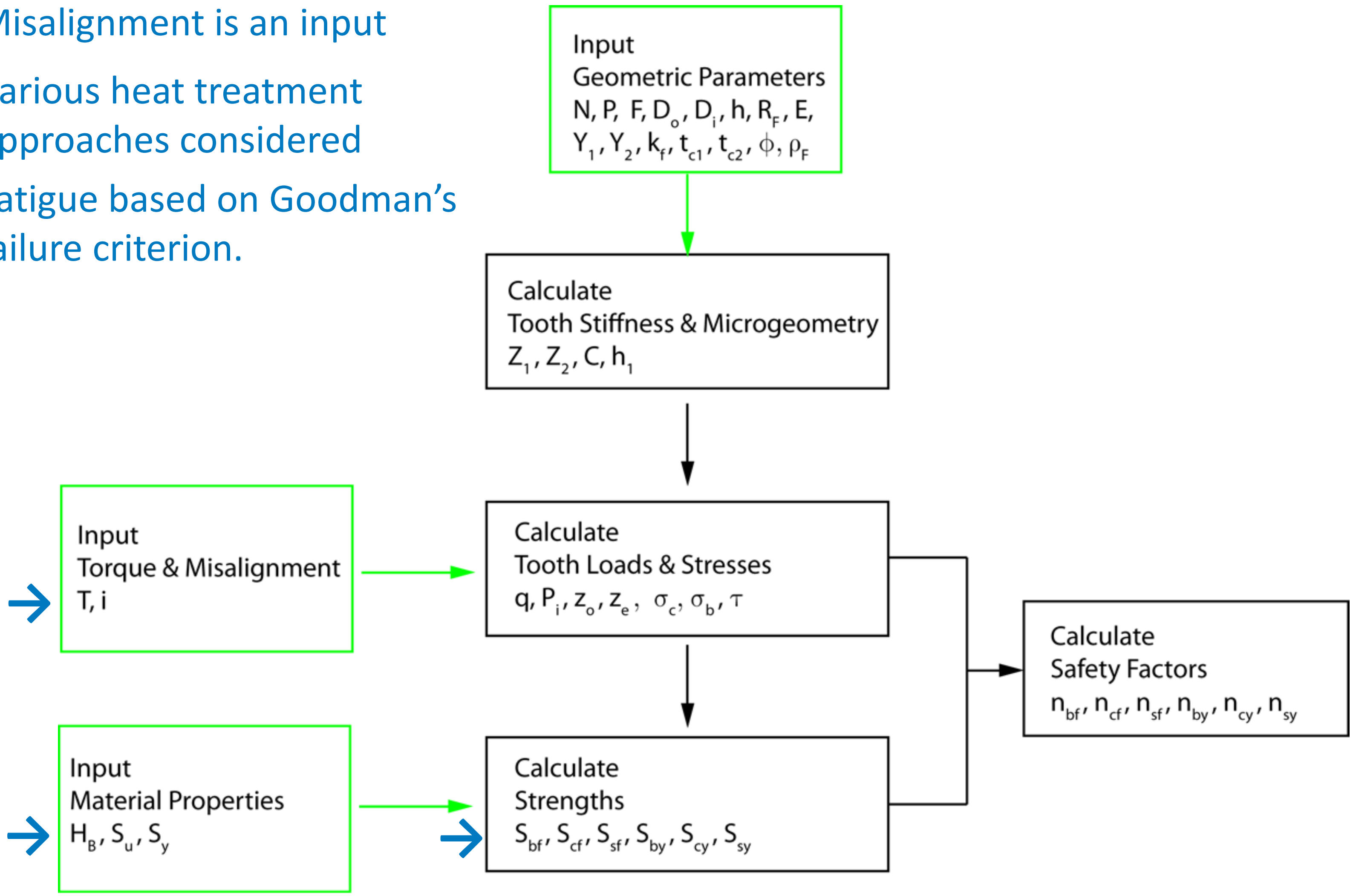
Safety factors

GEAR SCouP calculates safety factors

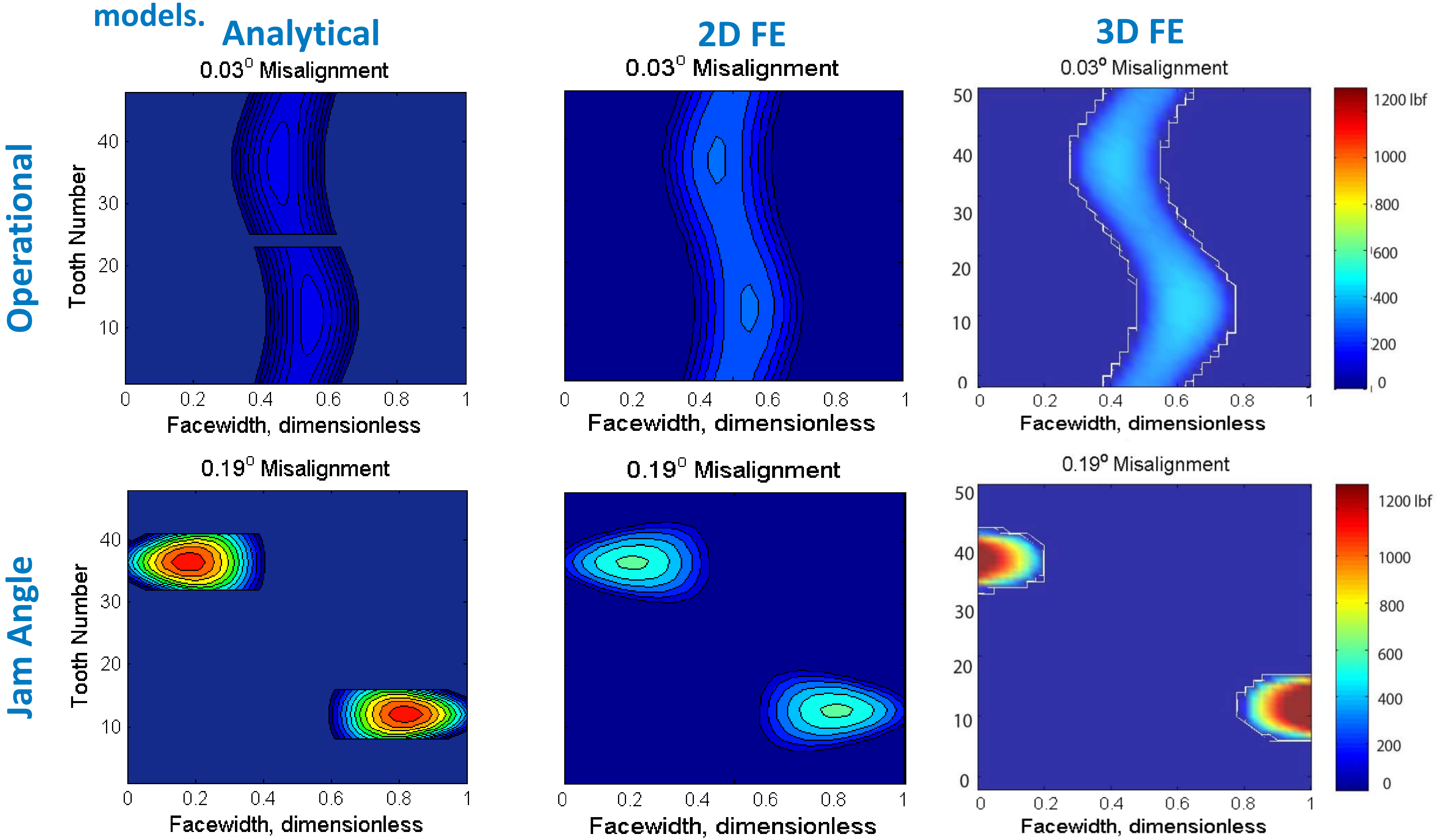
Flow Chart

- Misalignment is an input
- Various heat treatment approaches considered
- Fatigue based on Goodman's failure criterion.



