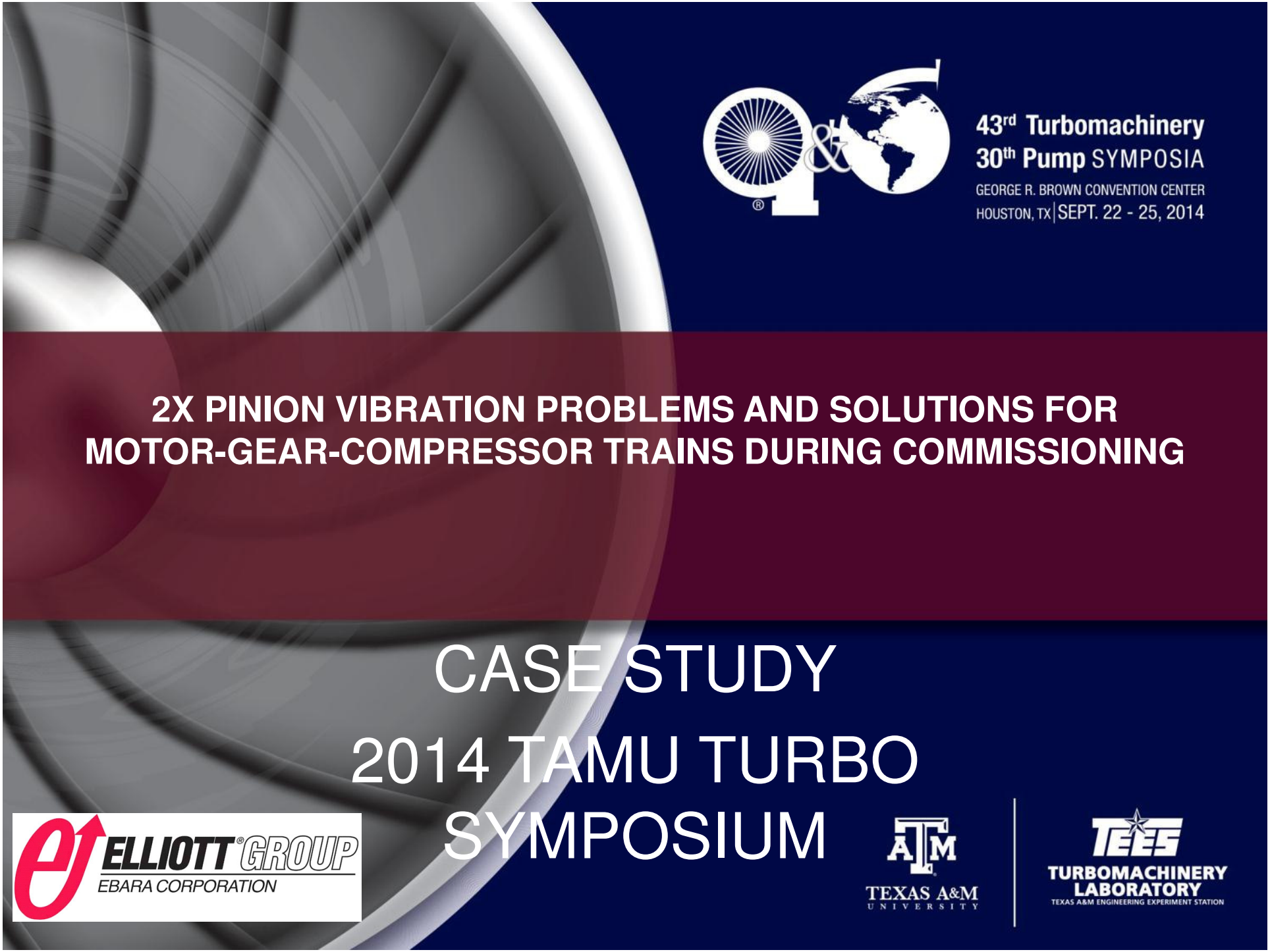

2X Pinion Vibration Problems and Solutions for Motor-Gear-Compressor Trains During Commissioning

