Proactive Shop Strategy for a Successful Turbine-Generator Rotor Outage

APPLIED ROTORDYNAMICS:
AN OUTAGE GUIDE
FOR SERVICE SHOPS AND CLIENTS

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For a Successful Outage

- Presenting a new approach to outage planning and rotor service
  - *Will not need any post-startup field balancing*
  - Can save $Millions in lost production time
  - Guaranteed and proven results
  - Based on a new view and understanding of rotordynamic behavior

Why Amend Outage Procedure?

- Practically all electric utilities in the US have good, established outage planning procedures
- However, amid tasks of scheduling and budgeting a total turbine-generator outage, plant engineers do not have time or resources to devote to the fine points of rotordynamics
- Plants traditionally use field balancing to resolve "unexpected" vibration issues, but this doesn't truly resolve the problem, and can create larger problems later

Why Amend Outage Procedure?

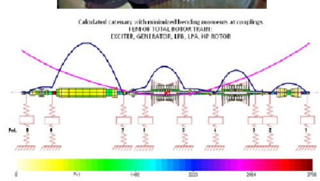
- Dynamics and vibration issues can lead to large financial losses from damaged equipment and lost power production
- Most power plants do not have proprietary rotordynamics analysis software needed for finite element modeling and rotor runout and alignment analysis; these activities are substituted by applying "standard procedures"
- Without detailed study, it's difficult to spot the small things that cause vibration problems, from a rotordynamics analysis perspective
- Typically, when using contractors, all responsibility for decisions falls on the plant – Following our method presented here, we as a contractor take responsibility, and guarantee results

For a Successful Outage

- New approach follows consistent steps
  - Creates added value, without adding any notable time or expense
  - Must be integrated into outage schedule from the start; ideally amended into Terms & Conditions of service contract
  - Same methods can also greatly enhance long-term unit reliability
    - Catches potential problems early (predictive)
    - Minimizes rotor forces/stresses that lead to later problems or damage

The Key Outage Steps

1. Condition assessment of rotordynamic behavior prior to & during shutdown by collecting vibration data
2. Thorough physical runout evaluation (full body, couplings, faces, rims, coupling boltholes)
3. Finite Element modeling
4. Machining (if needed)
5. Balancing by 2N+1 plane method
6. Reinstallation and (re)alignment based on improved rotor train condition



Why This Approach Works

- Guarantees identification and resolution of all eccentricities, whether induced from misalignment or intrinsic to the rotor
- These eccentricities are the basis of unwanted vibration and damaging forces
- Resolution of found problems is based on specific unit data and facts alone
- Takes into account true rotor-bearing behavior, and eliminates assumptions, leaving no "surprises"

The Central Point

- In a service environment, **>80-90%** of rotors exceed ISO-1940 eccentricity limit guidelines
- This too-high eccentricity is the fundamental root cause of most rotor vibration problems
- Knowing the dynamic effects of eccentricities of various types, we can successfully resolve all issues of high vibrations or forces
- Properly addressing and resolving rotor eccentricities during the outage will prevent nearly all problems at unit restart

Eccentricity Sources

- Machining errors
- A bow in the rotor
- Misalignment in installation
- Bent coupling(s) "forced" together

Eccentricity creates great difference in:
Dynamic behavior
Balancing approach
How it runs in the field

- Eccentricity Based on ISO 1940: (G2.5 rotors)
  - **< 0.5 mils** can be **neglected**, considered as "concentric"
  - **> ~ 2 mils MUST be taken into account during balancing**
  - **> 0.5 mils in coupling or journal MUST be machined**

- **Must take detailed runout readings!**

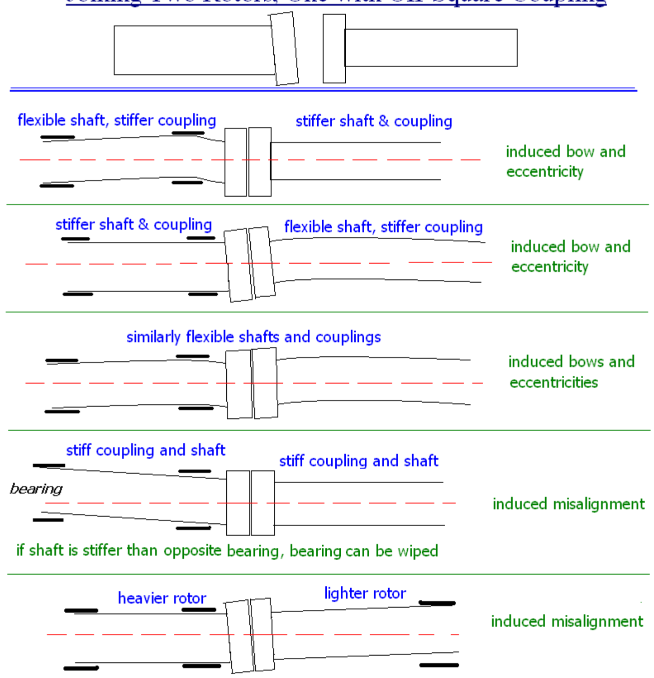
Problems from Coupling Eccentricity

- Bent rotor shaft can create off-square coupling; bent coupling can create eccentric shaft