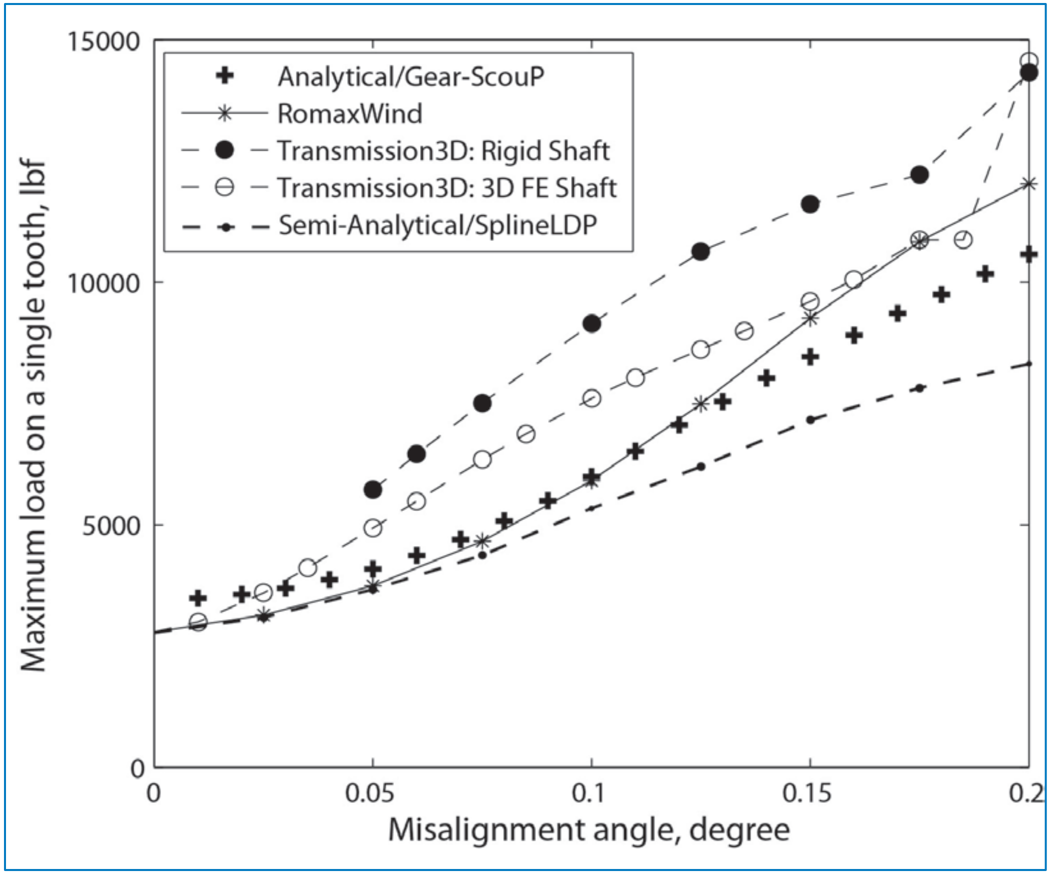
Results—Tooth Load Distribution

- Analytical model tooth stiffness based on Buckingham's empirical model
- Two-dimensional (2D) and three-dimensional (3D) finite element (FE) use different contact models.

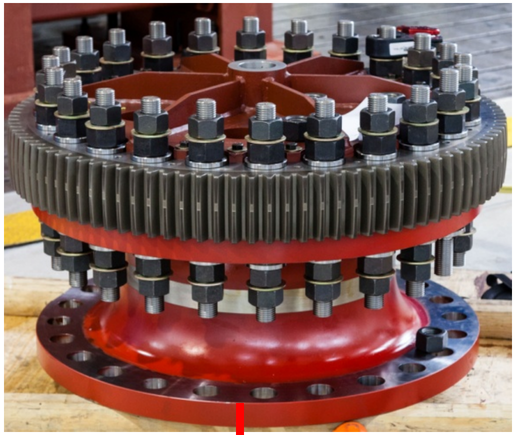


Results—Effects of Misalignment

- **Code-code comparison among various models**
- **Significant difference observed at large misalignment**
- **Experimental validation at the National Wind Technology Center's NWTC 5-MW dynamometer test facility.**



