Runout Measurements with Non-Contact Probes, and FE Modeling, Tools in Root Cause Analysis (II)

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ABSTRACT

After a major outage and after individual balancing of turbine and generator rotors, generator rotor had exhibited high vibrations upon a restart. A standard field vibration balancing approach did not yield any results. Five sets of non-contact probes were installed and used as dial indicators to verify the machined and assembled eccentricities. FE modeling and simulations helped to verify the root cause of the vibration problem. The lesson learned from this case is that when balancing rotors individually in high speed balancing facility, machining tolerances at points critical to alignment with other rotors cannot be overlooked and must be evaluated.

Keywords:
Turbine-Generators, High Speed Balancing, Eccentricities.

INTRODUCTION

The Unit had undergone an outage to rebalance LPB rotor at low speed, remove all weights from the LPB EE coupling, rewind and high speed balance the generator rotor. During re-installation of the Unit, the stator had to be moved to get LPB and generator coupling aligned to the specifications. Upon restart, the generator rotor had exhibited high shaft vibrations. Balancing contractors were called to attempt to balance the rotor, but had no success.

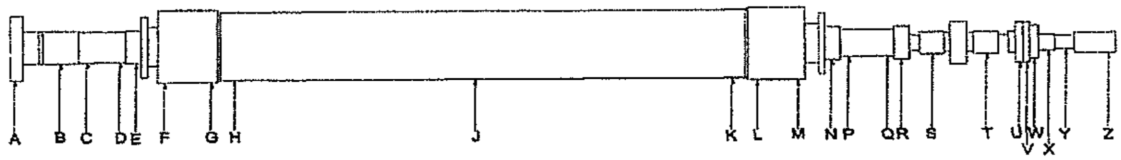
Repair shops involved were interested, as a customer courtesy, to assist in finding the root cause of the Unit's generator rotor high vibrations problem in the field.

DATA ANALYSIS

High Speed Balancing

As a standard procedure at the high speed facility, every rotor is checked dimensionally for preparation of bearings and oil seals, and pedestals layout. Runout checks are routinely done to evaluate the condition of the rotor and eventual preparation of weights and methods to be used in the balancing process.

Runout data on the rotor had revealed that the rotor body was eccentric to journals by about 0.004–0.005" (Fig. 1). This had prepared the balancer to anticipate a relatively large amount of balance correction of the first critical speed. This also gave a hint that the journals on this rotor had been re-machined at some point in the past.



	Cplg.		CE Journal			RCRR		Body	
	A	B	C	D	E	F	G	H	J
0	0.0035	0.0010	0.0001	0.0004	0.0008	0.0270	0.0220	0.0010	0.0010
45	0.0030	0.0015	0.0002	0.0010	0.0014	0.0250	0.0230	0.0020	0.0030
90	0.0030	0.0018	0.0001	0.0008	0.0016	0.0150	0.0320	0.0050	0.0025
135	0.0026	0.0014	0.0004	0.0006	0.0015	0.0020	0.0000	0.0030	0.0030
180	0.0015	0.0002	0.0003	0.0009	0.0010	0.0000	0.0210	0.0040	0.0040
225	0.0000	0.0000	0.0002	0.0008	0.0011	0.0070	0.0300	0.0030	0.0045
270	0.0000	0.0005	0.0001	0.0005	0.0005	0.0190	0.0240	0.0020	0.0025
315	0.0020	0.0008	0.0000	0.0000	0.0000	0.0255	0.0230	0.0000	0.0000
0	0.0035	0.0010	0.0001	0.0004	0.0008	0.0270	0.0220	0.0010	0.0010
Max	0.0035	0.0018	0.0004	0.0010	0.0016	0.0270	0.0320	0.0050	0.0045

	Body	RCRR			OE Journal			Slip Rings		Cplg.
	K	L	M	N	P	Q	R	S	T	U
0	0.0010	0.0040	0.0220	0.0001	0.0006	0.0008	0.0007	0.0024	0.0029	0.0028
45	0.0035	0.0055	0.0230	0.0006	0.0002	0.0003	0.0009	0.0011	0.0011	0.0015
90	0.0040	0.0150	0.0170	0.0008	0.0001	0.0001	0.0007	0.0002	0.0003	0.0006
135	0.0010	0.0010	0.0050	0.0006	0.0000	0.0003	0.0005	0.0000	0.0002	0.0014
180	0.0030	0.0000	0.0000	0.0004	0.0000	0.0000	0.0004	0.0006	0.0000	0.0010
225	0.0020	0.0080	0.0020	0.0005	0.0004	0.0004	0.0001	0.0009	0.0002	0.0000
270	0.0020	0.0140	0.0120	0.0001	0.0007	0.0007	0.0000	0.0018	0.0019	0.0011
315	0.0020	0.0110	0.0180	0.0000	0.0008	0.0010	0.0006	0.0020	0.0033	0.0032
0	0.0000	0.0040	0.0220	0.0001	0.0006	0.0008	0.0007	0.0024	0.0029	0.0028
Max	0.0040	0.0150	0.0230	0.0008	0.0008	0.0010	0.0009	0.0024	0.0033	0.0032

	Adaptor	Cplg.		Journal	
	V	W	X	Y	Z
0	0.0080	0.0055	0.0060	0.0070	0.0075
45	0.0050	0.0030	0.0035	0.0040	0.0035
90	0.0020	0.0015	0.0015	0.0015	0.0005
135	0.0030	0.0035	0.0040	0.0045	0.0045
180	0.0040	0.0053	0.0065	0.0085	0.0065
225	0.0015	0.0030	0.0025	0.0035	0.0035
270	0.0000	0.0000	0.0000	0.0000	0.0000
315	0.0050	0.0030	0.0030	0.0035	0.0045
0	0.0080	0.0055	0.0060	0.0070	0.0075
Max	0.0080	0.0055	0.0085	0.0070	0.0075

Figure 1. Rotor runout record

Also found was an indication of a "kink" on the CE side of the rotor shaft of about 0.0035". This "high spot" was also in line with the rotor body eccentricity high spot (Fig. 2). These findings were conveyed to the owner's observer during the balancing process in the Bunker. Both observations are not typically detrimental to the balancing process in the Bunker, but the observer was made aware of possible problems during the alignment and operation in the plant.

