Learning Objectives

A Gearbox Field Inspection Program:
- What to monitor and observe
- How to establish ongoing Maintenance Procedures to extend the life of a gear unit
- How to execute an investigation of a troubled installation
- How to avoid extensive collateral failures

We bring to you this AGMA Webinar Series:

Gearbox Field Inspections – Part I : Load Distribution
Gearbox Field Inspections – Part II : Lubrication
Gearbox Field Inspections – Part III : Condition Monitoring
Why do custom gears fail?

Commodity vs Custom

Custom gear boxes are normally conservatively rated. Due to special applications, unique layout and lack of historic operating data most engineers apply conservative life cycle factors to the toothing layouts. This means at least 40,000 hrs of service or $10^{10}$ load cycles.

Such high numbers virtually eliminate structural bending fatigue and provide extended life to the tooth surface, IF the following is maintained:

- 100% load distribution
- Adequate Lubrication

A common root cause of gear tooth failure:

Im proper load distribution

- Not properly utilizing all of the engaged tooth face surface

What is load distribution?

Design Considerations – Beyond Field Inspection

To interpret field inspections, one must understand certain design considerations, ie:

Load distribution factor
Dynamic factor
Lead and profile modifications
Manufacturing errors, such as:

- Tooth to tooth spacing
- Tip and root interference

ref: ANSI/AGMA 2015-1-A04
Design Considerations – Gear Accuracy

Load Distribution Factor – $K_H$ explained

We should consider the following three errors:
1. Helix slope deviation of pinion, $f_{H1}$
2. Helix slope deviation of gear, $f_{H2}$
3. Shaft parallelism error, $f_{par}$

The errors $f_{H1}$ and $f_{H2}$ can either be measured and averaged values from production or they can be determined from the gear quality number $Q$, e.g. $Q = 6$ (gear quality 6 as per ANSI AGMA ISO 1328-1-B14).

The error $f_{par}$ is more difficult to determine, as it not only considers the misalignment of one shaft to the other due to the misalignment of the housing bores, but it should also consider variations in bearing operating clearances and the misalignment between the gear pitch cylinder with respect to the corresponding shaft axis.

ref: ANSI/AGMA 2015-1-A04

Design Considerations – Manufacturing Errors

Load Distribution Factor – $K_H$ explained

$$K_H = 1.0 + K_{Hmc} (K_{Hpf} K_{Hpm} + K_{Hpm} K_{Hpf})$$

- $K_{Hmc}$ lead correction factor: 0.8 or 1.0 for modified or unmodified leads respectively
- $K_{Hpf}$ pinion proportion factor: varies and is dependent on the gear face width
- $K_{Hpm}$ pinion proportion modifier: varies and is dependent on the bearing span to gear element offset
- $K_{Hma}$ mesh alignment factor: varies based on 4 categories of gearing utilized
  - Open Gearing, commercial enclosed gearing, precision enclosed gearing, extra precision enclosed gearing
  - $K_{Hma}$ mesh alignment correction factor: 0.8 or 1.0, gearing is adjusted at assembly or for all other conditions respectively

ref: ANSI/AGMA 2101-D04

Effects on Rating

Load Distribution Factor – $K_H$ explained

Increases in the Load Distribution Factor have a negative effect on the power rating of the gearset for both:

- Pitting
- Bending

$$F_{pa} = \frac{P_{n1}}{1 + K_{Hmc} (K_{Hpf} K_{Hpm} + K_{Hpm} K_{Hpf})}$$

$$F_{pa} = \frac{P_{n2}}{1 + K_{Hmc} (K_{Hpf} K_{Hpm} + K_{Hpm} K_{Hpf})}$$

ref: ANSI/AGMA 2101-D04
Design Considerations – Operational Considerations

Dynamic Factor – *Kv* explained

Dynamic Factor, *Kv*, accounts for internally generated gear tooth loads which are induced by non-conjugate meshing action of the gear teeth. It is directly influenced by the gears’ own transmission error which is defined as the departure from uniform motion of the gear pair.

Key Influences:
- Excitation
- Dynamic Response
- Resonance
- Critical speeds

When gearing is manufactured using process controls which provide tooth accuracies which correspond to "very accurate gearing", values of *Kv* between 1.02 and 1.11 may be used, depending on the specifier’s experience with similar applications and the degree of accuracy actually achieved.

