Common Pitfalls of Power Transmission (PT) Systems

By
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Times change

Even in the world of large mechanical devices there is constant change.

One of the problems we all have is that we sometimes don’t keep up to date on our education.

This session will try to describe the most common areas where we see mechanical equipment reliability problems that have resulted from changes in our world.
We’ll talk about:

• VFD's – Electronic Variable Speed Drives
• Synchronous vs. V-belt drives
• Reducer (gearbox) ratings
• F= Ma and elastic deformation
• Hydrogen damage of steels
Some quiz questions:

1. Variable speed drives (VFD's) are generally thought of as great energy savers, but what mechanical problems can offset that advantage?
2. What are some trade-offs with synchronous belt drives compared with V-belts?
3. Are all 10 hp (7.5 kW) reducers equally durable? Why or why not?
4. When you design a machine or component support, what mechanical problems can result from structural deflections?
5. When does making something stronger cause more frequent failures.
Variable Speed Drives (VFD's)

- AC motors usually run at relatively fixed speeds, determined approximately by the line frequency divided by the number of poles, i.e., 3600, 1800, 1200, 900, rpm, etc.
- The first industrial and commercial VFD's were introduced about 40 years ago and are designed to be used on 3-phase AC motors. By changing the voltage and frequency delivered to the motor, they enable the motor speed to vary over a wide range.
- The operational benefits are that, with close speed regulation, processes can be precisely controlled and energy $$ can be saved.
The most common attraction is the energy $$ savings

**Fan and Pump Power Required**
where $P = \text{power required}$ and $N = \text{operating rpm}$

$$
P_1/P_2 = (N_1/N_2)^3
$$

For example, operation at 1600 rpm with a VFD controlled motor as opposed to 1800 rpm with a fixed speed motor would save 30% on energy costs.
But there are some surprisingly common problems

Minor (but long term nagging) problem – Most VFD's create voltage differences between the rotor and stator and the result is electrical arcing across the bearings and greatly shortened bearing life.

Major problem – Operating at speeds other than the original design speed can induce torsional vibration and torsional resonances with shaft, coupling, and bearing failures
VFD-caused bearing failure

These axial lines are commonly called “fluting” and are the result of repeated electrical discharge across the bearing.

One common solution is to install a grounding brush.
VFD's fluting from a Nebraska food mill motor after two months
VFD-induced torsional resonances in a coupling

A 300-pound piece of a gear coupling that failed from torsional fatigue
VFD's and torsional shaft failures

A shaft from a Washington paper mill that was operated at the wrong speed.

The fracture on a steep angle to the central axis indicates torsional stresses were involved.
... and bearing problems

Here we see a broken cage bar, the piece holding the rollers in position.

This is a bit difficult to understand until the rolling element bearing operation is explained.
How does a rolling element (ball and roller) bearing actually work?

- The “load zone” is the area where the elements, the balls or rollers, are trapped between and driven by the two rings.
- When the rolling element is in the load zone it drives (pushes) the cage.
- As soon as the element leaves the load zone it is driven by the cage.
- The result is that the cage bars, the pieces that hold the element in position, can see significant reversing (fatigue) forces.
With torsional resonances those forces can be substantially increased.

Ball bearing cage wear from torsional forces
More torsional vibration results

Cage damage from reversing wear

Fatigue fracture of cage

Fractured cage bar
VFD's can be great, but:

1. Check the resonant frequencies of the total system.
2. Check to see if your VFD results in a potential between the rotor and ground. If so, add a grounding brush.

Shaft and coupling failures usually happen within a few weeks. Fluted bearings can take over a year before the damage is recognized.
Next, on the subject of belt drives …

They are very convenient for changing shaft speeds and the first cost is relatively inexpensive, especially when compared with geared drives or VFD's
Common PT (power transmission) belts

Two V-belts – a modern raw-edged notched belt and an older classical wrapped belt

Three synchronous (timing) belts – the original with rectangular teeth, a comparatively quiet Goodrich Eagle, and a Gates Polychain
PT (power transmission) belt drive comparisons

V-belts vs Synchronous Belts

Initial efficiency:
- V-belt - 97%
- Synchronous belt – 98%

Long term efficiency
- V-belt - 94% (with regular maintenance)
- Synchronous – 98%

Industry standard design life
- V-belt – 25,000 hours
- Synchronous belts – \textbf{15,000 hours}
PT (power transmission) belt drive comparisons

**V-belts vs Synchronous Belts**

Initial efficiency:
- V-belt - 97%
- Synchronous belt – 98%

Long term efficiency
- V-belt - 94% (*This can drop to less than 90% with worn sheaves and loose belts*)
- Synchronous – 98%

Industry standard design life
- V-belt – 25,000 hours
- Synchronous belts – **15,000 hours***

* Add 40% to belt capacity for life equal to a V-belt
According to Gates, V-belt life is temperature dependent with a 50% life reduction for every 19\(^\circ\)F (10\(^\circ\)C) above about 90\(^\circ\)F.