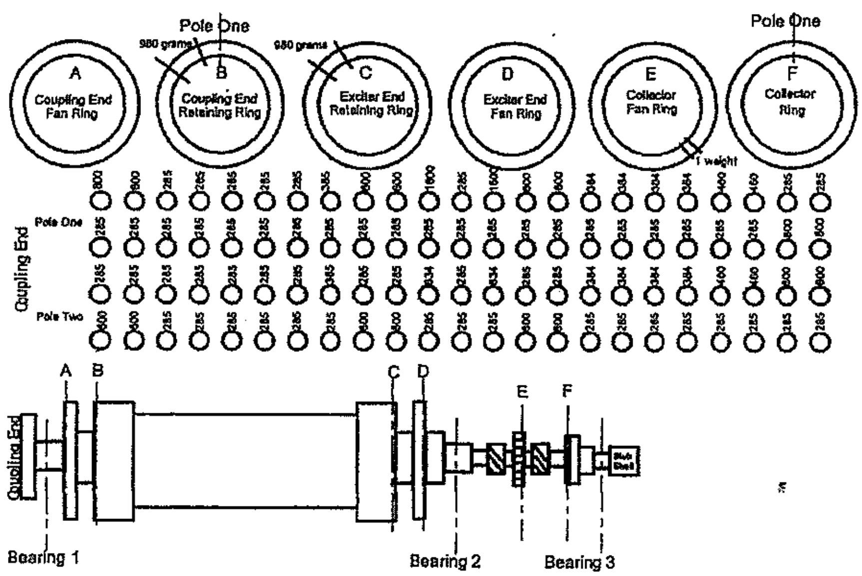


Figure 2. Rotor balance weight map

The rotor was balanced in the Bunker to below permitted and required residual unbalance limits, and data was witnessed and recorded. (Figs. 3–12).

Speed	CE Vertical		CE Horizontal		OE Vertical		OE Horizontal		Ped. #3 Vertical		Ped. #3 Horiz.		Brg. 1 Velocity		Brg. 2 Velocity		Brg. 3 Velocity	
RPM	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
	(mils)	(deg)	(mils)	(deg)	(mils)	(deg)	(mils)	(deg)	(Intg mils)	(deg)	(mils)	(deg)	(Intg mils)	(deg)	(Intg mils)	(deg)	(Intg mils)	(deg)
200	0.1	Min	0.2	Min	0.1	180	0.2	103	0.2	254	0.2	212	0.0	Min	0.0	Min	0.0	Min
400	0.1	Min	0.3	180	0.1	278	0.4	121	0.2	270	0.3	217	0.0	Min	0.0	Min	0.0	Min
600	0.2	319	0.9	181	0.4	302	0.9	146	0.2	261	0.3	215	0.1	Min	0.1	Min	0.0	Min
800	0.9	3	3.2	221	0.9	357	2.6	207	0.5	240	0.3	176	1.0	307	0.8	303	0.1	Min
1000	1.8	23	2.4	323	1.2	17	1.7	340	0.8	289	0.4	189	0.4	73	0.3	99	0.1	Min
1100	0.8	58	1.3	310	0.4	51	0.6	352	0.5	290	0.5	197	0.3	67	0.1	Min	0.0	Min
1200	0.7	67	1.2	307	0.2	45	0.4	9	0.5	288	0.5	201	0.2	63	0.1	Min	0.0	Min
1300	0.6	70	1.2	306	0.1	27	0.3	40	0.5	286	0.5	200	0.2	63	0.1	Min	0.0	Min
1400	0.6	72	1.2	306	0.1	349	0.4	73	0.5	286	0.6	202	0.3	67	0.1	Min	0.0	Min
1500	0.6	74	1.3	308	0.2	310	0.5	103	0.5	286	0.6	201	0.3	70	0.2	220	0.0	Min
1600	0.6	78	1.4	313	0.3	297	0.6	123	0.6	285	0.6	201	0.3	76	0.2	238	0.0	Min
1700	0.6	86	1.6	312	0.4	295	0.8	139	0.6	283	0.6	201	0.4	84	0.3	256	0.0	Min
1800	0.7	95	1.6	332	0.5	300	1.1	151	0.6	283	0.6	201	0.5	95	0.3	270	0.0	Min
1900	0.7	106	1.7	345	0.6	306	1.3	164	0.6	280	0.6	201	0.5	111	0.4	283	0.1	Min
2000	0.6	117	1.7	359	0.7	313	1.5	175	0.6	276	0.6	200	0.6	125	0.4	297	0.0	Min
2100	0.6	132	1.6	14	0.7	319	1.7	188	0.6	272	0.6	196	0.6	139	0.5	309	0.0	Min
2200	0.5	144	1.5	31	0.7	324	1.9	198	0.7	270	0.6	192	0.6	154	0.5	322	0.0	Min
2300	0.4	156	1.3	48	0.7	328	2.0	208	0.7	268	0.6	188	0.6	172	0.5	334	0.1	Min
2400	0.2	160	1.1	64	0.7	326	2.1	216	0.8	266	0.6	186	0.6	190	0.5	342	0.0	Min
2500	0.2	Min	1.0	81	0.8	323	2.3	223	0.9	263	0.7	182	0.6	207	0.6	352	0.0	Min
2600	0.3	97	1.1	91	0.9	310	2.5	231	1.0	261	0.7	180	0.7	220	0.6	2	0.0	Min
2700	0.8	117	1.6	112	1.4	310	2.9	248	1.1	257	0.7	180	0.8	241	0.7	17	0.0	Min
2800	1.2	160	2.1	147	2.0	332	2.9	265	1.4	260	0.7	178	1.0	268	0.7	30	0.0	Min
2900	1.1	191	1.9	176	1.9	352	2.5	274	1.5	266	0.7	170	1.0	288	0.6	33	0.0	Min
3000	0.9	210	1.6	197	1.6	4	2.1	278	1.8	269	0.8	163	0.9	308	0.6	38	0.1	Min
3100	0.9	217	1.2	212	1.4	12	2.0	285	1.7	272	0.9	162	0.8	327	0.5	47	0.1	Min
3200	0.8	223	0.8	220	1.1	18	1.6	292	1.8	276	1.1	162	0.6	345	0.5	56	0.1	Min
3300	0.9	224	0.6	212	0.9	19	1.3	299	1.9	279	1.2	165	0.5	0	0.4	68	0.2	263
3400	1.0	225	0.5	187	0.7	155	1.0	302	2.0	283	1.3	168	0.3	12	0.3	81	0.2	265
3500	1.0	228	0.6	163	0.5	2	0.5	302	2.0	288	1.4	173	0.1	Min	0.1	Min	0.3	274
3600	1.2	231	0.9	158	0.5	339	0.2	298	2.0	292	1.5	182	0.1	Min	0.1	Min	0.3	284