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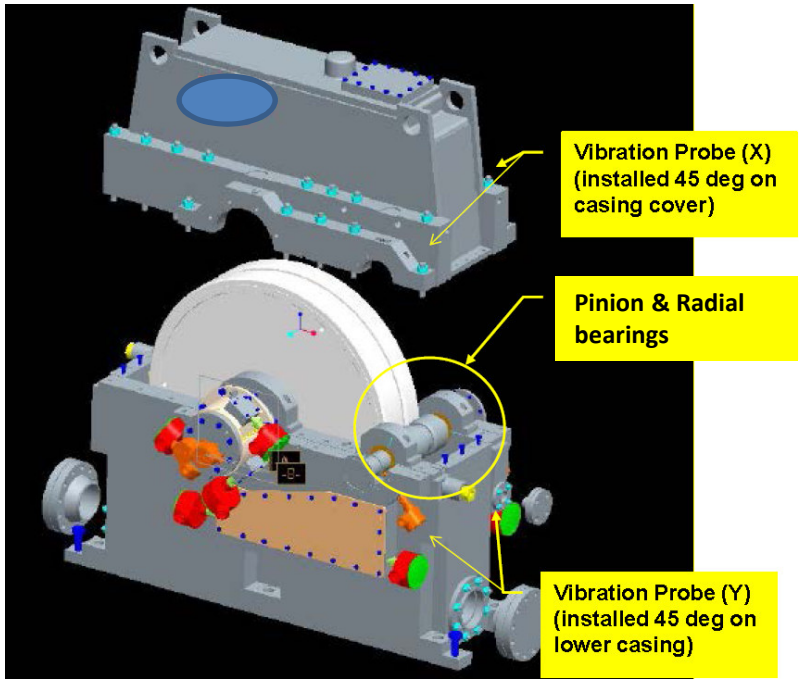
Problem Description

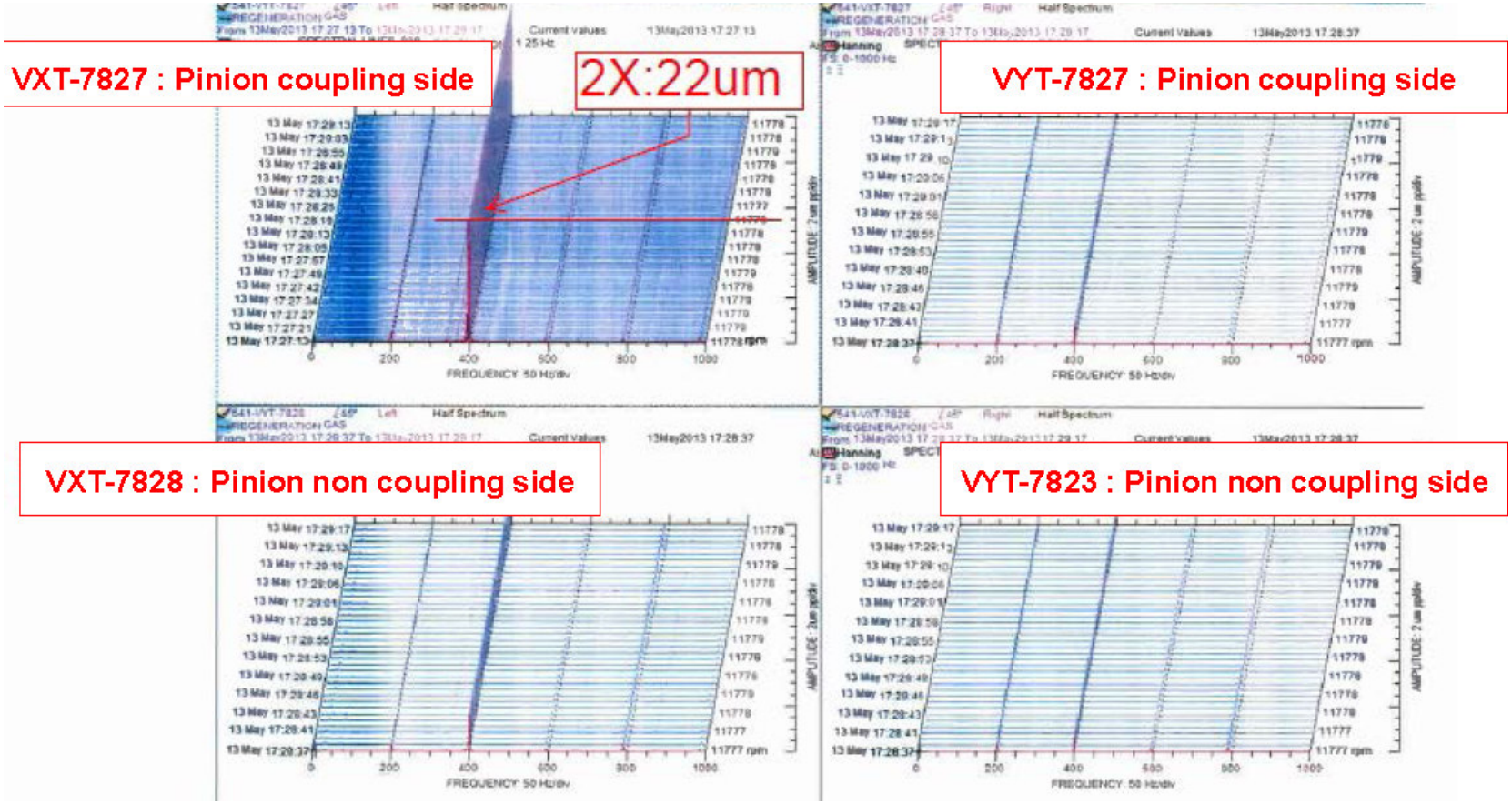
- Basic information:
  - Customer: ******
  - Gear Vendor: ******
  - Where: ******
  - When: 2013
  - RADIAL BEARING : PRESSURE DAM
  - THRUST BEARING : TILTING PAD
  - MINIMUM SPEED [rpm] : 1196 / 9796
  - RATED SPEED [rpm] : 1495 / 12245
  - MAX SPEED [rpm] : 1570 / 12857
  - GEAR RATIO, # OF TEETH : 8.1905 (21/172)
  - TRANSMISSION POWER (RATED/NOR) [kW] : 4500/3604