**200 hp motor – 94% efficient**

So it’s generating about 12 hp in heat and airflow losses with about 10 hp of that inefficiency as heat.
An air handler with a lightly loaded V-belt drive with a totally enclosed (sealed) guard

How hot are the belts?
What is the heat doing to belt life?
What condition are they in?
This is a heavily loaded V-belt drive with an open guard on a air conditioning system fan.

These belts are can be easily inspected to determine their condition and an important point is that the airflow will let them run much cooler – and much longer – than in a totally enclosed guard.
PT (power transmission) belt drive comparisons –

- Periodic inspections of V-belts can detect deterioration and allows planning for maintenance, either retensioning or replacement. (Typically there is no visual determination of a failing synchronous belt.)
- It appears that a lot of equipment designers don’t understand the OSHA regulations on guards.
- Installation of synchronous belts on a relatively flexible structure designed for V-belts can lead to early failure.
  - V-belts function by the friction on the sides of the sheaves and startup slippage is expected.
  - Synchronous belts drive on the teeth and don’t slip. The startup and the operating torque can cause the structure to flex, enough that, with the belts riding high on the sprocket teeth, they fail from high tooth bending stresses.
And synchronous belts have to be aligned more carefully …

Misaligned synchronous belt, due to structural deflection, on its way to an early death.
Quiz question – What are the trade-offs with synchronous belts compared with V-belts?

Synchronous belt drives are more efficient but:

1. The “book design life” is only 2/3 of the design life of a V-belt drive. (+40% to drive loads to make it equal.)
2. The structure has to be more rigid.
3. Alignment is much more critical.

I didn’t talk about it but there are times when synchronous belt drives are relatively noisy.
Three synchronous (timing) belts – left to right
- The original with rectangular teeth
- A comparatively quiet Goodrich Eagle
- A Gates Polychain
Reducer (gearbox) selection

What have competitive pressures done to the reducer industry? What has the effect been on reducer reliability, i.e., typical reducer life?
Reducer ratings

• Are you going by AGMA or ISO ratings?
  1. ISO is primarily a result of academic studies
  2. AGMA is primarily the result of field experience
  3. AGMA is the more conservative

• What is the service factor (sf)? (Reducers are designated by load classification, and then a service factor is applied to compensate for the unknowns in the actual operation. For example, a 10 hp fan drive sees much smoother loads than a 10 hp crusher drive.)
  1. In 1980 2.0 or 2.2 was a common service factor
  2. Now, 1.3 is a common service factor
  3. So, what is the difference?
Our empirical findings:

The service factor is the key to reducer reliability - the lower the service factor, the lighter and less rigid the reducer. (The reducer is designed to handle the rated power x sf.)

An approximation is that reducers are rated for running at peak horsepower for \((5000 \text{ hours})^{\text{sf}}\). At a 1.3 sf we typically see about a 3 year life before major maintenance is needed. At 2 it is more like 10 years.
A major contributor to the shortened life is the deflection of the housing and structure

Ball and roller bearing lives:

\[ \text{Life}_{\text{ball brg}} = (\text{bearing dynamic rating/load})^3 \]

\[ \text{Life}_{\text{roller brg}} = (\text{bearing dynamic rating/load})^{3.33} \]

Double the load on the bearing, cut the life by a factor of 8 for ball rearings and 10 for roller bearings.
Also …

In industrial applications there is a phenomena called “soft foot”. It is used to describe an application, typically a motor, pump, or reducer where the four mounting feet are not in the same plane.

The result of the soft foot is that the housing and, as a result, the bearing bores are distorted, the bearing loads are increased, and the bearing lives are decreased.

We’ve been noticing a lot of single bearings with that same bore distortion. How can that happen?
Compare two reducers, an older heavy one and a modern lighter one. How do the deformations compare with equal loads?

Or, what happens when they fabricate a fan bearing support out of 3/16” plate instead of ¼” plate?
What are the clearances inside a typical ball bearing?