Figure 3. Resonance Data Summary

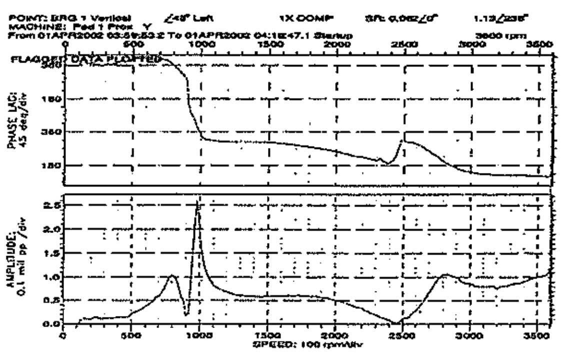


Figure 4. BODE plot bearing #1 vertical

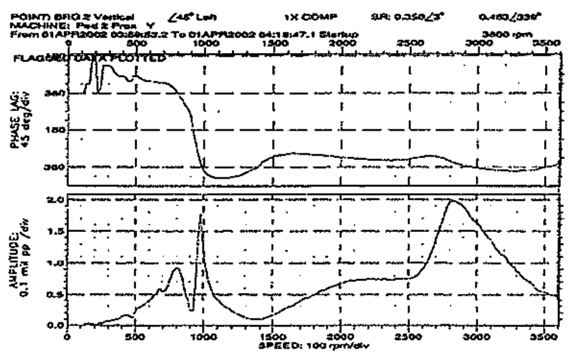


Figure 6. BODE plot bearing #2 vertical

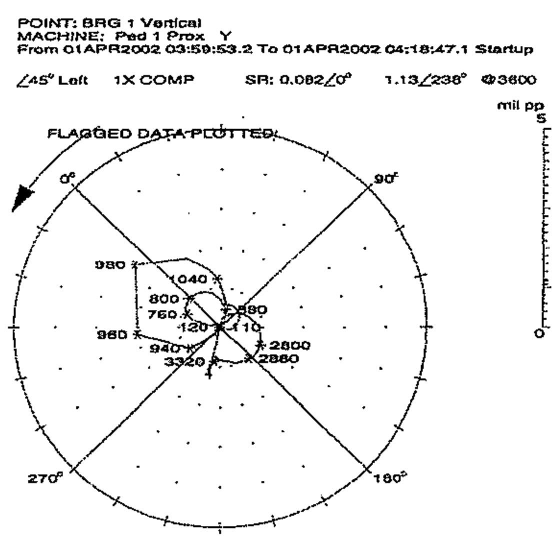


Figure 5. Polar plot bearing #1 vertical

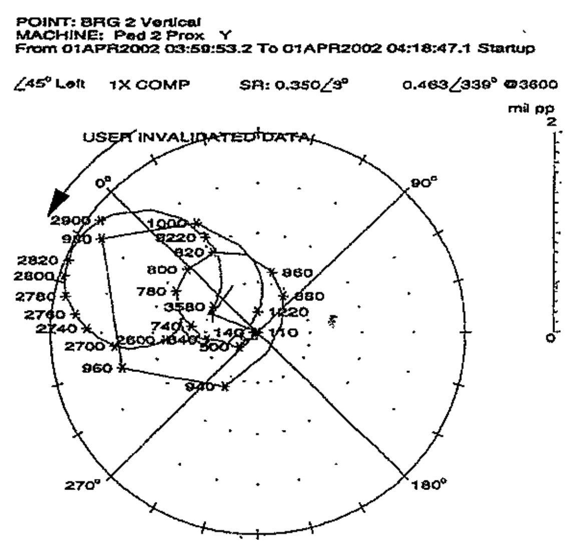


Figure 7. Polar plot bearing #2 vertical

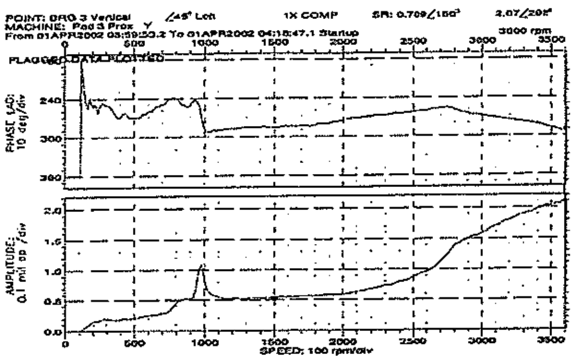


Figure 8. BODE plot bearing #3 vertical

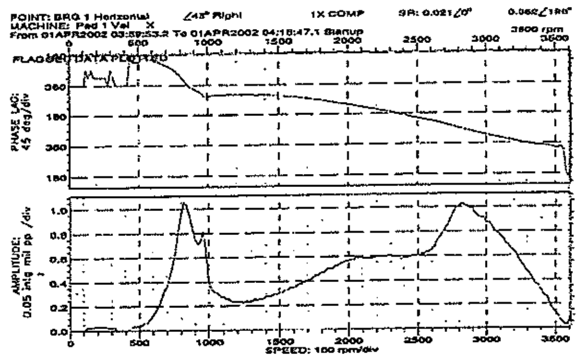


Figure 10. BODE plot bearing #1 horizontal

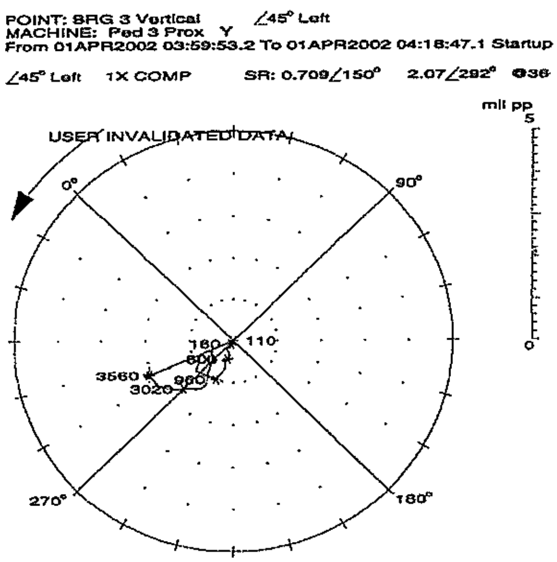


Figure 9. Polar plot bearing #3 vertical

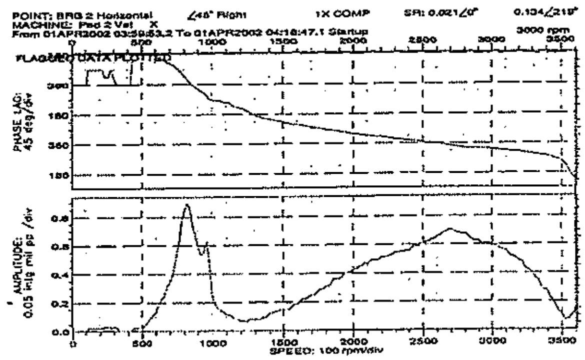


Figure 11. BODE plot bearing #2 horizontal

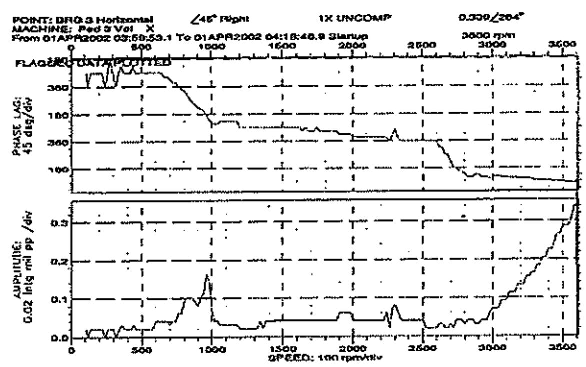


Figure 12. BODE plot bearing #3 horizontal

Field Balancing

When the Unit was rolled to speed for the first time after re-assembly at the site, very high vibrations were exhibited at journals #7 and #8, i.e., generator front and rear bearings. Vibrations were measured with permanently installed shaft riders located vertically at each bearing.

Vibrations were verified by balancers and defined as "dynamic", i.e. out of phase. Two balance attempts did not yield any improvement, and with an agreement between the owner and repair shop, a Consultant, was commissioned to attempt to find the root cause of the vibration problem.

Field Laser Alignment