- What happened:
  - 4 identical equipment trains, 3 tested. All 3 have the same symptom: 2X vibration at coupling side of the pinion. Vibration from all other probes including the motor and the compressor is low.

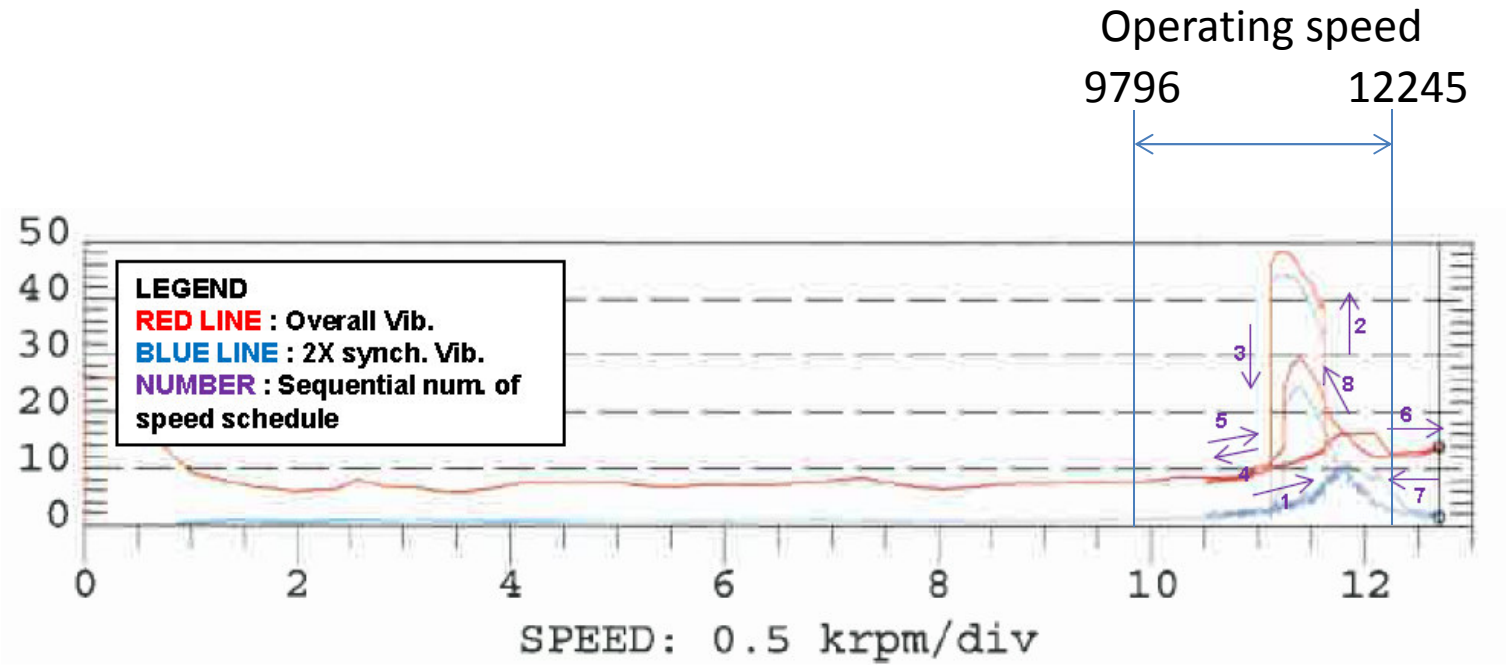
Problem Description - Continued

- Waterfall plots



Problem Description – Continued2

Bode Plot: Pinion Coupling Side X Direction



Root Cause Analysis

- Possible causes:
  - 1*: Coupling misalignment
  - 2*: Motor/VFD
  - 3: Bearing looseness