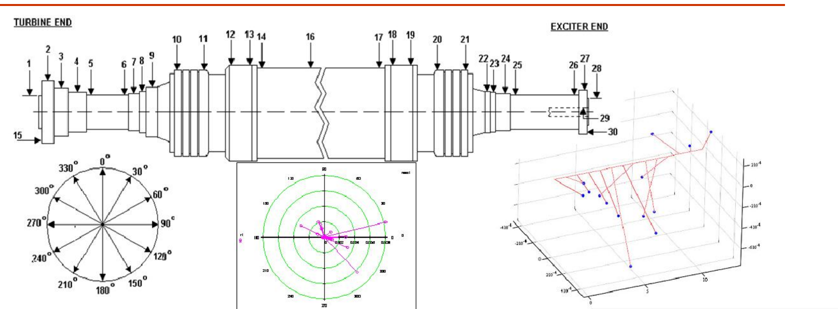
- Off-square couplings can induce:
  - Bows and/or cyclic bending in more flexible components (a cause of rotor cracks)
  - Axial vibration, which can lead to fatigue/cracks in rotors and LSBs

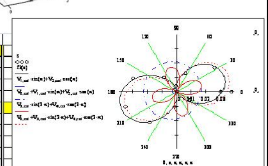
- If rotor is bowed/bent and is stiffer than bearing, the bearing can be wiped

Joining Two Rotors, One with Off-Square Coupling



Sample of Runout Evaluation: Note High Eccentricities





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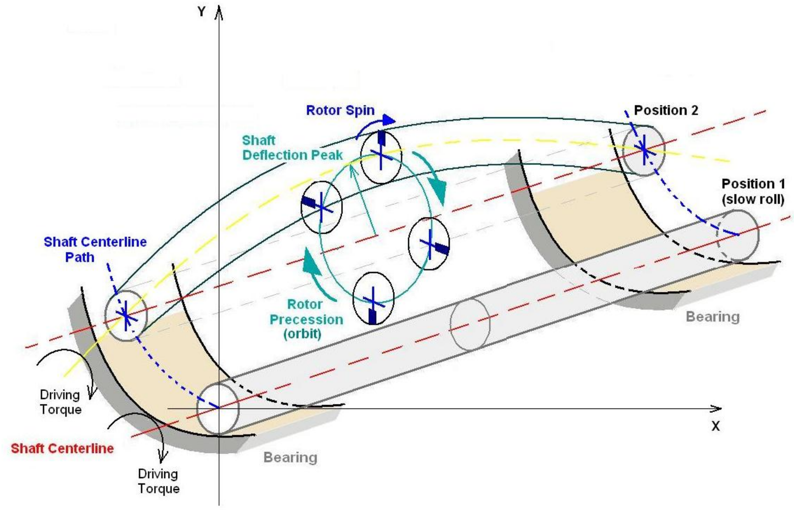
90	0.0016	0.0004	0.0000	0.0000	0.0003	0.0005	0.0006	0.0012	0.0020	0.0039	[illegible]	[illegible]
120	0.0000	0.0000	0.0000	0.0003	0.0006	0.0014	0.0016	0.0014	0.0028	0.0129	[illegible]	[illegible]
150	0.0020	0.0006	0.0007	0.0009	0.0012	0.0021	0.0022	0.0030	0.0033	0.0311	[illegible]	[illegible]
180	0.0044	0.0008	0.0006	0.0006	0.0007	0.0011	0.0010	0.0005	0.0010	0.0363	[illegible]	[illegible]
210	0.0056	0.0015	0.0011	0.0005	0.0003	0.0005	0.0003	0.0004	0.0000	0.0282	[illegible]	[illegible]
240	0.0059	0.0014	0.0009	0.0004	0.0001	0.0002	0.0002	0.0009	0.0017	0.0105	[illegible]	[illegible]
270	0.0048	0.0008	0.0004	0.0001	0.0000	0.0006	0.0007	0.0011	0.0007	0.0000	[illegible]	[illegible]
300	0.0027	0.0003	0.0001	0.0002	0.0002	0.0012	0.0016	0.0012	0.0005	0.0105	[illegible]	[illegible]
330	0.0017	0.0004	0.0002	0.0002	0.0003	0.0013	0.0017	0.0011	0.0013	0.0296	[illegible]	[illegible]
Max	**0.0059**	**0.0015**	**0.0011**	**0.0009**	**0.0012**	**0.0021**	**0.0022**	**0.0030**	**0.0033**	**0.0371**	**0.0153**	**0.0030**
	Evaluated Eccentricity (one per rev)											
1X Amp	0.0021	0.0002	0.0002	0.0002	0.0003	0.0003	0.0002	0.0005	0.0009	0.0033	0.0015	0.0009
Angle	262.1	291.4	250.2	183.8	148.2	173	162.7	174.1	152.1	168.1	117.1	77
	Evaluated Eccentricity (two per rev)											
2X Amp	0.0012	0.0006	0.0004	0.0002	0.0003	0.0008	0.0009	0.0008	0.0009	0.0171	0.0062	0.0004
Angle:	58.7	50.5	40.6	16.2	175.8	158.8	155.7	142.5	138.3	15.4	161.7	28
Angle:	238.7	230.5	220.6	196.2	355.8	338.8	335.7	322.5	318.3	195.4	341.7	308

