Dow Centennial Centre
Fort Saskatchewan, Alberta
Oct. 25, 2018

Methods of Mitigating Torsional Transients in Turbomachinery

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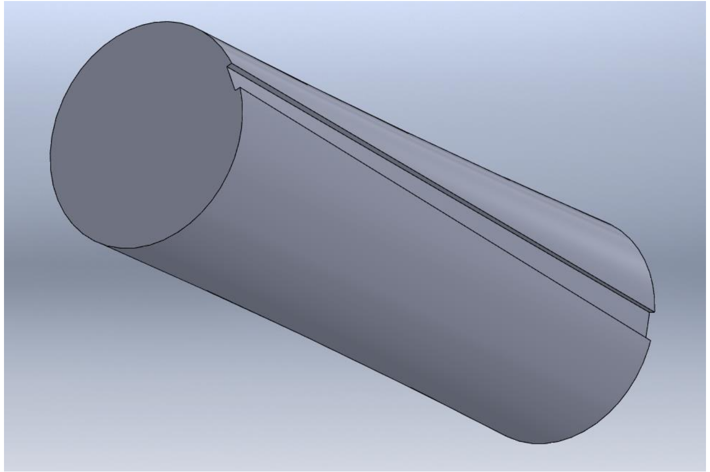
2018 Maintenance, Reliability, Operations Technical Conference

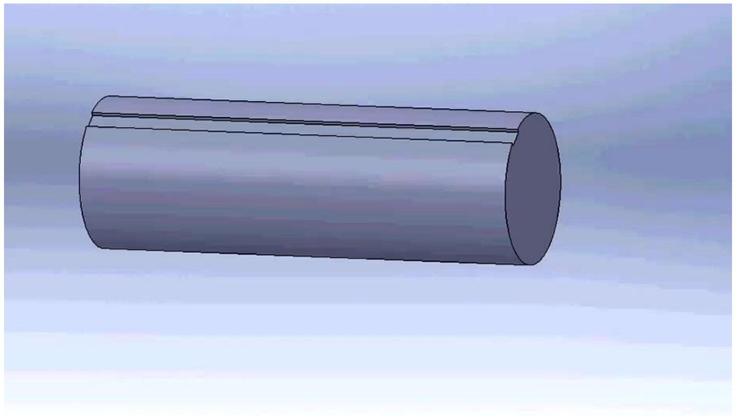
Presentation Agenda

- Torsional vibration basics
- Shaft twisting
- Oscillation
- Vibration
- Natural frequency
- Damages that can occur when shafts twist repeatedly
- Classes of torsional vibration
- Solution approaches to mitigate dynamic torque
- Matching of solution approaches to classes of vibration

Torque and Shaft Twisting

- Shafts respond to torque by twisting
  - The more torque, the more twist
- Repeated back and forth motion is called oscillation
- Vibration occurs when oscillation is driven by an exchange between twisting spring energy and rebound motion





Twist ⟷ Rebound

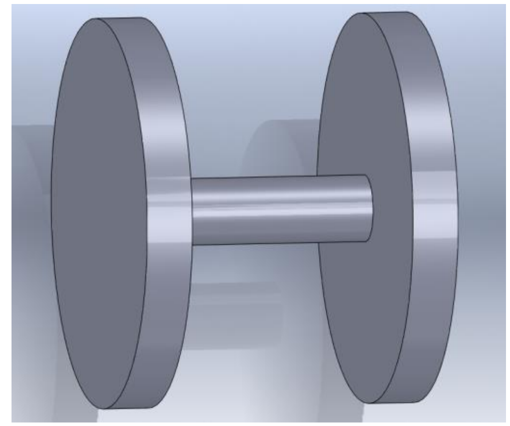
Repeat

Natural Frequency

Shaft Systems possess a property known as Natural Frequency "N"

This property can be determined by calculation

When hit or shaken the shaft will respond strongest at N



J_1 K J_2

$$N = \frac{1}{2\pi}\sqrt{\frac{K(J_1 + J_2)}{J_1 J_2}}$$

Where: N is frequency: CPS

K is torsional stiffness: in-lb/rad

J is element inertia: in-lb-sec^2

Ref: 6 table 5.4.1 modified for units, 5

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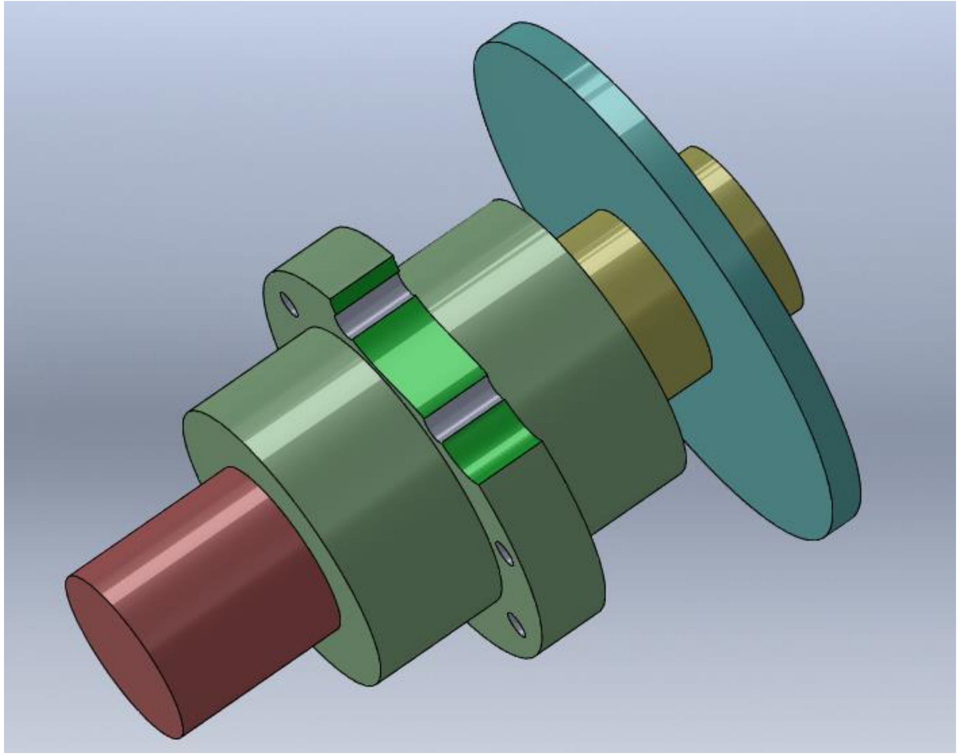
Shaft Systems