  - 4: Gear imbalance/bad teeth/alignment
  - 5: Gear soft-foot
  - 6: Shaft run-out
  - 7: Bad measurements
  - …

*: Most possible reasons

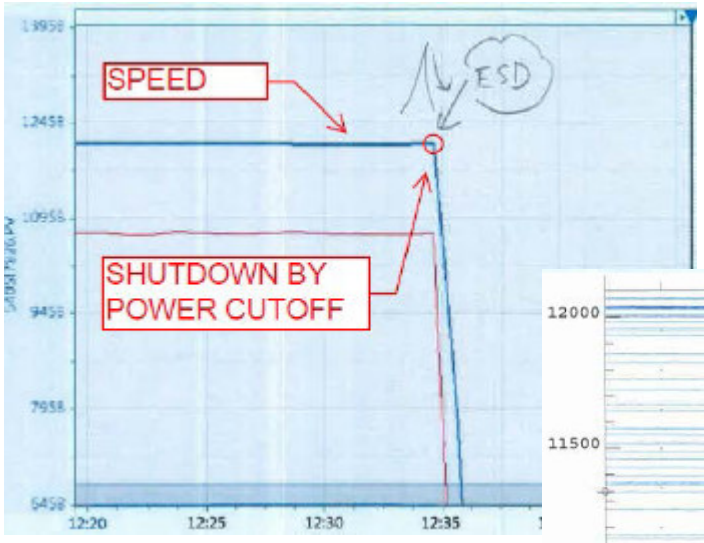
Root Cause Analysis – Continued2

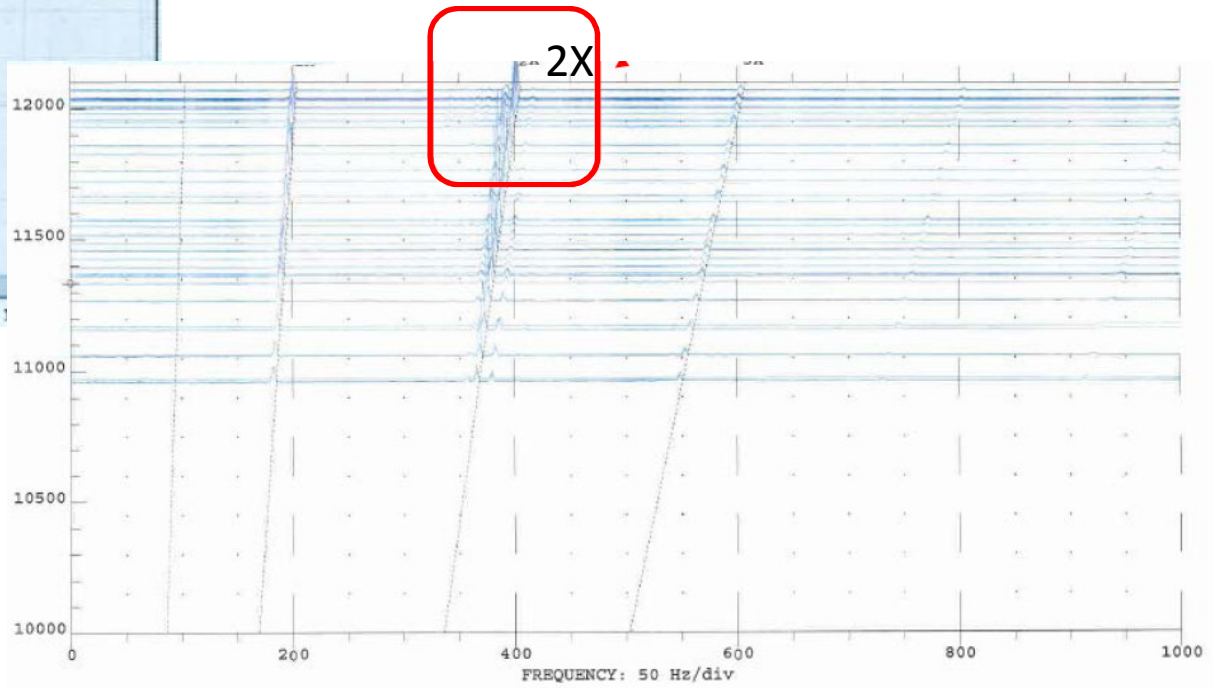
- Investigation:
  - Coupling alignment was the first thing checked (cold alignment only)
  - Bearing looseness: tolerance checked
  - Gear imbalance/bad teeth: blue checked/visual
  - Gear soft-foot: checked
  - Shaft run-out: checked
  - Bad measurements: checked