After reviewing the rotor runout data and noting a possible alignment problem due to a "kink" in the rotor, it was recommended to verify current alignment. Laser equipment was utilized, and final data had indicated that the stator has to be moved to bring the generator bearings in line with the LPB bearing (Fig. 13). The move was not performed because of a jammed coupling bolt, which could not be immediately removed.

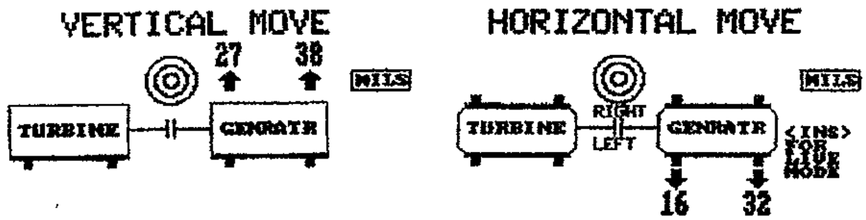


Figure 13. Laser alignment data

Slow Roll Runout with Proximity Probes

Another verification of bearings alignment was done utilizing temporarily installed pairs of proximity probes at bearings #6, #7, #8 and LPB-Gen coupling. These readings (plots) had confirmed the laser readings about a required stator move (Fig. 14).

Despite the need for alignment, the magnitude of the move could not have been the sole cause of the encountered vibrations.

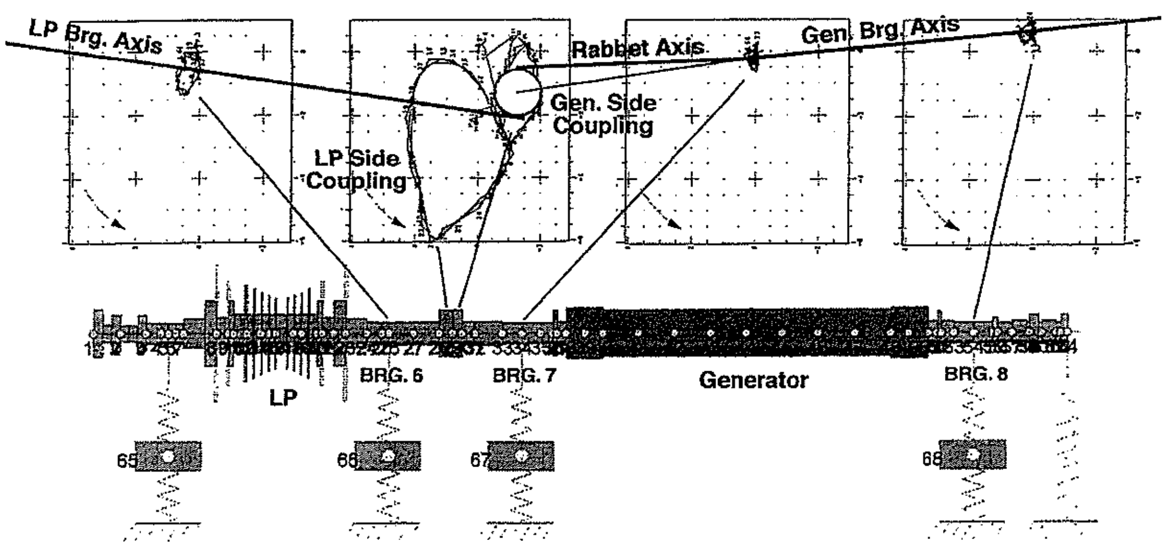


Figure 14. Bearings centerline offsets and local runouts

FE Modeling – Generator Rotor in BOS

The rotor was initially modeled with the eccentricity at journals, which gave a large simulated unbalance response. Eccentricity was reduced simulating balancing process, until unbalance response (shaft absolute) was obtained similar to actual one recorded in BOS (shaft relative and bearing absolute). This serves the purpose of model verification and for better visualization of potential whirling mode shapes (Figs. 15–19).