Real shaft systems include various elements connected together:

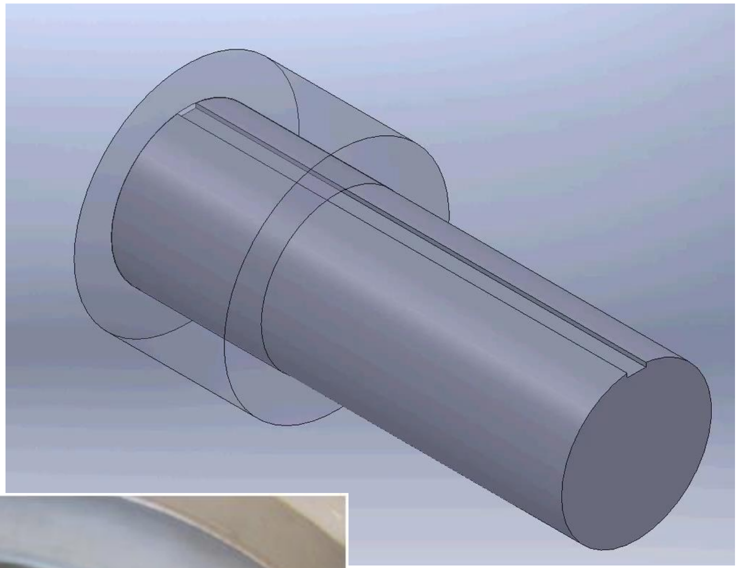
- Shafts
- Flanges
- Impellers
- Gears
- Hubs

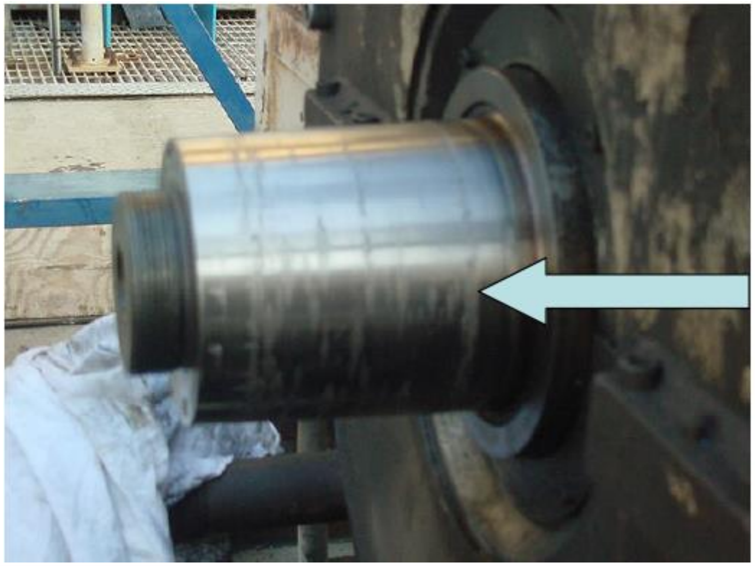


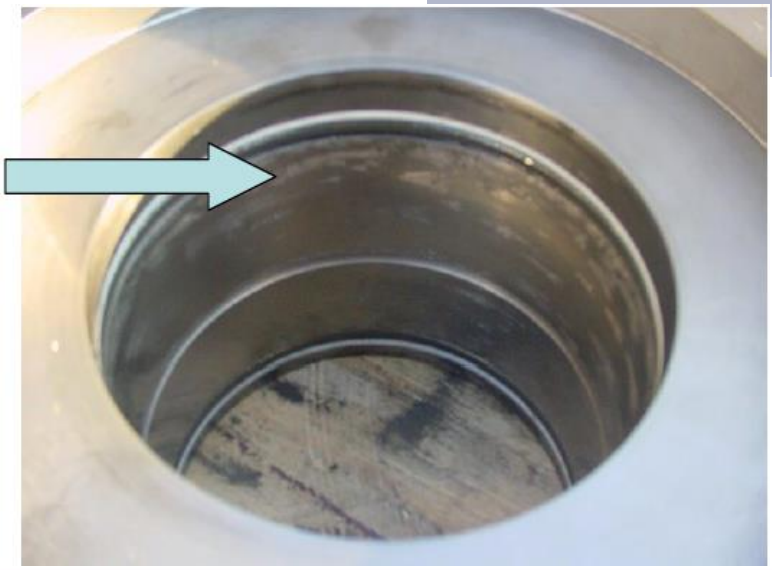
Shaft Systems

Various shaft elements exhibit varying stiffness's

- Each shape twists differently when torqued
- When connected together torque leads to:
    - Localized stress concentrations
    - Localized sliding Movements
        - Galling
        - Fretting