The above are not likely the true causes, because three identical trains exhibit exactly the same symptom

Root Cause Analysis – Continued3

- Motor/VFD problem is ruled out by cutting off the power:
  - 2X shows up even with power cut-off





Root Cause Analysis – Continued4

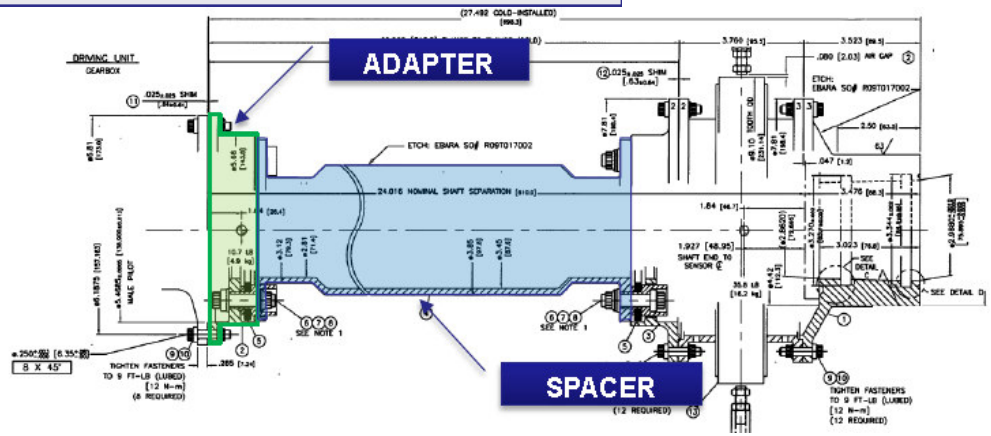
- The only possibility left: hot/dynamic misalignment generates 2X excitation
- What causes the 2X?
  - literature: only parallel misalignment yields 2X (Ovalle etc.). The sources could be:
    - The disk, diaphragm, bolts, etc. characteristics
    - Interaction between Pinion and Compressor/ coincidence of critical speeds (Seon etc.)
  - The simplistic modeling for 2X excitation is (Ovalle):
    - $K=A*\sin(\omega t)$, so that $F=K*\sin(\omega t)=A*\sin^2(\omega t)=A*(1-\cos(2*\omega t))/2$, where
      - K is the dynamic stiffness of the coupling
      - ω is the running speed
      - A is the magnitude
      - F is the force/excitation from the coupling
- How to predict/calculate misalignment force?
  - For constant misalignment force (Gibbons): 5-6 lbf, calculated based on the alignment measurement, transmitted power, speed etc.
  - For dynamic misalignment force: ?
- Measure hot misalignment?
  - Schedule is tight
  - Hot misalignment may not be reflecting/equal to the dynamic force
  - Effectiveness of correcting hot misalignment is questionable