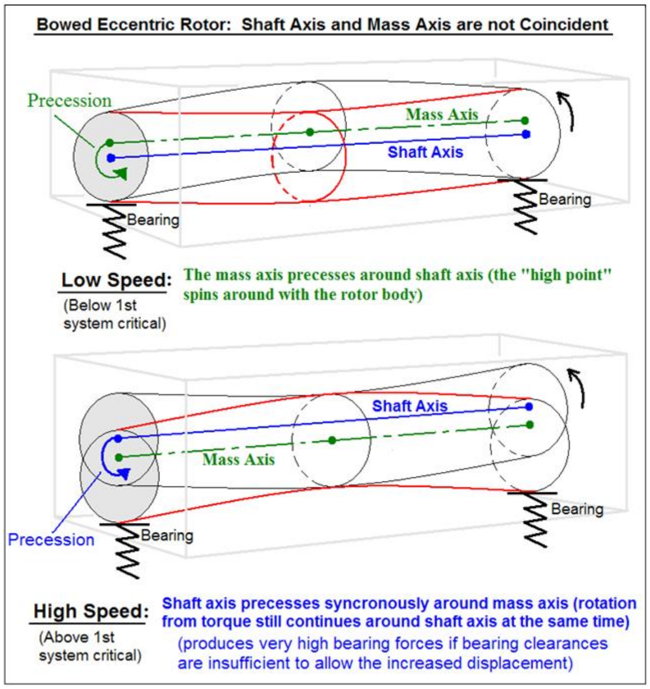
Why does Rotor Mass Eccentricity Create Problems?

- "Vibration" vs. Precession and Spin



Why does Rotor Mass Eccentricity Create Problems?

- Below 1st system critical:
  - All rotation around geometric axis
- Above 1st system critical:
  - Spinning still around geometric axis
  - Synchronous rotation (aka, precession) of geometric axis around mass axis
  - **Mass axis becomes center of rotation**
- Change in axis causes static equilibrium to change, which causes rotor position to change



Geometric Axis vs. Mass Axis

- If balancing an eccentric rotor solo (uncoupled) in a balancing facility by standard methods:
  - All balancing performed above 1st critical will balance the rotor around its mass axis

  However…
  - In the field, the rotor will be constrained to its geometric axis for all speeds
  - This will lead to the "well-balanced" rotor having high vibrations in the field

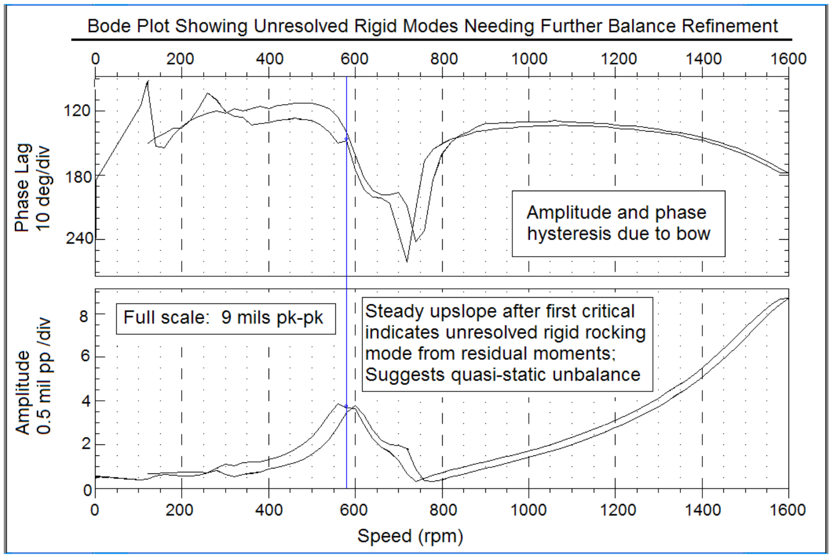
Balancing Rotors with Mass Eccentricity

- Goal: eliminate effects of inertia forces from mass eccentricity
- Must deal separately with rigid mode responses and bending modal responses
- Must properly distribute weights between sufficient number of balancing planes