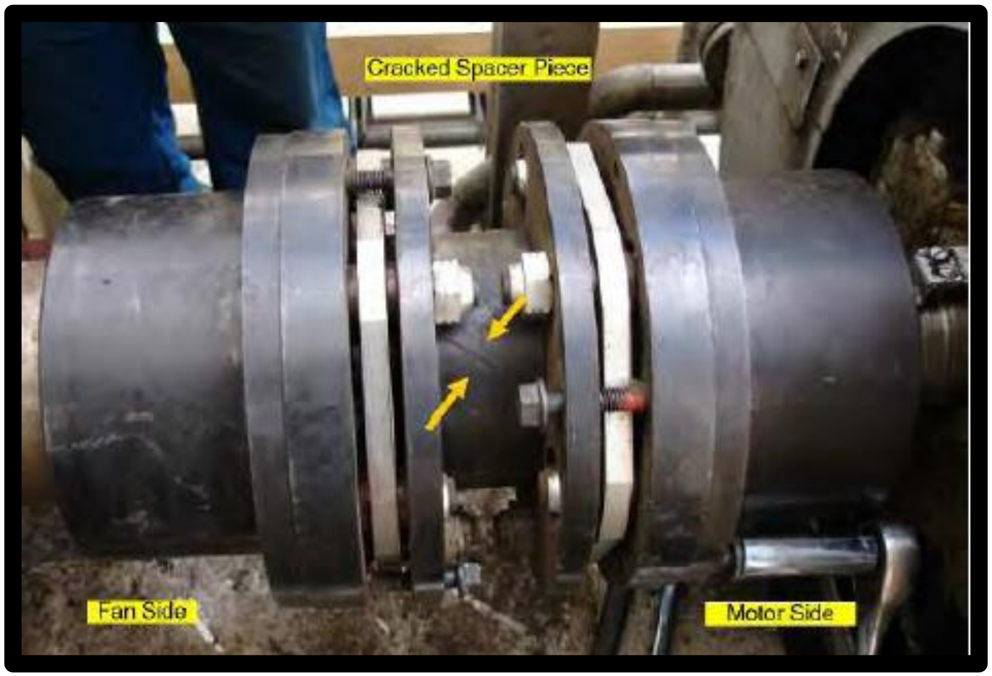




Reference 8

Shaft Systems

Stress concentrations near section changes
tend to attract failure initiation



Cracked coupling spacer due to torsional vibration[1]

Coupling spacer with split crack due to high amplitude torsional vibration[3]

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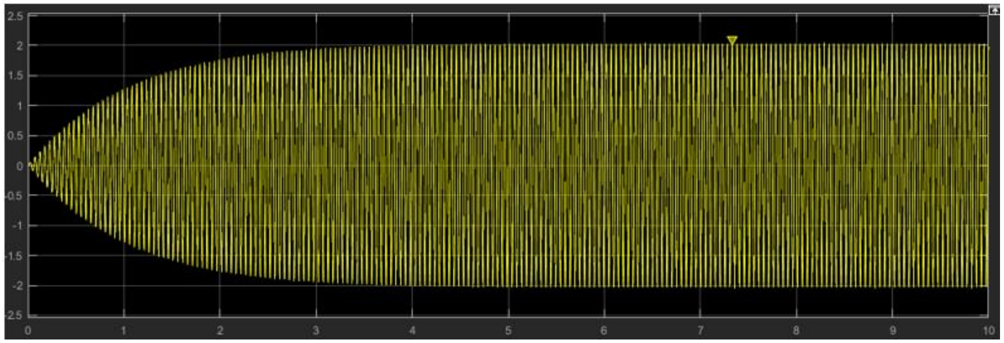
Equipment Problems

If driving frequency matches N then vibration amplitudes can build over time leading to high dynamic torque amplitudes.



Time example of system taking 7.3 sec to build to full torque amplitude[5]

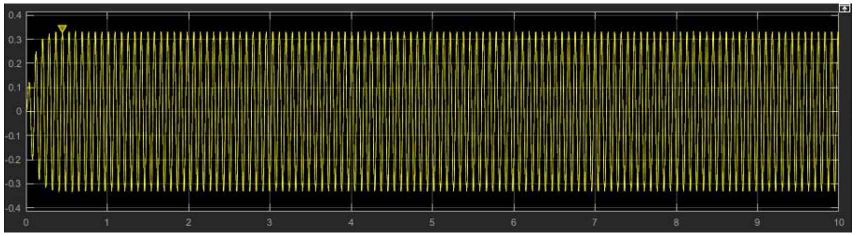
Equipment problems occur when:

- Vibrational torque amplitudes are high
- Torsional vibration occurs for a long period of time

Classes of Vibration

Steady State

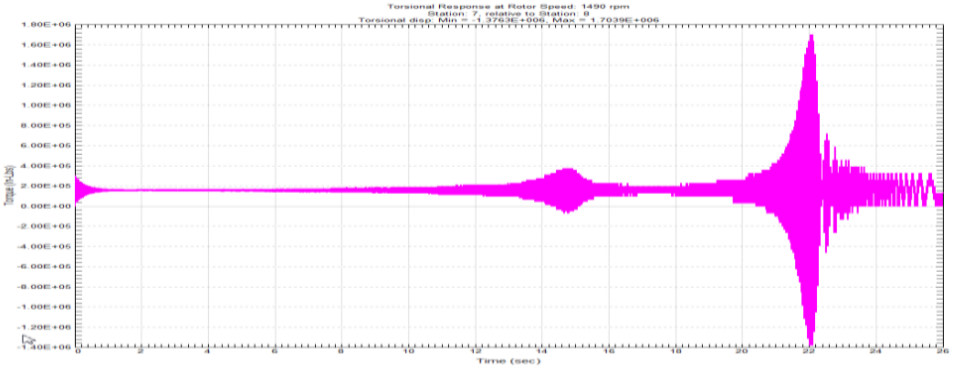
- VFD drives
- Reciprocating machines
- Other positive displacement machines



View of Steady Dynamic Torque [5]