NREL 5-MW Dyno Spline Coupling



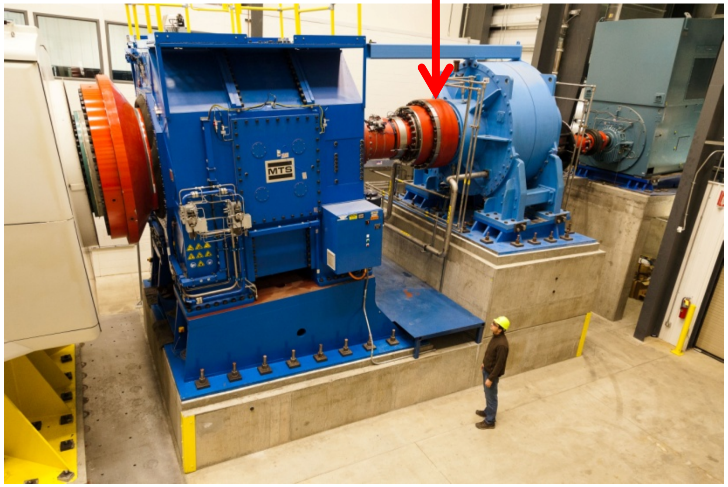
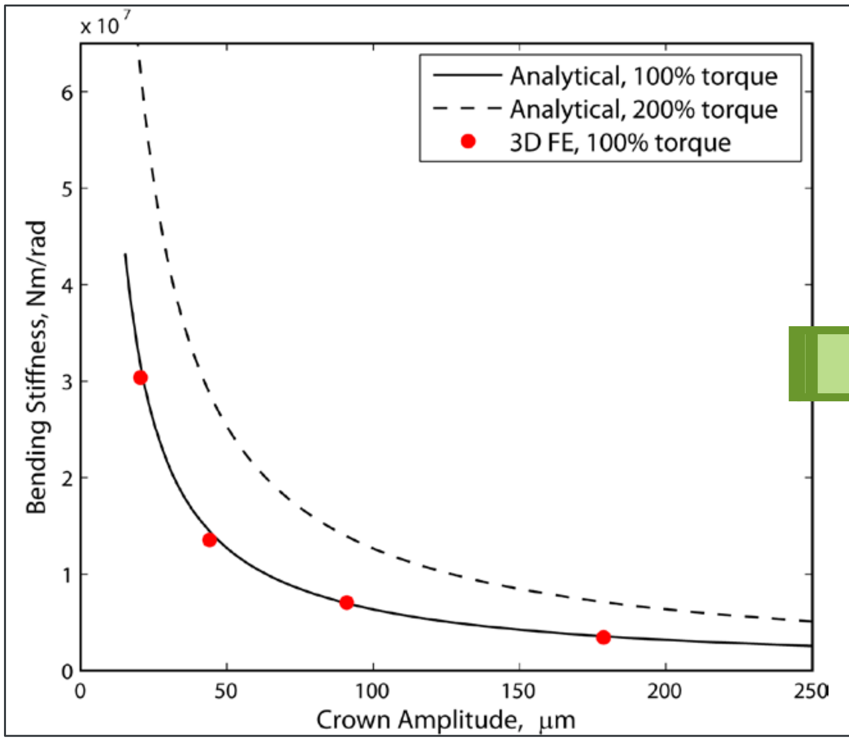


Photo by Mark McDade, NREL 28218

Results—Spline Stiffness

- **Excellent agreement between SCouP and 3D FE**
  - SCouP calculation can be used as input for multibody models.
- **Stiffness decreases with tooth modification & increases with torque.**

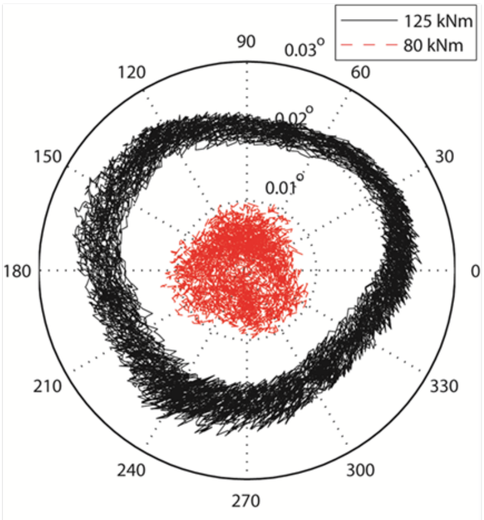


Dynamic models
1. **SIMPACK**
2. **SAMCEF**
3. **Lumped-parameter.**

Spline stiffness is an important input for multibody models.