*C3 is standard
*C4 is used for higher temperature applications

<table>
<thead>
<tr>
<th>Bore Example</th>
<th>Radial Internal Clearances</th>
</tr>
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<tbody>
<tr>
<td>mm</td>
<td>in</td>
</tr>
<tr>
<td>Precision</td>
<td>C3</td>
</tr>
<tr>
<td>12</td>
<td>1/2</td>
</tr>
<tr>
<td>180</td>
<td>7.0</td>
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Thermal expansion of mild steel = 0.0075”/ft/100°F (1.12mm/m/100°C)
Thermal expansion of 300 series stainless steel = 0.011”/ft/100°F (1.64mm/m/100°C)
Thermal expansion of aluminum = 0.016”/ft/100°F (2.39mm/m/100°C)
Those internal clearances are critical in operation

Relative Life vs. Internal Clearance

6310 deep groove bearing
50 mm bore (almost 2”)

Effective Internal Clearance (inches)

6310 Ball Bearing with a 3,350 N (340 kgf) radial load
(data from NSK text
In diagnosing what caused a bearing problem, a very important technique is to cut the bearing apart and inspect the ball (or roller) paths.

These sketches show parasitic loads:

- **Normal inner ring path, outer ring is out-of-round**

- **Excessive thrust load (paths high off center lines)**

- **Outer ring not square to the shaft (ring misalignment)**

- **Inner ring not square to the shaft (ring misalignment)**

- **Normal inner ring path combined with additional preload resulting in excessively wide paths, i.e. possible shaft fit problem, etc.**

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A common result of a weak structure is a pinched bearing with a distorted outer ring and increased loading.

Proof of a Parasitic Load

6310 Ball Bearing with a 3,350 N (340 kgf) radial load (data from NSK text Technical Report - 1992)

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Fan Bearing Deflections

Examining the ball path in the outer ring
Structural stiffness is proportional to the thickness cubed!
If that fan base is made with $\frac{3}{16}"$ steel, instead of $\frac{1}{4}"$, the deflection is more than doubled!

AMCA1 - Single width, single inlet fan with separate motor

It gets through the 1-year warranty but the long-term result is a repeated maintenance problem.
Similar problems happen with gears when housings deflect (dynamic soft foot)
More quiz questions:

1. Variable speed drives (VFD's) are generally thought of as great energy savers, but what mechanical problems can offset that advantage?

2. Are all 10 hp (7.5 kW) reducers equally durable? Why or why not?

3. When you design a machine or support, what mechanical problems can result from structural deflections?
What are two areas where making something stronger will cause it to fail more frequently?

The less common one is “low temperature embrittlement”. – Generally as carbon steel has higher carbon content and higher strength, it has less impact strength. That is a not a problem that we frequently see.

A much more common one is …
Hydrogen damage

The probable mechanism:
1. All corrosion generates atomic hydrogen
2. The hydrogen atom can easily travel through metals.
3. Most of the time the atoms rapidly form molecules, but some decide to see the world.
4. They find vacancies in the metal’s atomic structure and sometimes combine there.
5. The increased volume creates internal stress.
6. With ductile materials there is some distortion while brittle materials crack!
• The metal bar, in this case steel, is being attacked. The end product depends on the specific liquid and metals, but the reactions are all similar.

• Hydrogen liberation is a normal corrosion feature. Most of the hydrogen ions combine to form H₂ gas (but there are always some free ions present to cause problems).

• Electrons flow inside the metal bar then return through the liquid.
Hydrogen Damage

- **HIC** (Hydrogen Induced Cracking) –
- Irregular, frequently branched cracks

In a high strength martensitic stainless stud used in tire mfg.
(This is a wet fluorescent magnetic particle inspection)

Of a steel spring used in a pharmaceutical plant

Crack origin
Hydrogen cracking in a high strength bolt

We’ve seen hydrogen damage in Grade 5 and Grade 8 bolts and their ASTM equivalents.
If you see multiple-branched and irregular cracks there are serious metallurgical problems involved and an expert should be consulted.

(You can try to weld repair the visible cracks, but there are thousands of other cracks not visible to the eye.)
Some comments:

• NACE says hydrogen cracking can occur in steel alloys harder than HRC 22.
• Sulfur compounds have a tremendous effect because they act to prevent the $\text{H}_2$ recombination.
• As engineers design equipment for higher stresses they tend to use higher strength bolting. If corrosion occurs there will be occasional hydrogen damage.
• Atmospheric corrosion has caused failures of steel fasteners at HRC 36.
• My opinion is that a great reference is the paper by Mac Louthan http://sti.srs.gov/fulltext/WSRC-STI-2008-00062.pdf
The last quiz question (plus)

So, when does making something stronger cause more frequent failures? Why does that happen?

Are there other questions or comments???

Thank you and please don’t hesitate to call (315-436-1257) or email (sachscracks@att.net) if you have questions.