Transient Excitation

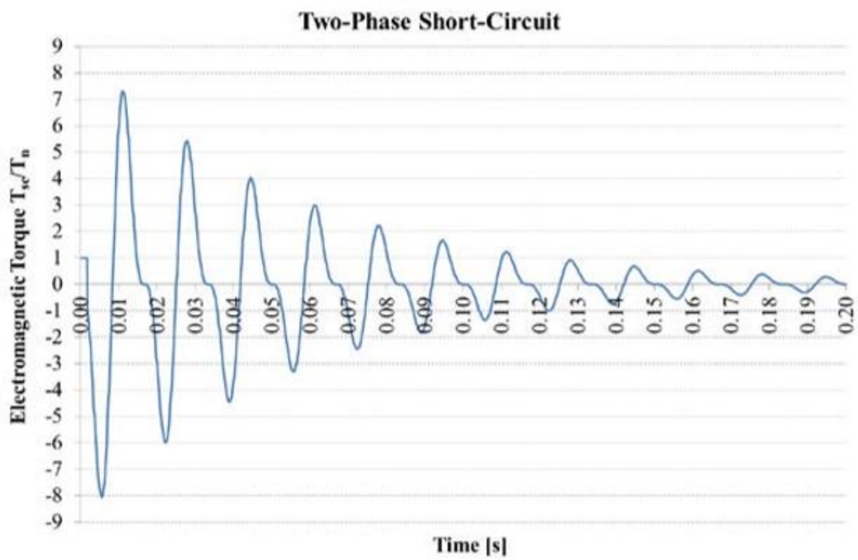
- Synchronous motor line starts
- Local Grid Excitations



Torque vs. time for synchronous motor line start [4]

Classes of Vibration

Spikes
- Short circuits
- Liquid slugs in compressors



Short circuit spike torque by induction motor due to short circuit [2]

Sudden Stops (Step Torques)
- Slug Ingestion in Mixers

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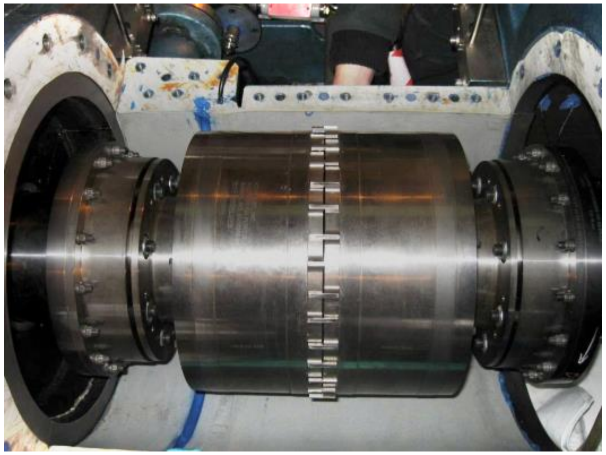
Dynamic Torque Solutions

1. Avoidance
   - Calculation of interferences and setting “Block Out” speeds
   - Torque Monitoring, control, alarm & trip



Dynamic Torque Solutions

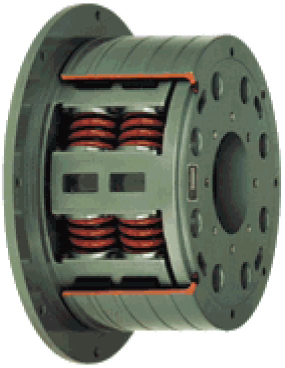
Categories

1. Damping Couplings
    - Rubber Couplings
        - Dampen by hysteresis in rubber

Dynamic Torque Solutions

Categories

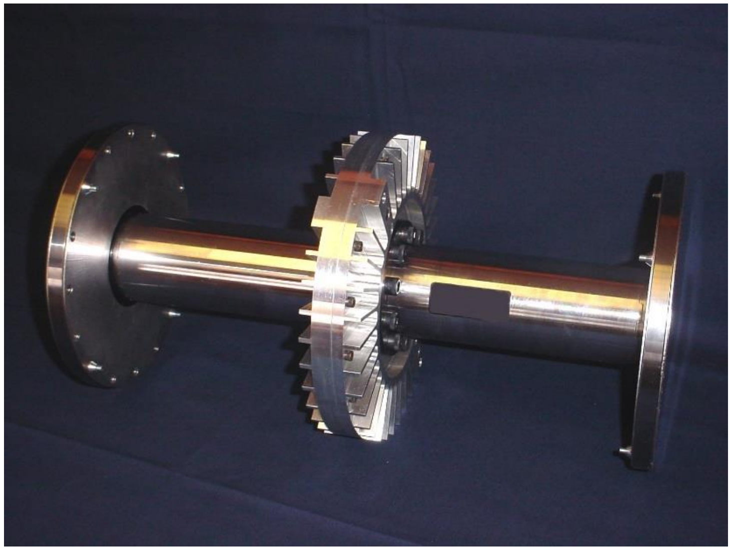
1. Damping Couplings
   - Spring Couplings
     - Attenuation by low stiffness



Dynamic Torque Solutions

Categories

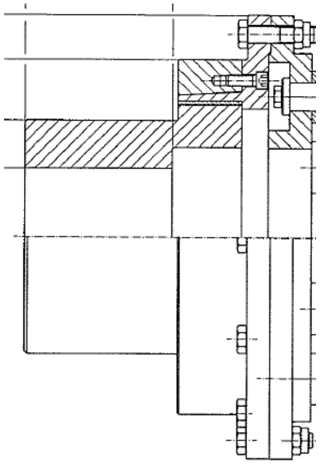
1. Damping Couplings
   - Spring & Damper Couplings
     - Dampen with fluid viscous damping