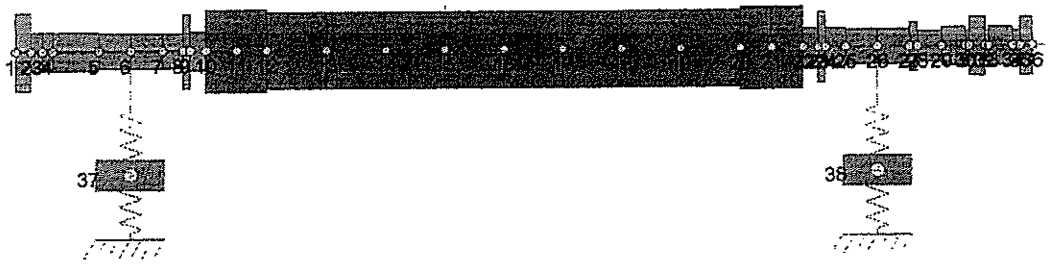


Figure 15. Modeling in balancing bunker BOS

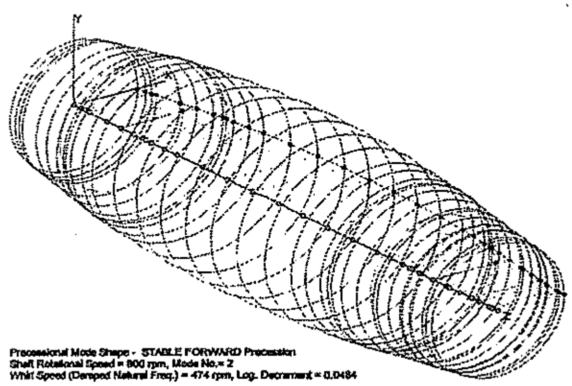


Figure 16. Balancing in bunker BOS: stable forward, 800 rpm, mode 2

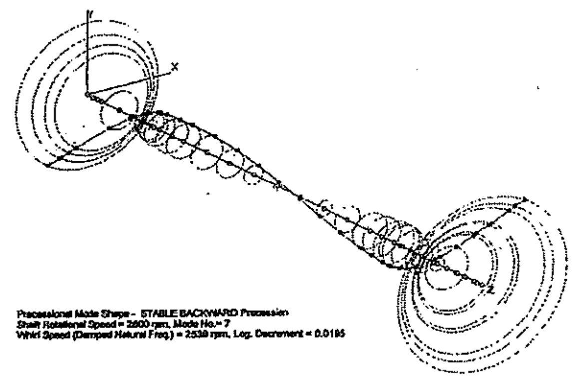


Figure 18. Balancing in bunker BOS: stable backward, 2600 rpm, mode 7

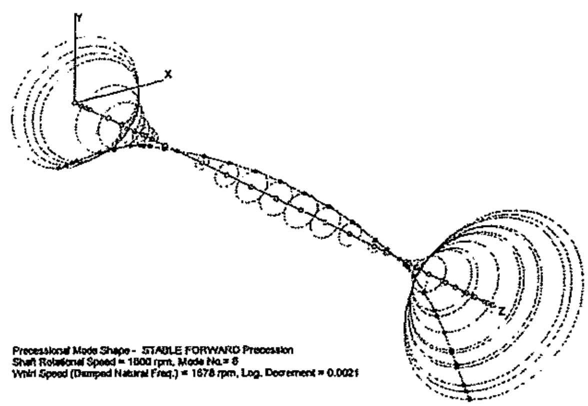


Figure 17. Balancing in bunker BOS: stable forward, 1600 rpm, mode 6

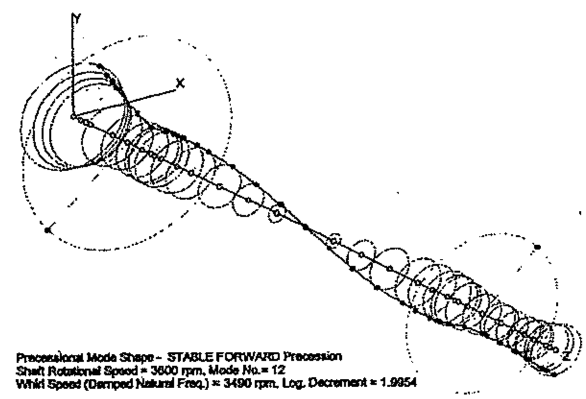


Figure 19. Balancing in bunker BOS: stable forward, 3600 rpm, mode 12

FE Modeling – Generator Rotor in SITU

The original model was retained with changes added to the support system for better simulation of the actual site conditions. At both ends of the rotor, a "spring" was added to simulate the effect of LPB and exciter shafts. Bearing stiffness, damping and pedestal masses were tuned to obtain critical speeds observed at the plant. Eccentricities at journals were reintroduced after a suspicion that the original rabbet was not concentric with the re-machined journals. This can be supported with the facts that the original bolt holes centerline was retained and the original coupling bolts were still being used.

The eccentricities were needed to be introduced in the model as the only excitation driver to produce simulated amplitudes and a whirl mode to match the actual ones. This model had shown that due to coupling eccentricity to generator journals, a "dynamic" unbalance response and a corresponding whirl mode would not allow successful balancing at all speeds, i.e., at criticals and at operating speed using only two balancing planes. The original unbalance response and two field balancing attempts were simulated. (Figs. 20–24).