Effects on Rating

Dynamic Factor – *Kv* explained

Increases in the Dynamic Factor have a negative effect on the power rating of the gearset for both:

- Pitting
- Bending

To use the intended design values for *Kh* and *Kv*, the gearing must be maintained in accurate alignment and adequately lubricated so that its accuracy is maintained under the operating conditions.
**The Rating Point**

How is a Gear Rated?

- SCUFFING

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**Effect of Applied Torque on a Rotor**

Deformation of the Tooth

- without loading torque applied
- with loading torque applied at left end
- Tooth contact patterns of a spur toothed pinion – with no longitudinal modification applied to rotor

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**Gear Teeth are Not Rigid**

- Gear teeth deform due to tooth bending and shear stresses at the point of contact.
- Every gear has manufacturing errors, which alter the load distribution. Since gear teeth are relatively stiff, small errors have a significant effect. This can be exemplified by the sudden loading that takes place at the initial point of contact.
- To soften impact as the rotors move in and out of mesh, tooth flanks are; tip relieved and not tip and root relieved
- Thus greatly reducing abrupt load changes
Tooth Profile Modification
Deformation of the Tooth

- Allowance for Elastic Deformations
- Bending
- Shear Stresses
- Toothing Errors
- Temperature Differentials between pinion and wheel
- Shock Loading
- Allowance for centrifugal force

Deformation of Teeth and Rotors
Tooth Flank Modifications

- Gears are subjected to a torque resulting in elastic deformation of:
  - Tooth parts
    - Individual teeth bend
    - The entire rotor body
  - Pinion/wheel bodies twist
  - Pinion/wheel bodies bend

- Churning losses in the gear mesh and frictional losses in the bearings heat up the gear drive components causing thermal expansion.

- These effects plus the pumping action of the air/oil mixture within the gear mesh (based on the angle of the gear helix) results in temperature variations across the face width of the gear tooth flank.

Typical Tooth Lead Modification
Single and Double Helical Design
Proper Load Distribution

A gear set’s capacity depends on a certain operating load distribution. The capacity calculation always takes into account the full face width of the gear set operating at full design load. Proper installation at commissioning assures this.

Overtime changes in the condition of the installed equipment, wear of associated components such as the bearings and in extreme cases changes in the operating environment may negatively influence the load distribution.

Initial Pitting

Hertzian Stress/Fatigue – What is it?

Hertzian stress refers to the localized stresses that develop as two curved surfaces come in contact and deform slightly under the imposed loads.

Hertzian fatigue refers to the weakening of a material caused by repeatedly applied Hertzian stress.

Once upon a time your gearbox was only a twinkle in a gearbox designers eye....
He balanced hundreds of parameters to come up with the installation of interest to meet a torque transmittal specification:

- Configuration (CD…)
- Material type
- Active Face
- # of teeth/ratio
- Helix Angle
- Heat treat / Hardness
- Gear accuracy grade
- Bearing type/size
- Lubrication
- Countless others...

Parameters we cannot control

Things we CAN Maintain:

- Configuration (CD…)
- Material type
- Active Face
- # of teeth/ratio
- Helix Angle
- Heat treat / Hardness
- Gear accuracy grade
- Bearing type/size
- Lubrication
- Countless others...

I can influence these!!!

Summary: load distribution

A gear tooth surface has a particular bearing area.

As one element transmits force to another element the design requires that 100% of a prescribed amount of surface area, A, be used to transmit the force.

Assuming one gear element transmits a particular force, \( F_t \), to the mating element:

\[
\text{Load Distribution (pressure)} = \frac{F_t}{A} \left( \frac{F_t}{0.9A} + \frac{F_t}{0.8A} + \frac{F_t}{0.7A} \right)
\]

Decreasing Denominator results in increased pressure and therefore higher load on each unit area of gear tooth engaged.
Hertzian Fatigue

MACROPITTING

Macropitting is a fatigue failure driven by Hertzian contact stress. Cracking and detachment of the surface fragments results.

Pitting
Poor Contact due to shaft misalignment

Poor contact due to shaft misalignment (improper load distribution) caused by fit deterioration
Pitting

Failing bearings closest to the bevel pinion

Tooth Bending Fatigue
Why is Load Distribution important?

Improper load distribution leads to localized overload which can result in a crack in bending and ultimate breakage.

Scuffing
Why is Load Distribution important?