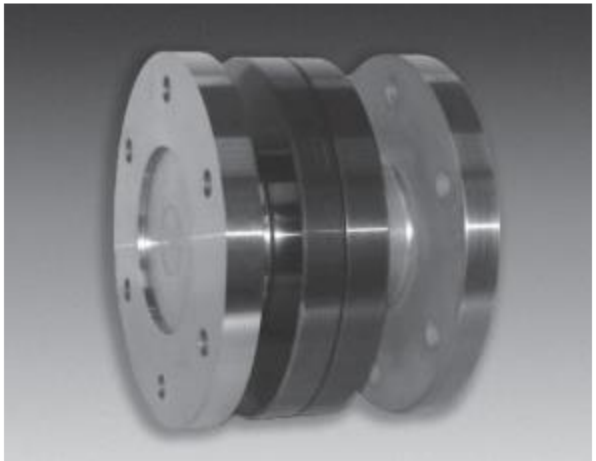


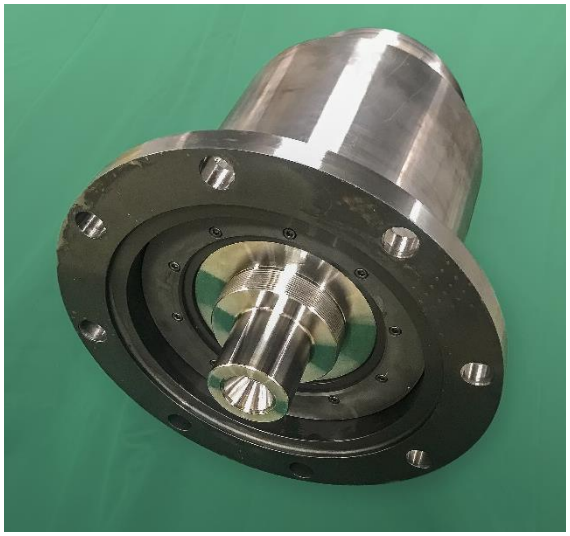
Dynamic Torque Solutions

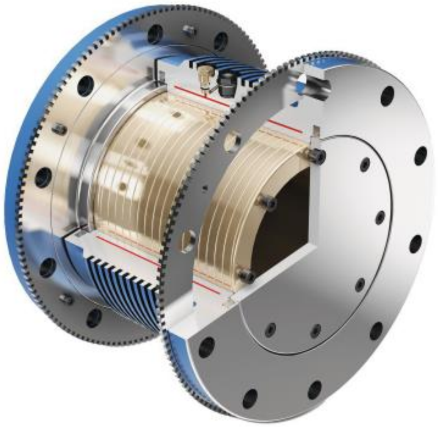
Categories

3. Slip Clutch Couplings
   - Hub Mounted
   - Spacer Mounted





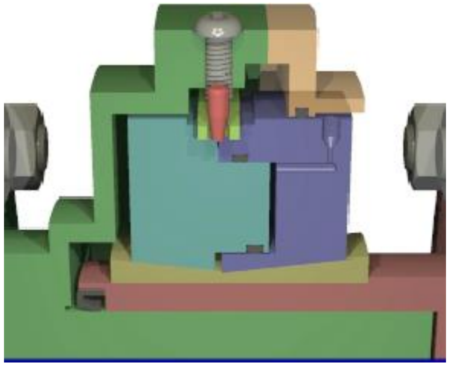


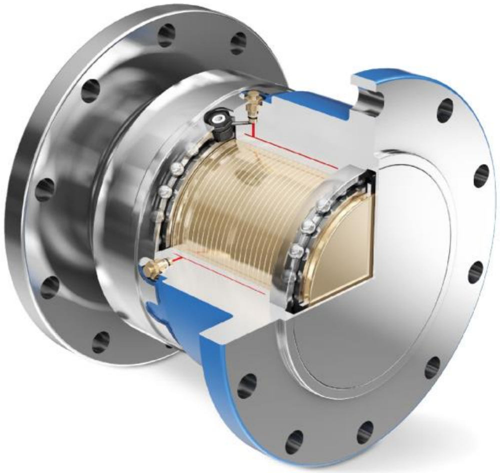


Dynamic Torque Solutions

Categories

4. Torque Fuses
   - Fully release to separate machines





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Solution Approach vs. Torsional Type

Steady State with High Dynamic Torque

- Often associated with reciprocating equipment
- Torsional excitations produce high dynamic energy
    - Damage can accumulate quickly
    - Dissipation rate high
        - Dissipation may not be practical for primary driving harmonics

Solution Approach vs. Torsional Type

Steady State with High Dynamic Torque

- Avoidance/ Know your equipment
    - Know your primary driving frequencies
    - Manufacturers are the best sources for this information
        - Ask for it
        - Find it in your documentation
        - Implement block out speeds
            - Programming of controls
            - Postings for operators

Solution Approach vs. Torsional Type

Steady State with High Dynamic Torque

- Avoidance/ Equipment Changes
    - Changing equipment to new designs will affect train response
    - A change may fix one problem but cause another
        - Motor
        - Coupling
        - Any moving part
    - Plan to reevaluate new equipment configurations
    - May need to set new block out speeds

Solution Approach vs. Torsional Type

Steady State with High Dynamic Torque

- Avoidance/ Process Drift
- "A snake in the grass"
- Equipment aging
  - Changing stiffnesses
    - Bolt loosening
    - Foundation crumbling
    - Structural cracks in housings

Solution Approach vs. Torsional Type

Steady State with High Dynamic Torque

- Avoidance/ Process Drift
- Robust PM
  - Find a problem before it causes a problem
- Dynamic Torque Monitoring
  - Can provide real time monitoring and/or control

- Monitoring of cross-coupled interactions
  - Lateral gear movement due to torque loads
    - Proximity probe measurements
    - Need to filter for torsional frequencies
  - Reference information only

Solution Approach vs. Torsional Type

Steady State with Low Dynamic Torque

- Often associated with:
  - VFD Motors
  - Screw pumps & compressors
- Torsional excitations produce low dynamic energy
  - Dissipation rate low
    - Dissipation is usually possible