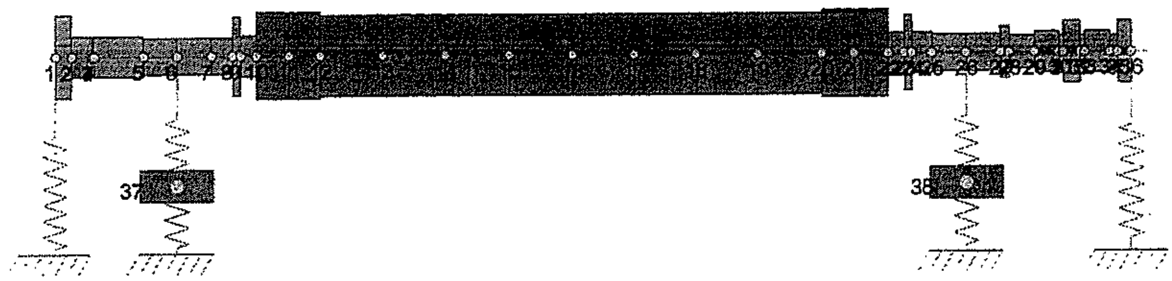


Figure 20. Modeling– generator shaft journals eccentricity at both bearings

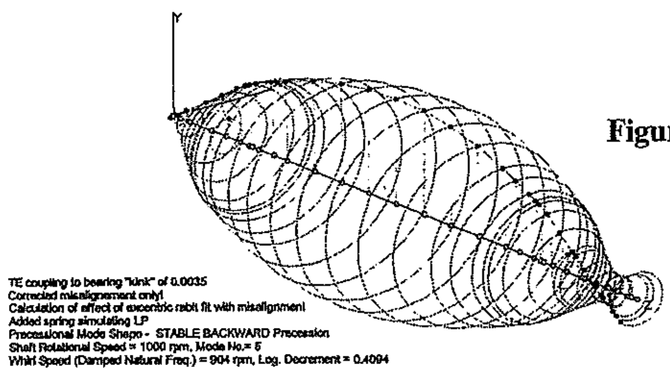


Figure 21. Modeling– TE coupling to bearing

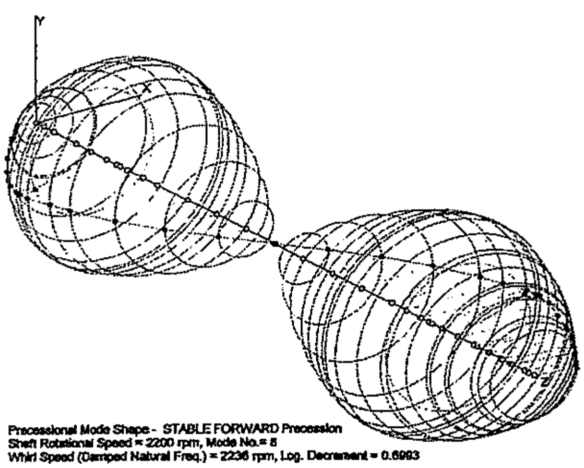


Figure 22. Precessional mode shape– stable forward 2200 rpm, mode 8

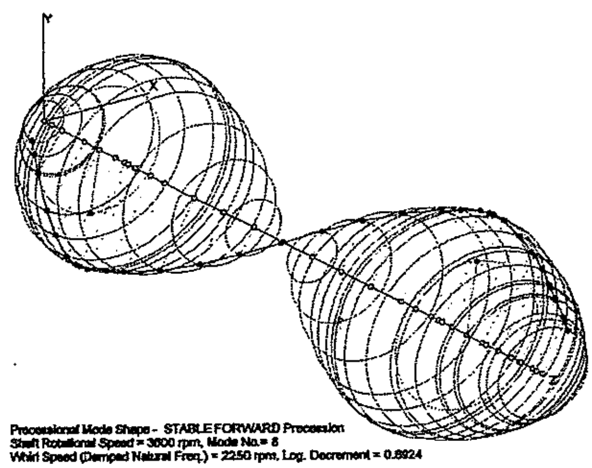


Figure 23. Precessional mode shape– stable forward 3600 rpm, mode 8

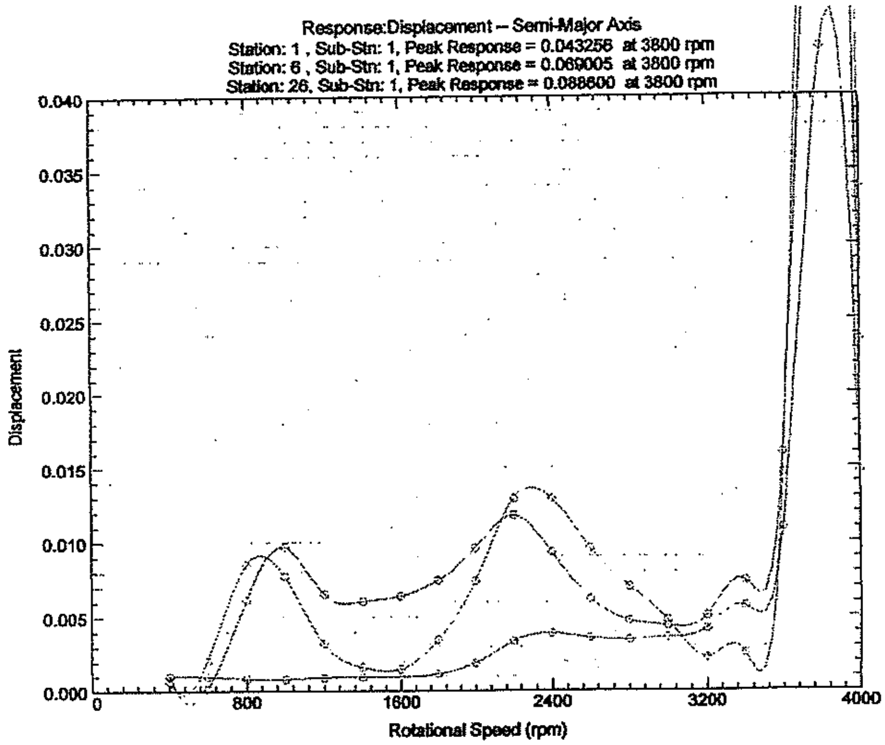


Figure 24. Simulated first run in place

FE Modeling – Generator and LPB Rotor

An additional model simulation was performed with LP and generator rotors connected. (Figs. 25-31). The undamped criticals speeds produced give us the modes to be anticipated in the field. These eigenvectors reveal that balancing of the generator rotor cannot be achieved without extending balancing to additional planes on the rotor train. This model could be used as an answer to a question, raised during the vibration problem investigation: "Why could we not balance the generator at least to pre-outage condition"?

There are several major differences between the generator (rotor train) before and after the outage:

- All generator rotor weights, (factory and field installed, about 60 lbs), were removed before the rotor was high speed balanced. It is important to keep in mind that in the Balancing Facility, the rotor is balanced spinning around its journals as a center of rotation, where all