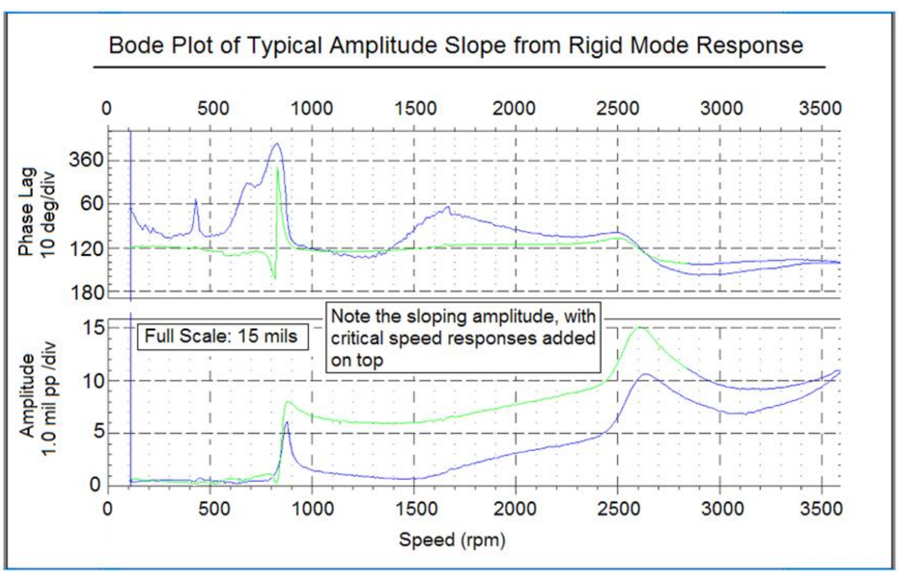
Rigid Modes vs. Bending Modes

- Rigid mode responses:
  - Arise from distributed mass eccentricity
  - Proportional to rotor speed
  - Visible at all speeds
- Flexible mode responses:
  - Arise from amplification at criticals
  - Size depends on system damping
  - Visible only near critical speeds
- ***Balancing of flexible mode responses requires that the rigid modes are already resolved (with bearing forces vanished)***

Example of Unresolved Rigid Mode



Rigid Mode plus Resonant Responses



Rotor Balancing

- Current methods: (flexible rotor balancing)
  - N-method
    - Based on displacement readings
    - Works well for concentric rotors
    - On eccentric rotors, distorts shaft, creates high forces
  - N+2 method
    - Based on bearing force readings
    - Requires balancing through all critical speeds
    - Works for eccentric rotors operating above only 1st mode, but not higher modes
- Neither method removes effects of inertia forces on significantly eccentric, flexible rotors

Rotor Balancing: New Method

- Quasi-High Speed Balancing Method
- Approach: **Use 2N+1 Balancing Planes**

  *(**N** is the rotor's highest mode in its operating speed range)*

Based on the principle:

- *A truly rigid rotor can be balanced in any **2** arbitrarily-selected planes*

Rotor Balancing: New Method

- Rotor divided into "Rigid Elements"
  - Based on FEM Modeling
  - Planes selected at modal element nodes
  - In practical terms, "rigid" means the largest modal element in the FE model that doesn't bend, within full operating speed range
- Each "Rigid Element" is balanced in 2 planes
- Solve rigid modes first, at speed < 50% above 1^{st} critical speed
- Solve residual modal responses last, if apparent at operating speed

Balancing Rigid Mode Responses First

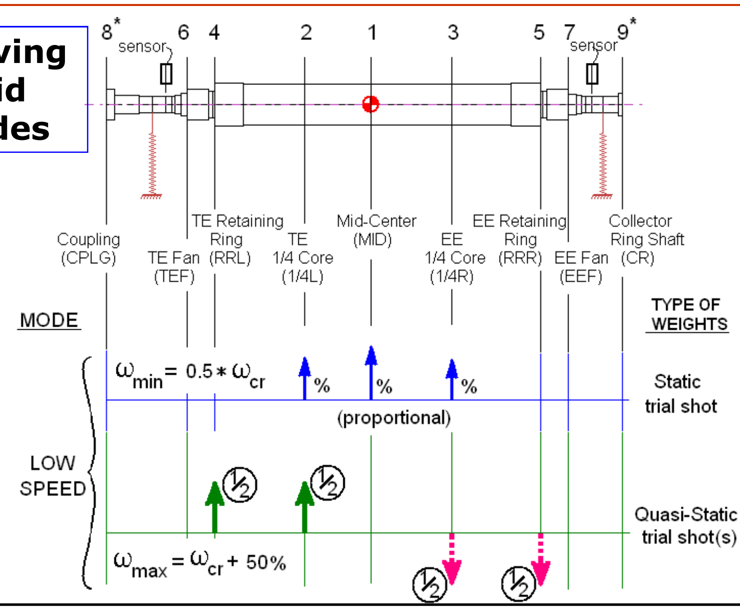
- Lateral rigid mode:
  - Must distribute weights across 3 central planes (50% of correction mass must be at CG plane)
- Rocking rigid mode (Quasi-Static)
  - Distribute weights in pairs in 2 more planes
- Use trial shots with influence coefficients to get solution
- Mass axis is now coincident with shaft axis