Solution Approach vs. Torsional Type

Steady State with Low Dynamic Torque

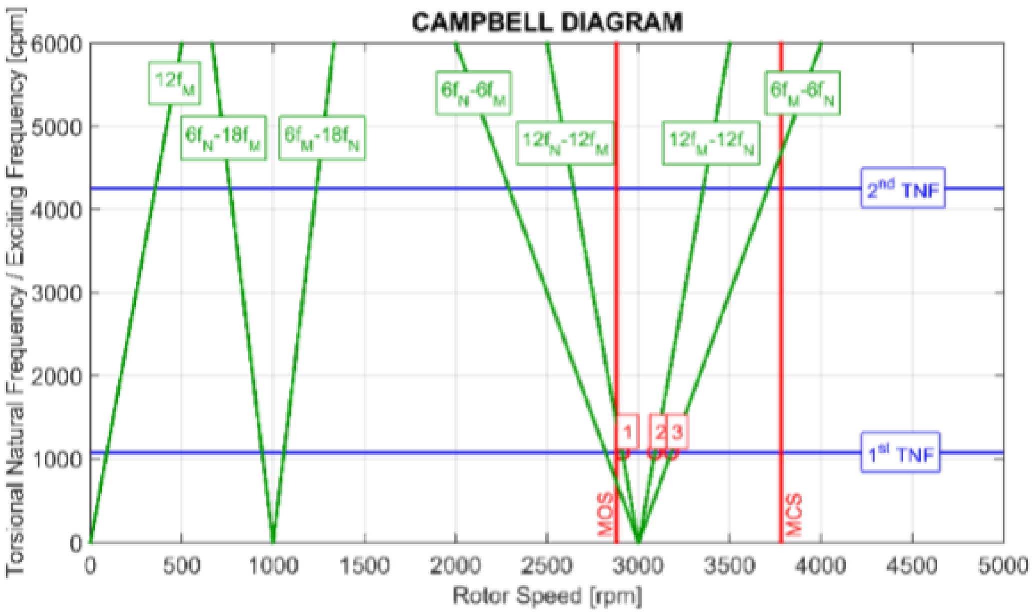
- Avoidance/ Know your equipment
    - Same approach as for high steady state
    - Know your equipment and process
    - Drift has been a factor in a number of failures

Solution Approach vs. Torsional Type

Steady State with Low Dynamic Torque

- Avoidance/ Special Case, VFD Motors
  - Equipment specifically designed to provide broad speed ranges
  - The electrical drive systems produce many low level signals that can get into shaft string
  - Induction motor slip makes load an additional driver of frequency

Notice that there are three interferences at N1 & two more at N2. Reference 7



Solution Approach vs. Torsional Type

Steady State with Low Dynamic Torque

- Avoidance/ Process Drift
- Dynamic Torque Monitoring
  - Can provide real time monitoring and/or control
  - Slow energy accumulation/dissipation should be taken into account when setting control gains
- Monitoring of cross-coupled interactions
  - Lateral gear movement due to torque loads
    - Proximity probe measurements
    - Need to filter for torsional frequencies
  - Reference information only

Solution Approach vs. Torsional Type

Steady State with Low Dynamic Torque

- Damping devices
- A small amount of damping can protect against low dynamic torques.
- Coupling locations are often excellent places to apply damping
    - In three or more body trains it is important to check damp effectiveness at target locations
- For VFD motor drives it is conservative to assume that operation will fall on a natural frequency at some time

Solution Approach vs. Torsional Type

Steady State with Low Dynamic Torque

- Damping devices
- Top Graph, damping at coupling 1 would be most effective.
- Lower graph, couplings 2 & 3 would be more effective

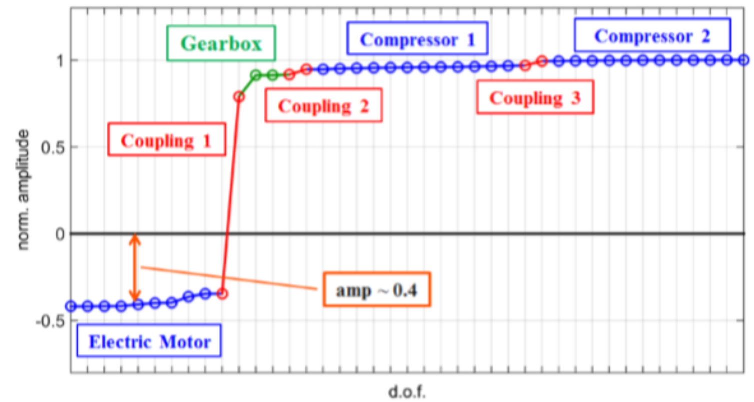


Figure 4 First Torsional Mode Shape (~100 rad/s)

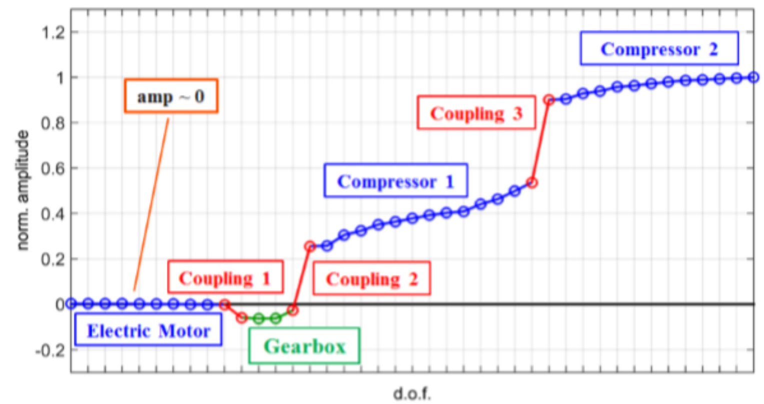


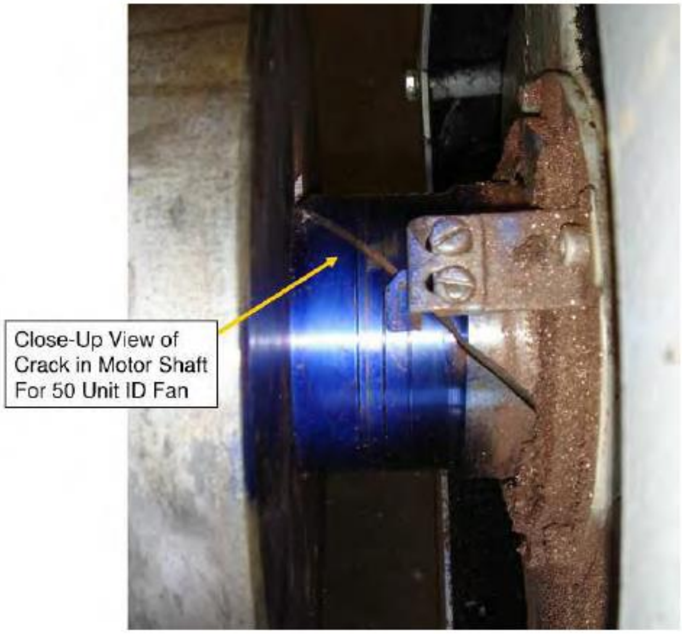
Figure 5 Second Torsional Mode Shape (~450 rad/s)