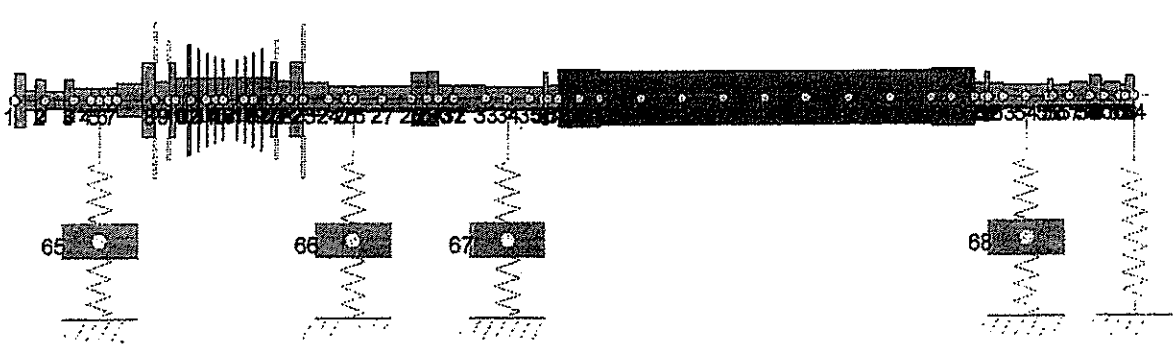


Figure 25. Modeling– generator shaft journals eccentricity at both bearings

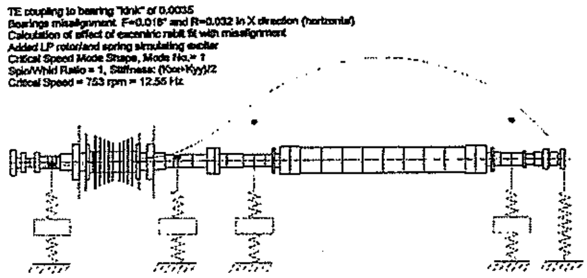


Figure 26. Modeling– TE coupling to bearing mode 1

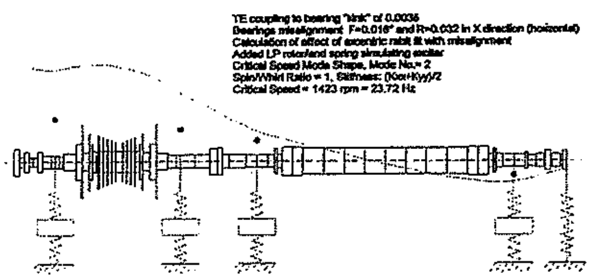


Figure 27. Modeling– TDE coupling to bearing mode 2

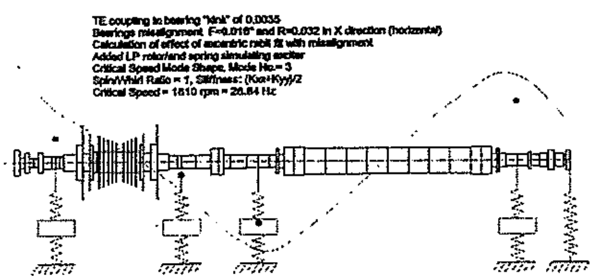


Figure 28. Modeling– TE coupling to bearing mode 3

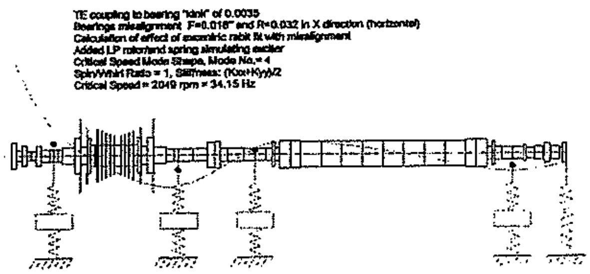


Figure 29. Modeling– TE coupling to bearing mode 4

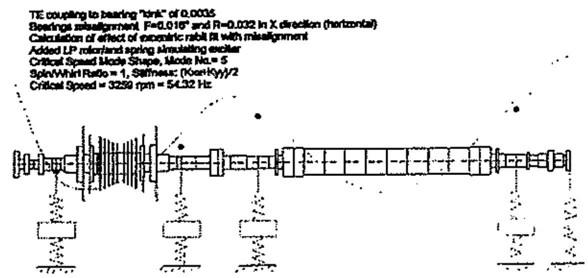


Figure 30. Modeling– TE coupling to bearing mode 5

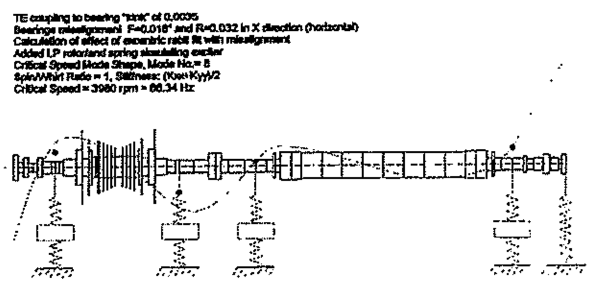


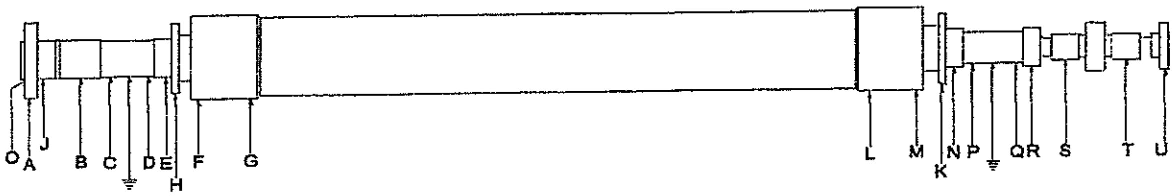
Figure 31. Modeling– TE coupling to bearing mode 6

vibration readings are taken as a measure of quality of balance condition of the rotor. Vibration displacement at extremities were not monitored, as it is not usually done.

- There were weights (about 3 lbs) removed from the LPB-generator rotor coupling.
- There were weights (about 20-30 lbs) removed from LPB, which was then balanced at low speed.
- There was a stator move to achieve coupling alignment.
- There were at least fourteen (14) balancing runs performed during previous major outage, which were due to the generator rotor condition not discovered during the outage.

Runout Evaluation

Rather than start re-balancing in the field, as it was done after previous outage, it was decided to remove the rotor for inspection. The run out readings on the rotor after it was pulled from the plant were evaluated. These readings include TE coupling rabbet but still no indication of the coupling face perpendicularity. The most important readings show the total eccentricity between TE coupling rabbet and TE journal (Brg. #7), of 0.003". Other eccentricities in relation to a common center are printed. (Figs. 32–34).



	TE Rabbet	TE Cplg.	TE OB OS	TE Journal		TE IB OS	TE RG		Fan TE	Body	Fan CE	CE RR		CE IB OS	CE Journal		CE OB OS	IB CR	OBCR	CE Cplg.
	O	A	B	C	D	E	F	G	H	J	K	L	M	N	P	Q	R	S	T	U
0	2	1/2	1/2	2/10	0	0	5	30	0	0	0	0	5-1/2	0	1/2	1/2	0	2-1/2	3-1/2	4
45	2-1/2	0	1/2	1/2	0	1/2	5	23	1/2	0	4-1/2	3	1/2	1/2	0	0	2/10	2-1/2	2-1/2	3-1/2
90	7-1/2	0	0	0	7/10	1-1/2	4	0	1-1/2	1/2	4	0	0	1	1-1/2	1/2	1-1/2	2	1/2	2
135	1	1-1/2	1/2	0	7/10	2	0	34	2-1/2	1-1/2	4	5	2-1/2	1/2	1	1-1/2	2	1	1	2
180	0	3	1-2/10	1/2	1/2	1	4	35	2	2-1/2	3	10	6-1/2	1/2	1-1/2	1-2/10	2	1	2-1/2	3-1/2
225	1/2	2-1/2	7/10	1/2	1/2	1	17	26	2	1-1/2	5	3	10-1/2	1	1-1/2	1-1/2	1-1/2	1/2	1-1/2	2
270	2	1	2/10	1/2	1	1-1/2	26-1/2	29	2	1/2	5	5	11-1/2	1	1	1/2	1/2	0	0	0
315	2-1/2	1	2/10	0	7/10	1	20	33		0	3	8	9-1/2	0	7/10	1/2	0	1	1-1/2	2
0	2	1/2	1/2	2/10	0	0	5	30	0	0	0	9	5-1/2	0	1/2	1/2	0	2-1/2	3-1/2	4