Solution and Result

An relatively simple solution: change the coupling weight to shift the critical speed

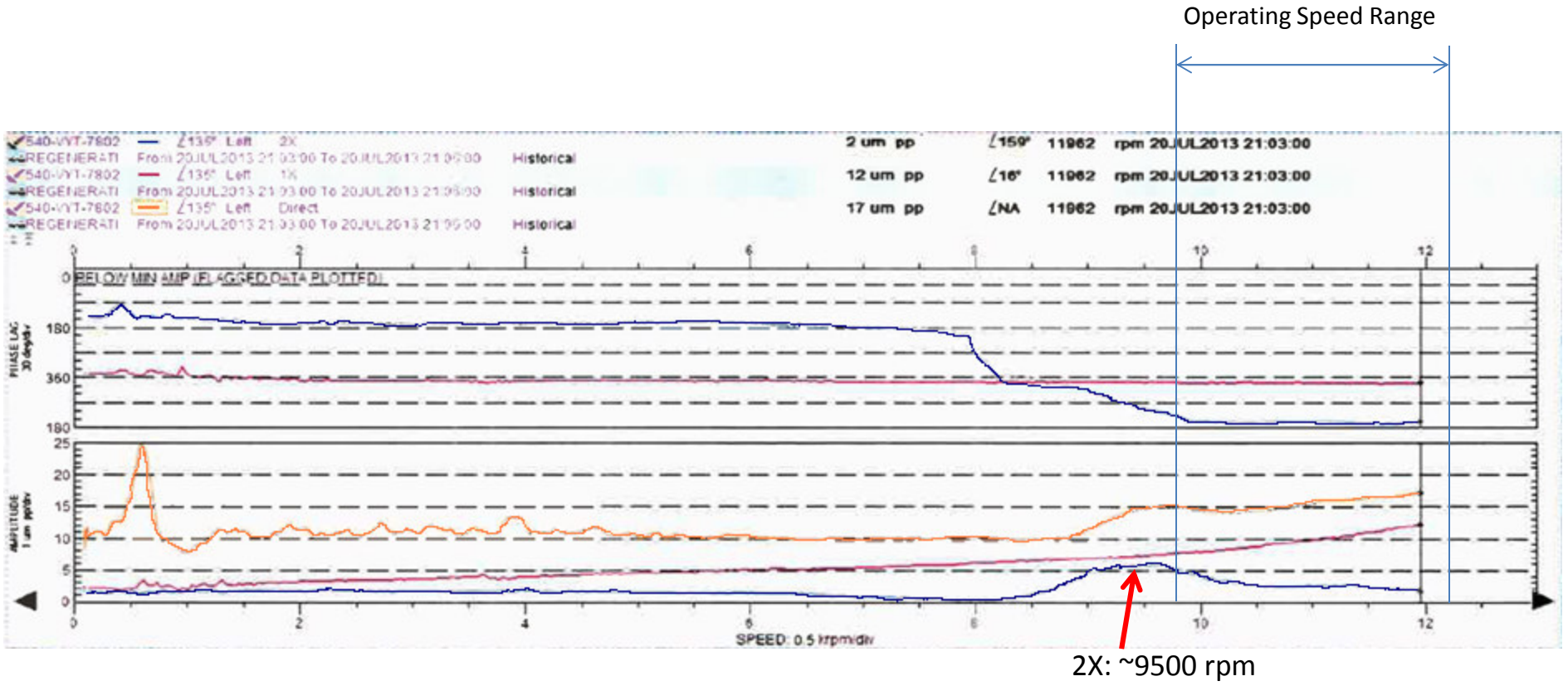
NO.	DESCRIPTION	CRITICAL SPEED by Gear Vendor (CPM)	CRITICAL SPEED by ELLIOTT (CPM)	REMARKS (HALF WEIGHT ON PINION)
1	Original Coupling	23614 (11807 rpm)	23400-24000 (11700-12000 rpm)	4.9kg(10.7Lb)
2	Titanium Space Coupling	25545 (12773 rpm)	25000-25800 (12500 – 12900 rpm)	3.4kg(7.6Lb)
3	Heavy Adapter Coupling	19158 (9579 rpm)	19000-20000 (9500-10000 rpm)	9.5kg(21Lb)