Balancing Higher Modal Responses

- Must use purely modal weight distributions, such that:
  - $\Sigma M = 0$ **and** $\Sigma F = 0$
- *Must not disturb rigid mode solution*
- For out-of-phase response of rotor-ends at operating speed, use S-shot
- For in-phase response of rotor-ends at operating speed, use V-shot

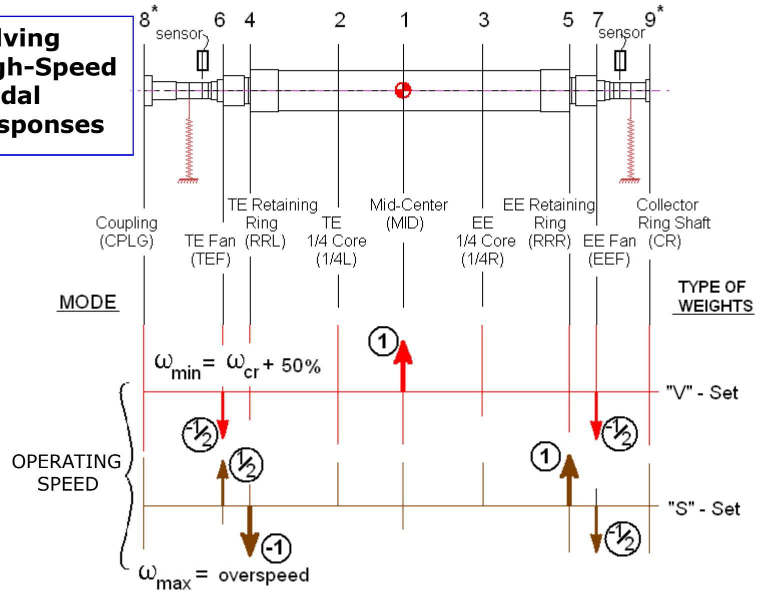
Selection of Balancing Planes

Solving Rigid Modes



Selection of Balancing Planes

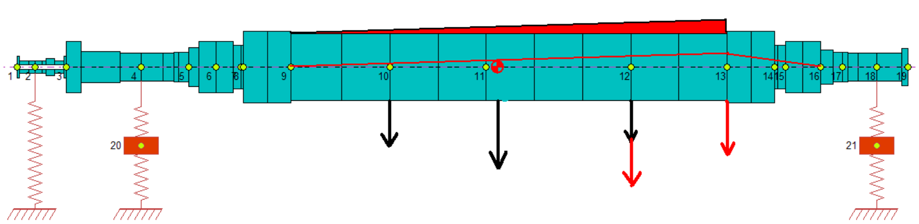
Solving High-Speed Modal Responses



Quasi-High Speed Balancing Result

- End result of rigid mode balancing is a balance weight distribution that will mirror the mass eccentricity

Rotor with body eccentricity



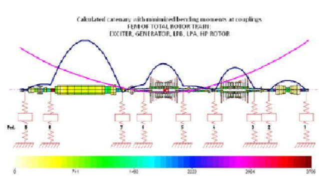
- Rotor will be balanced at all speeds
- Rotor will run “dynamically straight”

Balancing Summary

- Distributed mass eccentricities create inertial forces, which flip axes at peak of 1st critical
- Proper rigid mode balancing eliminates effects of inertial forces
- Must balance in minimum of 2N+1 planes
- An eccentric/bowed rotor balanced in this way is guaranteed to run smoothly upon installation in the field.

Review of Outage Steps

1. Condition assessment of rotordynamic behavior prior to & during shutdown by collecting vibration data
2. Thorough physical runout evaluation (full body, couplings, rims, faces and fits)



3. Finite Element modeling
4. Machining (if needed)
5. Balancing by our 2N+1 method
6. Reinstallation and (re)alignment based on improved rotor train condition