Reference 7

Solution Approach vs. Torsional Type

An approach to avoid with all steady state dynamic torque

- Replacing a failed coupling with a larger coupling can create a bigger problem

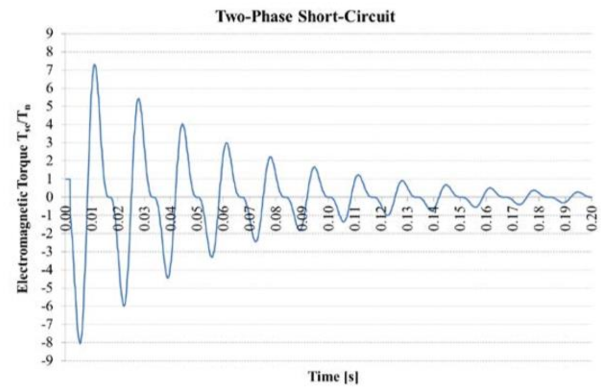


Cracked shaft due to Torsional Vibration[1]
Note, Shaft after original coupling failed and was replaced with larger coupling.

Larger Coupling[1]

Solution Approach vs. Torsional Type

Transient Excitation



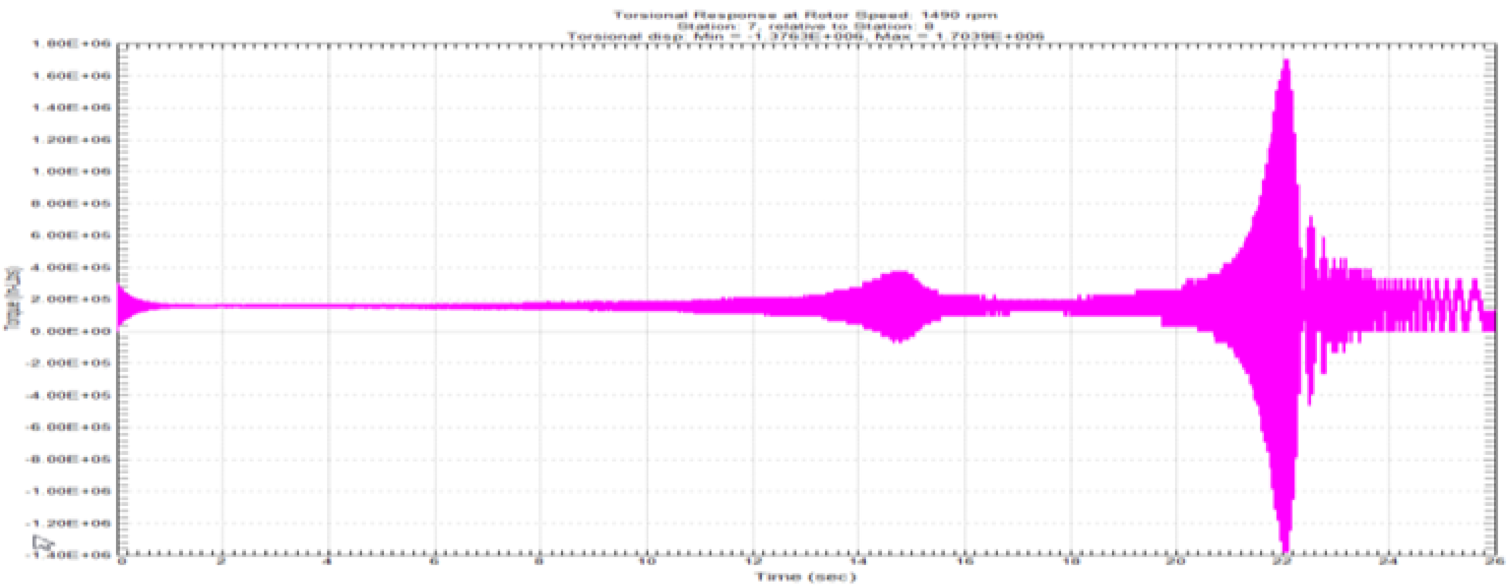
Short circuit spike torque by induction motor due to short circuit [2]

- Synchronous Motor line starts
  - These are known and expected
  - Often limit the life of machinery
  - Avoidable by limiting # if starts
- Local grid disturbances
  - Unplanned events
  - Poorly defined disturbances
  - May or may not include complete loss of power
  - Island grids are susceptible
  - Sometimes caused by nearby equipment
  - A growing focus associated with renewable energy sources
- Ride thru is often the goal

Solution Approach vs. Torsional Type

Transient Excitation

- Synchronous Motor line starts
  - Damage accumulation occurs at the short but large area
  - “the belly of the snake”



Torque vs. time for synchronous motor line start [4]

Solution Approach vs. Torsional Type

Transient Excitation is often not completely avoidable

- Avoidance/ Damage Avoidance
    - Designing robust equipment
    - Limiting starts where possible
    - Increasing startup acceleration can lower torque levels
        - Limited by process parameters
        - Influenced by load equipment inertia

Solution Approach vs. Torsional Type

Transient Excitation

- Damping Couplings
    - Can dramatically reduce amplification[4]
        - One case standard couplings exhibit 10.2 p.u.
        - Damping couplings reduce amplification factor to ~3.0-4.0p.u.
        - An improvement that dramatically increases equipment start life.
- When selecting Damping couplings:
- Be sure to consider the energy dissipation capabilities of a candidate product.