Note: Pinion model and bearing coefficients are provided by Gear Vendor



Solution and Result - continued

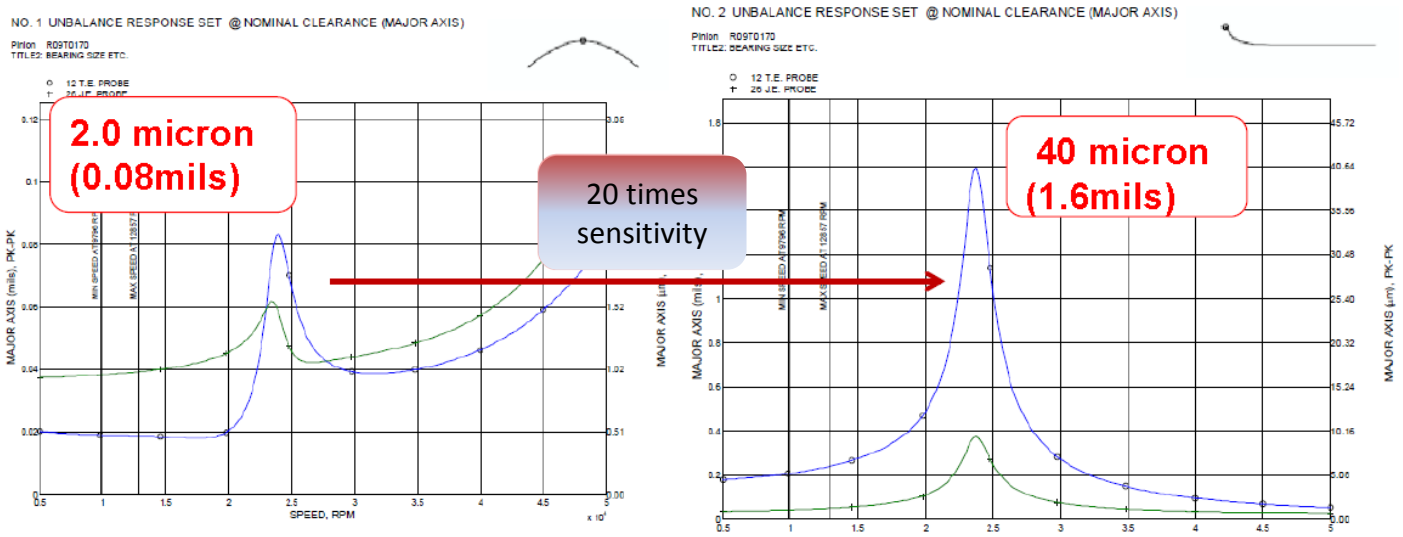
- Heavy Adapter Coupling Test Result



The prediction is close, and the problem is solved!

Lessons Learned

- There are many gears with VFD/Turbine drives may operating smoothly with 1st critical speed in the 2X range, why these gears have problems?
- What are different/special about these gears?
  - Bearing load: 440 psi (high in general, but common for gears)
  - Bearing design: with fins
  - Coupling: with power wheel (complex and heavy)
  - Pinion: very sensitive to coupling unbalance/excitation (see plots below)
  - Compressor second critical speed: 21400-22800 rpm (close to 2X)



Lessons Learned - continued

- Analytically, with the current pinion-bearing model, the excitation from the coupling needs to be ~100 lbf to reach the maximum measured 2X amplitude (~1.4 mils), but the calculated misalignment force is only 5-6 lbf. There are a few possibilities:
  - The calculated Bearing coefficients may not be very accurate (damping might be significantly lower) for high load and/or high speed (see Kocur's survey for the diversity of the calculated coefficients by different vendors).
    - Gear vendor tried to modify the location of the bearings to lower the 2X, but not effective enough.
  - Dynamic excitation from the coupling might be much larger than static/constant alignment force.
  - The second critical speed of the compressor might contribute significantly to the dynamic excitation (Seon).

Lessons Learned – continued2

- What can we do to prevent problems in the future?
  - Avoid pinion 2X speed range if possible.
  - Otherwise (open for discussion)
    - For gear:
      - Check bearing load
      - Check bearing type/design
      - Check coupling side unbalance sensitivity (overhung length/bearing span)
      - Check empirical data to backup the design/application
    - For compressor:
      - Check the possible coincidence of the critical speed.
    - For Coupling:
      - Check coupling type, structure

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