Review of Outage Steps

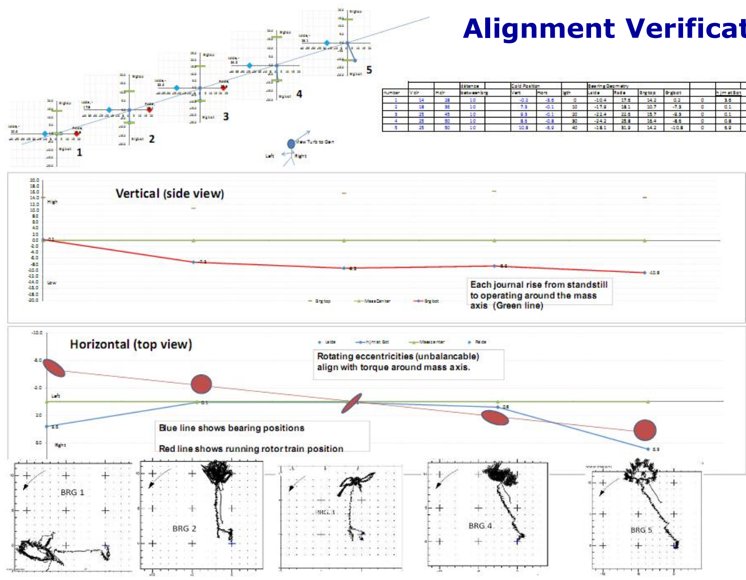
- Condition Assessment
  - Get prior to and during shutdown:
    - DC shaft centerline position from standstill (off gear) to full speed/load
    - Vibration amplitudes/phase through all speeds, with two probes per axial location if at all possible
    - Shaft orbits through all speeds
    - Bearing and pedestal seismic readings
    - Bode, Polar, and Full Frequency Spectrum plots

Review of Outage Steps

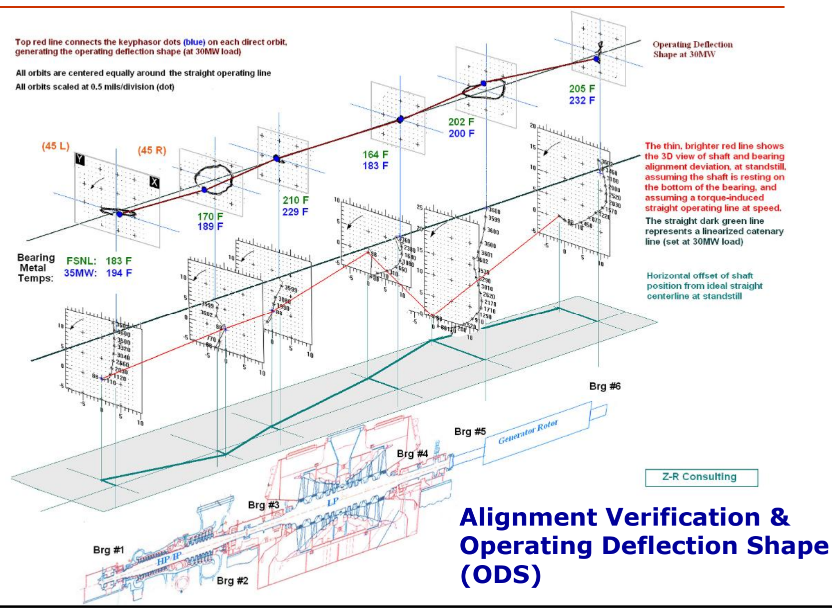
- Condition Assessment
  - Purpose:
    - Verify dynamic condition, resonances, evidence of eccentricities or misalignment, or other problems
    - Can point to root cause of vibration issues, and identify possible solutions
    - Determine operating deflection shape (ODS)
    - Determine alignment condition and bearing positions

Review of Outage Steps

Alignment Verification



Review of Outage Steps

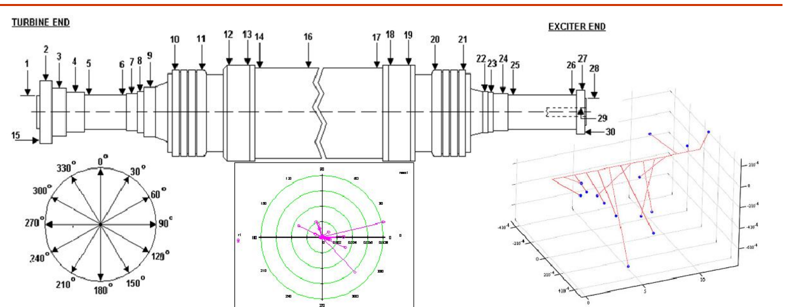


Alignment Verification & Operating Deflection Shape (ODS)

Review of Outage Steps

- Rotor Runout Evaluation
  - Critical step to identify what MUST be machined, and what can be balanced
  - Should take readings every 30° (or minimum 45°):
    - Multiple planes on rotor body, at all radius changes
    - Coupling faces, rims
    - Can include checking journal roundness or taper
  - Must mathematically evaluate 1x and 2x eccentricities
    - Provides reference for "best" achievable post-balance amplitude readings