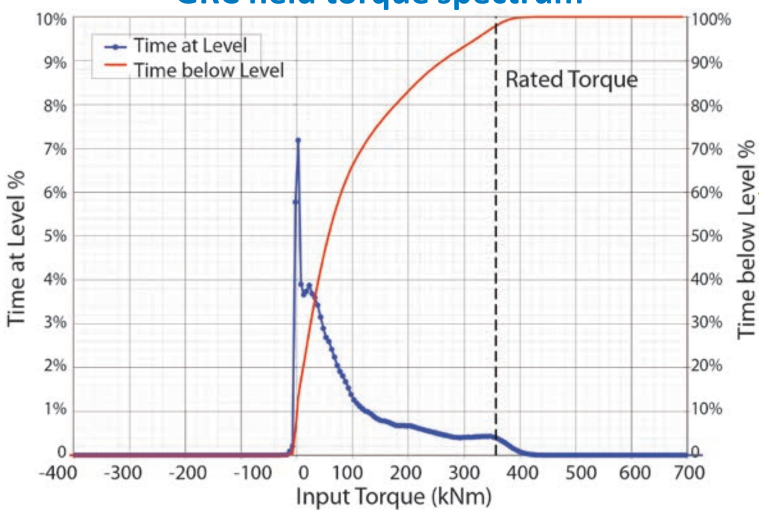
Results—Safety Factor

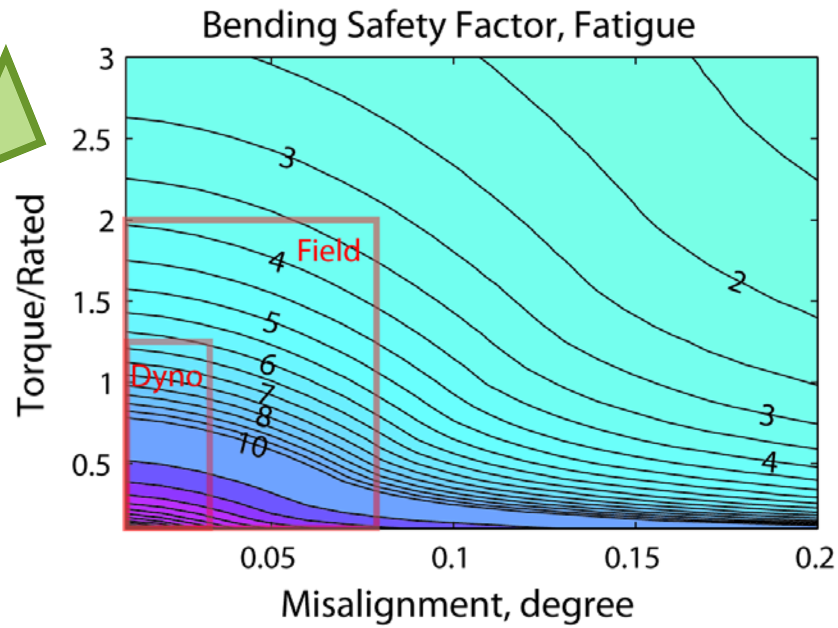
GRC test: spline misalignment



- Direct measurement on spline is extremely difficult
- When combined with GEAR SCouP or FE models, the sun orbit measurement facilitates the best available evaluation of the spline design.

GRC field torque spectrum





Conclusions

- **Analytical model was developed for evaluating sun spline design**
  - Results compare favorably with FE analyses, simulation time orders of magnitude less
  - Yields insights into spline design and resulting loads and stresses
  - Can be a real-time condition monitoring tool
  - Can be integrated with multibody dynamics models
- **Major findings through sensitivity analysis include:**
  - When spline misaligned
    - Number of teeth in contact decreases and the maximum load increases sharply
    - Contact area deviates from tooth center and moves toward tooth ends
    - In the extreme, spline teeth are edge loaded and are at risk of failure
  - Torque affects spline load share, maximum tooth load, and safety factors
    - Evaluate the spline design within the entire torque spectrum
- **Upgrade of tooth contact model is ongoing**
  - Conformal and nonconformal contact
- **Future development will account for geometric spacing error, fretting, and life calculation.**

Contributions to AGMA 6123

- **Semiempirical assumptions are made regarding number of teeth in contact, spline length, and load distribution factor**
  - Gear SCouP calculates these parameters and their effects on safety factors
- **Section 10.4.3 oversimplifies the load distribution factor**
  - GEAR SCouP calculates effects of misalignment and crowning.
- **Section 10.4.4.3 states "*teeth should be crowned to avoid high end loading…*" but gives no method**
  - Gear SCouP is suitable for performing an optimization study.
- **Section 10.4.8.2 suggests designing "*couplings…with adequate …clearance so that they will not jam*" but gives no method**
  - This study derives the jam angle and can reduce the number of design iterations required to determine the spline geometry.

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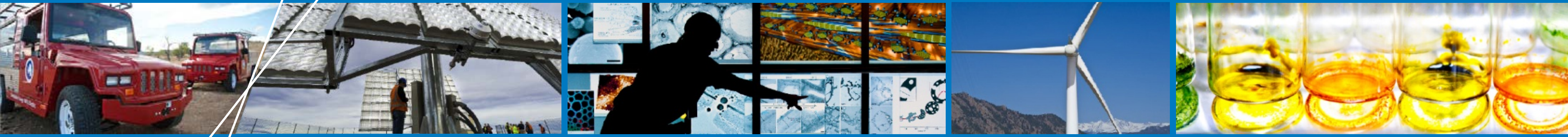

Gear SCouP and Demonstration

https://pfs.nrel.gov

Username: grc_public

Password: GRC_ALL

Email: yi.guo@nrel.gov

Phone: 303-384-7187

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Contact information

Yi Guo

Email: *yi.guo@nrel.gov*

Photo by HC Sorensen, Middelgrunden Wind Turbine Cooperative, NREL 17855