Figure 32. Readings with rotor running on journals by OEM

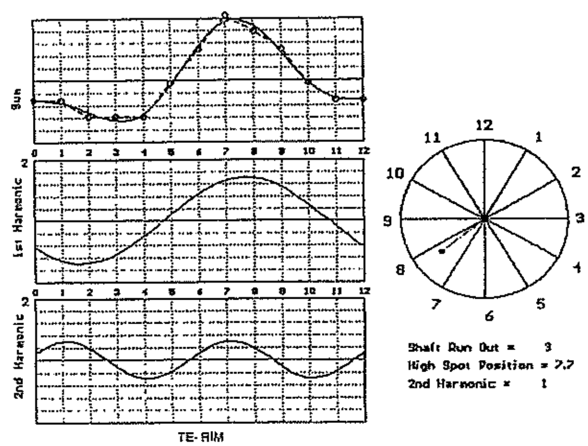


Figure 33. Analysis of shaft run out measuring point 2

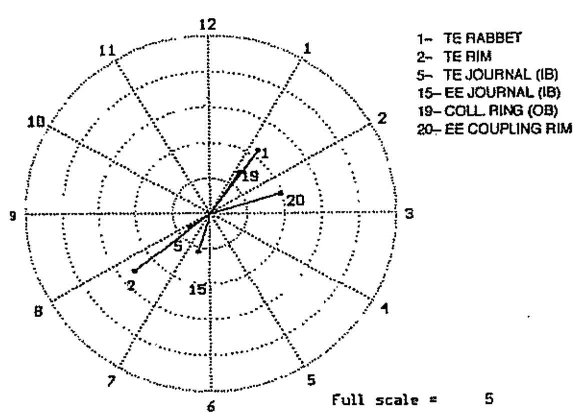


Figure 34. Shaft run out diagram

The method of the runout evaluation consists of data plotting, smoothing the time curve and then performing an FFT analysis. This method then separates the first harmonic (eccentricities with a reference to the origin of coordinate system as "Zero", and a second harmonic, which is so prevalent on asymmetric rotors , like a two pole generator. The graphical presentation of the analysis results helps visualize the relative relation of the eccentricities, between the critical elements: coupling rim and rabbet fit, used for the alignment, and the journals, which axis represent the axis of rotation.

CONCLUSIONS AND RECOMMENDATIONS

In order to find any root cause of any problem, some matrix of time and events should always be created. Even without a full history, a brief review of the events covering the generator rotor, it becomes evident that the root cause of today's problem was introduced in the past when, the rotor was refurbished by the OEM. After the outage and upon restart, the Unit was exhibiting very similar vibration behavior encountered now, during the initial run to speed. The Generator rotor was eventually brought to an acceptable running condition at operating speed, but with a compromise at the LP rotor, LPB coupling and with high critical speed vibrations. Since this is a base load Unit, high vibration at critical speed is not detrimental. All this was achieved utilizing fourteen (14) balancing trial moves in the plant. That alone shows the complexity of the problem and cost associated with its solution. An estimate by the author sums it up:

14 runs x 2 days/run..28 days
14 runs x $20,000 (fuel/run)..$280.000
Balancing cost, labor..$40,000
Lost Production (500 MW @ $5/MW)...............$1,800,000

After considering the alternatives, it was recommended by the author to remove the rotor, carefully examine eccentricities and re-machine the rotor to the original specifications and tolerances.

Another alternative would have been to just correct for a "kink". That would require bringing the coupling rim, rabbet (spigot) and bolt holes centerline concentric with journals. Coupling face, back face and bolt holes would have to be brought perpendicular and parallel to the journals.

With the first version, there may be minimized coupling reworking, but rotor must be rebalanced at high speed. With the second alternative there will be more extensive rework on the coupling but rebalancing at high speed may not be needed. Some field balancing could still be expected.

It is unfortunate that the issue about the rabbet eccentricity and offset to journals could not, and was not verified during the outage process, knowing the vibration history of the rotor. Also this entire investigation in place, with data collected and created in it, is based on the coupling high eccentricities, as the only unknown, undocumented value, but highly susceptible, based on the history of the rotor. Later, this coupling eccentricity was verified, after rotor was removed for another inspection by the OEM.

Second part of possible problem is the result of balancing a "bowed" rotor in the balancing bunker. The Rotor body geometric center was offset by ~0.005" because of re-machining journals to clear the previous damage. A "Bowed" Rotor can be successfully balanced in the Bunker, i.e., minimize forces transmitted to bearings, but that is done by "deforming" geometric axis of the bowed rotor, rather than minimizing only elastic deflection axis, as it is done on a "straight", unbalanced rotor. Balancing a "Bowed Rotor" also requires a much larger amount of correction weights, and in the process may distort the axis of the coupling overhangs. This effect may or may not be correctable in the field, and cause high vibrations, despite the fact that the rotor was well balanced in free mode in the bunker, and rotor cold alignment was good.

If the problem with the "displacement" of the overhang is suspected, some balancers may spend numerous balancing runs (50,100 or more), in the balancing facility, while monitoring coupling (overhang) axial displacement. Each run is used, not to balance, but to "tweak" modal weights locations, until just the right combination of the moments is generated to satisfy (compromise) the journals and coupling vibrations.

Whether this method substitutes for the machining correction of the deformed rotor it remains a topic for discussion.

Finally, only partial machining was performed and the rotor was re-balanced at high speed with attention to couplings "displacements". Balancing process in the Bunker this time took five times the numbers of runs and five times overall duration, in comparison to previous "normal" balancing procedure. The generator was successfully re-started, with the need of two runs for field trim balancing, and with vibrations at operating speed still not in satisfactory range especially passing through the critical speeds.

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