Sample of Runout Evaluation



	1	2	3	D	5	6	7	10	11	12		
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270	0.0048	0.0008	0.0004	0.0001	0.0000	0.0006	0.0007	0.0011	0.0007	0.0000		
300	0.0027	0.0003	0.0001	0.0002	0.0002	0.0012	0.0016	0.0012	0.0005	0.0105		
330	0.0017	0.0004	0.0002	0.0002	0.0003	0.0013	0.0017	0.0011	0.0013	0.0296		
Max	**0.0059**	**0.0015**	**0.0011**	**0.0009**	**0.0012**	**0.0021**	**0.0022**	**0.0030**	**0.0033**	**0.0371**	**0.0153**	**0.0030**
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Angle:	58.7	50.5	40.6	16.2	175.8	158.8	155.7	142.5	138.3	15.4	161.7	28
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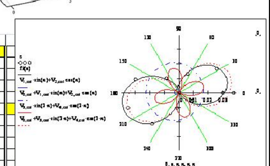

Sample of Coupling Evaluation

Coupling Face Alignment Evaluation

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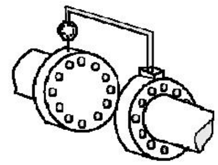
Plant and Unit: ____________

Date: ____________

Indicator reading on: LP2



Enter standard 16-point coupling face data in the box below :

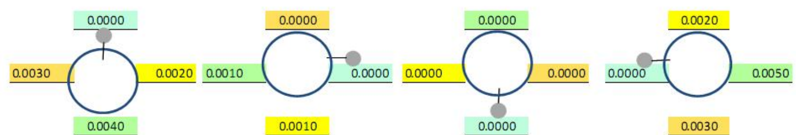
Dial Indicator Position:		FACE Top	Right	Bottom	Left
	TOP	0.4490	0.4510	0.4530	0.4520
	RIGHT	0.6020	0.6020	0.6030	0.6030
	BOTTOM	0.7310	0.7310	0.7310	0.7310
	LEFT	0.8730	0.8760	0.8740	0.8710

minimum per row:
0.4490
0.6020
0.7310
0.8710

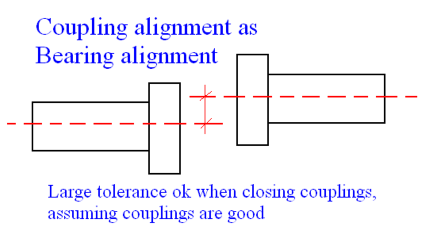
Indicator mounted on: LP1

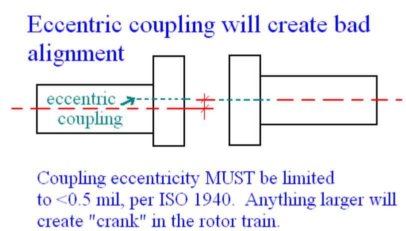
Dial Indicator on: *TOP* *RIGHT* *BOTTOM* *LEFT*

In Inches:



Effect of Coupling Eccentricity

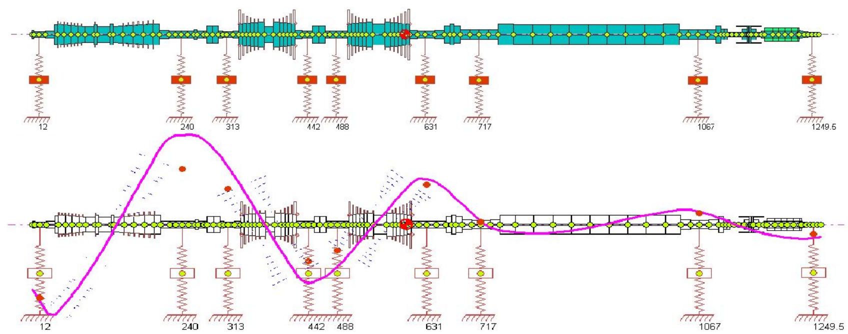




- Coupling defects create compromised alignment
- ISO 1940 tolerances for coupling/bearing alignment are ~10x higher than eccentricity tolerances
- Many bad rotors get reinstalled because rotor eccentricities can be hidden by liberal alignment tolerances

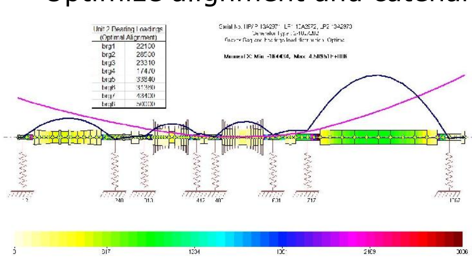
Review of Outage Steps

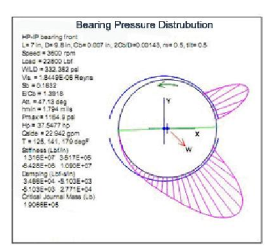
- Finite Element Modeling & Simulation
  - Takes into account measured runouts
  - Calculate and verify machine resonances, as well as bearing behavior/properties
  - Identify balancing planes (for 2N+1 Method)



Review of Outage Steps

- Finite Element Modeling & Simulation
  - Can accurately simulate rotor-bearing behavior:
    - Incorporate eccentricities, machining repairs
    - Simulate balancing, obtain initial solution
    - Simulate effect of bearing position or design changes
  - Calculate internal bending moments/stresses
  - Optimize alignment and catenary/elevations