If the lubricant film is insufficient to prevent significant metal-to-metal contact, the oxide layers that normally protect the gear tooth surfaces may be broken through, and the bare metal surfaces may adhere together.

The sliding that occurs between gear teeth results in tearing of the welded junctions, metal transfer and damage.
Why improper load distribution occurs

Misalignment of shafts due to:
- Improper set up at assembly and/or commissioning
- Uneven foundation
- Uneven bearing wear (clearances)
- Foundation changes
- Metallurgical changes (HS)

Incorrectly modified leads

Prussian Blue and Red Layout Fluid Checks
Verification of Static and Dynamic Load Distribution

Prussian blue, what is it?
How to apply

Prussian blue aids in the precision fitting of machined surfaces. Allows the easy recognition of high spots on bearings, valves, gears and other close tolerance components.

Steps:
1. Clean teeth with quick drying solvent. Teeth MUST be oil free.
2. Apply to both sides of at least 3 teeth of the larger gear element a VERY LIGHT even coating.
Prussian blue, what is it? & how to apply

Prussian blue, what is it? & how to apply

Use clear tape which is wide enough to reach the tip of the tooth down to the root.

Make sure the tape is completely clean. No fingerprints or debris!!!

Apply the tape to the tooth on which the bluing has transferred.

With a clean cloth, rub the entire surface of the tape ensuring the tape makes contact with the entire area of the gear tooth.

Mark the ends of the tooth with a marker so the tooth tip and root location can be discerned.

Have a fresh sheet of white paper about 6 inches longer than the gear tooth length at the ready on a flat surface.

Peel the tape away from the tooth starting from one side at a severe angle.

Apply the clean paper. Clearly indicate if the transfer is from the loaded or loaded flank. Mark the tip, root and coupling end.

Static Blue Tooth Contact:
Check Results

Static Blue Tooth Contact:
Check Results
Typical Tooth Lead Modification
Single and Double Helical Design

Dykem Red or Blue, what is it?
What is it and how to apply it.

Dykem Layout Fluid provides a uniform, deep color. It is designed to allow the scribing of sharp, clear, precise lines in steel for metal work. These properties allow us to clearly decipher where the contact has been made from tooth to tooth during full load, full speed operation.

To Apply:
1. Clean teeth with quick drying solvent.
2. Apply even coating to 3-4 evenly spaced groups of both sides of at least 3 teeth per group.
3. Allow to dry. (just a minute or 2)

Full Load Dynamic Check with Dykem Blue
Check Results
Prussian Blue and Red Layout Fluid Checks
Verification of Static and Dynamic Load Distribution

Static Blue and Full Load Dynamic with Dykem Red Check Results

Bevel Gear Tooth Contact

CORRECT TOOTH CONTACT
When assembled correctly, the contact will occur on both pairs in the middle of the flanks and center of force width but somewhat closer to the toe.
Bevel Set Tooth Contact
Illustration Sketch

Trending and documenting of tooth contact with each subsequent inspection

Bevel Gear
Tooth contact

Bevel gear tooth contact is very touchy!!

Bevel Set Tooth Contact
Correction

Lateral displacement of contact zone
Procedure as follows:
This should result in a normal contact zone pattern.
**Bevel Set**

Poor Tooth Contact due to Bearing Wear

In normal use, a contact area becomes polished. A wear ridge may form which may move as the bearings become worn. If new bearings are fitted then the position of the ridge will move. Problems may occur of the teeth slipping off the ridges leading to noise and possibly removing thin shards of metal.

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**Advantages of gearboxes with separable bearing caps**

- Custom fitting of the radial bearings in the casing bore. Precise control of parallelism between the pinion and bull gear rotors is possible.
- Easier maintenance: as the rotating elements remain secured and aligned after removal of the casing upper half.
- No oil leakage problems: as the upper casing half does not have to fix the bearings.
- Simplified mounting of the instruments.

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**Maintenance and Inspections**

Advantages of having a Portable Hand Rotor Baring Device

Used for ease of rotation of the entire drive train - driver/gear/driven train:

- Portable ratchet wrench and extension.
- Hex stub shaft extension mounted on wheel non-drive end.
- Guide bushing for ratchet tool extension cap.
- Sensor and sensor adapter which activates a customer supplied limit switch to avoid start-up with the ratchet attached.
Things we CAN DID Maintain:

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I can did influence these!!!

Questions and Answers