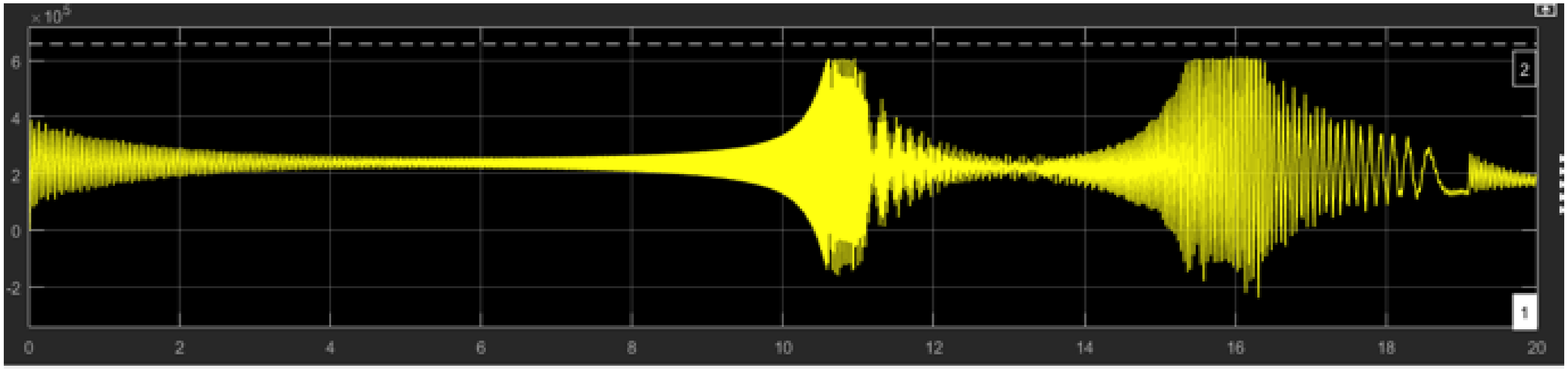
Solution Approach vs. Torsional Type

Transient Excitation

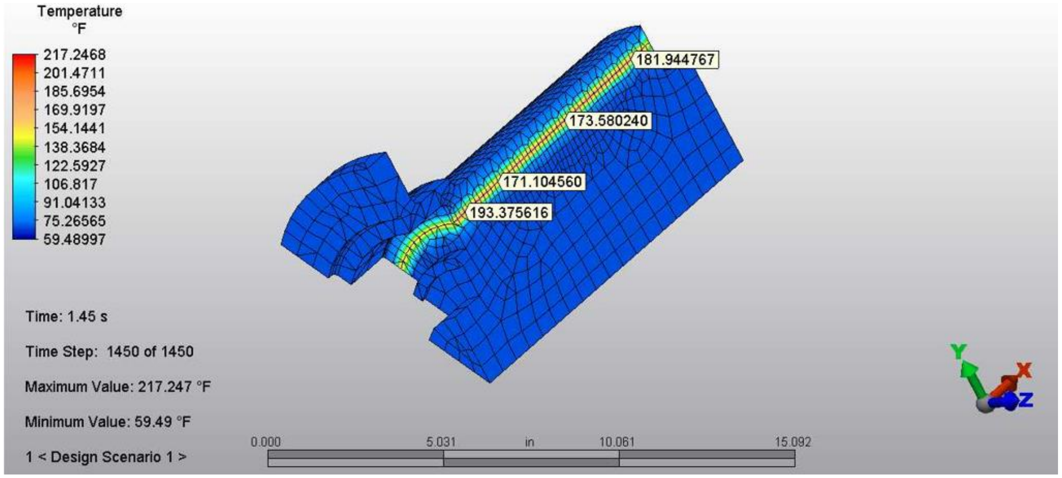
- Slip Clutch Couplings
  - Can dramatically reduce amplification[4]
    - One case standard couplings exhibit 10.2 p.u.
    - Damping couplings reduce amplification factor to ~3.5-4.0p.u.
    - An improvement that dramatically increases equipment start life.
- When selecting slip clutch couplings:
- Be sure to consider the energy dissipation capabilities of a candidate product.

Solution Approach vs. Torsional Type

Slip Clutch Couplings



Synchronous motor line start torques with slip clutch device[5]



Thermal example of slip clutch after start event [5]

Solution Approach vs. Torsional Type

Severe Transients

- Characterized by extreme shock energy potential
- Dynamics are usually associated with post event ring-down
    - Not usually a factor

- Survival of energy receiving equipment is the goal

- Event energies can be far greater than any device can absorb

- Torque Fuses are used for full disconnection

References

1) Torsional Vibration Problem With Motor/ID Fan System Due to PWM Variable Frequency Drive, 37th Turbomachinery Symposium, Troy Feese & Ryan Maxfield
2) Torsional Excitation Upon Short –Circuit In Induction Motors In Conventional High Speed Trains, 46th Turbomachinery Symposium, Tuomo Aho, Janne Nerg, Christopher Baum
3) Torsional Vibration Problem with VRD Motor/ID Fan at an Oil Refinery, 2014 Reliability.com, Troy Feese
4) Optimizing Component Selection in Synchronous Motor Compressor Trains Based on Technical and Financial Considerations, 46th Turbomachinery Symposium, Martin Maier, Garry Studley
5) Riverhawk Engineering Archive, R. Whitney
6) Mark's Standard Handbook for Mechanical Engineers, 9th ed. By Eugene Avellone & Theodore Baumeister III, McGraw Hill Book Company, ISBN 0-07-004127
7) Torsional Modal Damping of A LCI Driven Geared Moto-Compressor Train: Evaluation, Optimization Criteria and Active Control, 36th Turbomachinery & Pump Symposia, Gaspare Maragioglio, Daniel Sgro, Paolo Calore, Lorenzo Failla, Pierluigi Tenca
8) The Evaluation of the Coefficient of Friction Used to Calculate Hub Slip Torque, Case Study 6, 36th Turbomachinery Symposium, Pat McCormack, Monica Crowe, Jeff Buck, Bill Robichaux

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