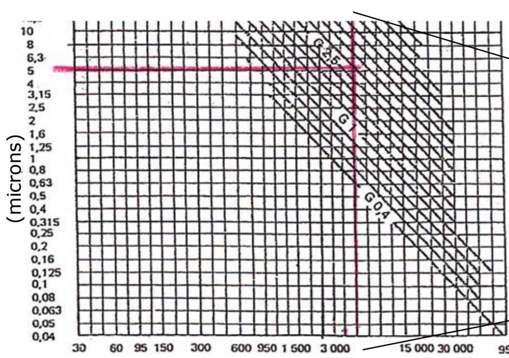


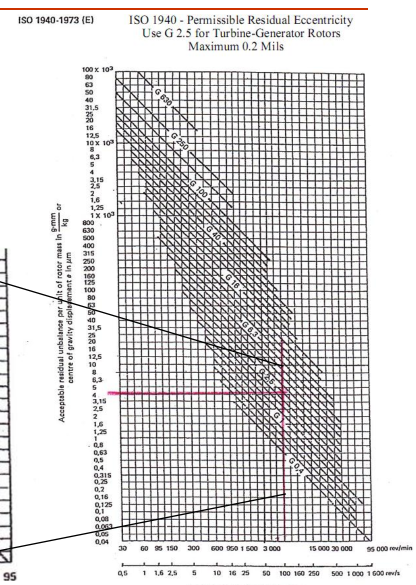
Review of Outage Steps

- Machining (In Shop)
  - Off-square couplings must be machined to ISO 1940 tolerances
  - If necessary:
    - Throw journals/centers to compensate for bow
    - Machine necessary balance planes (to have 2N+1 planes available, if rotor is bowed)
    - Correct journals if out-of-round or tapered

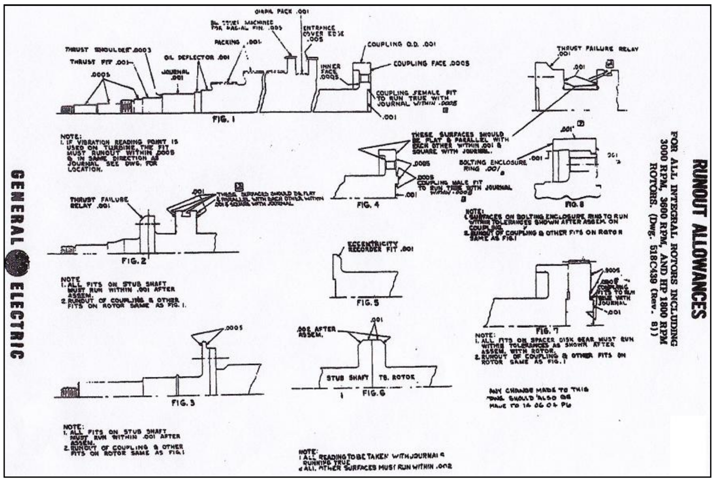
Review of Outage Steps

- ISO 1940 eccentricity guidelines suggest maximum of 0.2 mils
- By experience, up to 0.5 mils can be allowed





Review of Outage Steps



- Machining runout tolerances are followed according to major OEM standards (GE)

Review of Outage Steps

- Rotor Balancing by 2N+1 Method
  - Preferably performed in high speed bunker
  - If only low speed balancing machine is available, balancing must also be done in 2N+1 planes (minimum of 3 in all cases)
  - Field balancing after an outage (lowering relative shaft displacement, but with residual high seismic velocities) does not “balance” the rotor - It only masks one problem by creating another

Review of Outage Steps

- Rotor Balancing by 2N+1 Method
  - In general, if any balancing process requires installing an equivalent generated force of more than 10-20% of rotor weight, then one is not dealing with unbalance causing elastic rotor deflection, but rather, is dealing with excessive mass eccentricity

Review of Outage Steps

- Reinstallation and Alignment
  - Standard alignment procedures are sufficient, as long as all rotors and couplings are brought to proper eccentricity tolerances
- What Causes Bad Alignment?
  - Forced compromise during bearing alignment, because of bad rotors with unidentified eccentricities
  - Worn and repaired bearings, and deviation from reference information from the initial installation (oil bore readings)

Summary for Successful Outage

- Must identify and resolve all eccentricities
  - Account for any coupling offsets and non-perpendicularity, and rotor bows
  - Can resolve by combination of machining & proper balancing
  - Data collection and analysis must be scheduled ***prior*** to outage to properly identify and resolve all problems
    - Vibration data taken only upon a post-outage restart, via displacement and seismic readings, can point to problems and indicate if high forces are involved, but it is then too late to make proper corrections
    - Field "balancing" is not a true solution, and is not true balancing
- By incorporating proper outage steps, a successful restart with no field balancing can be guaranteed

Thank you for listening

Questions?