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Structural Dynamic Behavior of Turbo Generator Foundation Connected with Passive Supplemental Damping Devices

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***Abstract* - Study the dynamic properties of Turbo-Generator foundation with and without passive supplemental damping are considered in this paper using finite element method. The high vibrations of machines especially Turbo-Generators machines lead to use massive masses of foundations to absorb the big amount of dynamic loads generated by machines. The work in this paper investigates the effect of using passive supplemental damping devices such as lead rubber bearings to accommodate these big amount of dynamic loads, also investigates how it could lead to change the dynamic responses of Turbo-Generator foundations to be in the safe frequency range with less masses and better dynamic performance. The analysis of the system with and without supplemental damping devices is performed which shows the significant effect of using damping devices. The results show that damping devices could lead to decrease masses of top deck of the machine foundation by 20% with acceptable dynamic responses compared with foundations without supplemental damping devices. A proof of the high significant of damping devices especially lead rubber bearings in decreasing the construction cost and changing the dynamic behavior of Turbo-generator machine foundation is presented by performing a detailed comparison study with and without damping devices.**

Keywords: Dynamic Analysis, Machine Foundations, Turbo Generators foundations, Passive supplemental damping devices, Lead Rubber Bearings, Finite Element Modeling, dynamic response.

I. INTRODUCTION

Safety, stability, durability and reliability of structure should be considered while designing the foundation system, Nawrotzki et al., (2008). The usage of supplemental damping devices could have a significant effect on the performance of the generators foundation and could lead to a significant reduction in the construction cost specifically in case of generators used in mega power stations.Turbo-generators in power stations are often placed on foundation structures that are flexible over the running range of the machine and can therefore contribute to its dynamic properties. The generators foundation is to be simulated using finite elements models, where the efficiency of supplemental damping devices is thoroughly studied,specifically through usage of base dampers such as (Lead Rubber Bearings).

According to the fact that Turbo-generator foundations are subjected to significant dynamic loads during operation in addition to ordinary structural design and environmental loads, Jayarajan (2014). The followings need to be considered

- High Resonance which may be occurred in turbo generators and hence the natural frequency of foundation system coincides with the operating frequency of the machine.
- The amplitudes of motion and velocities at operating frequencies may exceed the limiting amplitudes and velocities, which are generally specified by machine manufacturers.

Accordingly, factors will be studied in this research are:

- Simplified and effective finite element modelling in representation of such complicated problem.
- Validation of the FEM using SAP2000 program.
- Effect of Passive Damping Devices on dynamic response of T.G Foundation through usage of Lead Rubber bearings.
- Comparison between dynamic responses of T.G foundation with/without Lead rubber bearings.
- Study the Dynamic Response of T.G Foundation after Decreasing Top Deck Mass using Lead Rubber Bearings.

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II. MODELLING OF TURBINE GENERATOR FRAME FOUNDATION

Design of Frame Foundation is relatively a complex task compared to any other foundation. There are many parameters that influence machine-foundation response. The stiffness of Frame Structure plays a vital role in design. Individual vibration characteristics of columns, beams, cantilever projections etc., besides being part of the system, have also been found to significantly influence the response.

1. Foundation Data

Foundation material properties are as follows:

Concrete Grade	M25
Mass density of concrete	2.50 t/m3
Elastic Modulus E	3.00E+07 kN/m2
Poisson's ratio	0.15
Shear Modulus G	l.30E+07 kN/m2

Top Deck L=13.80 m, B = 8.00m, Thickness =1.80 m

Base RaftL=13.30 m, B = 8.00 m, Thickness =2.00 m,

And the following figure 1 shows the turbine generator machine foundation geometry (plan and elevation).

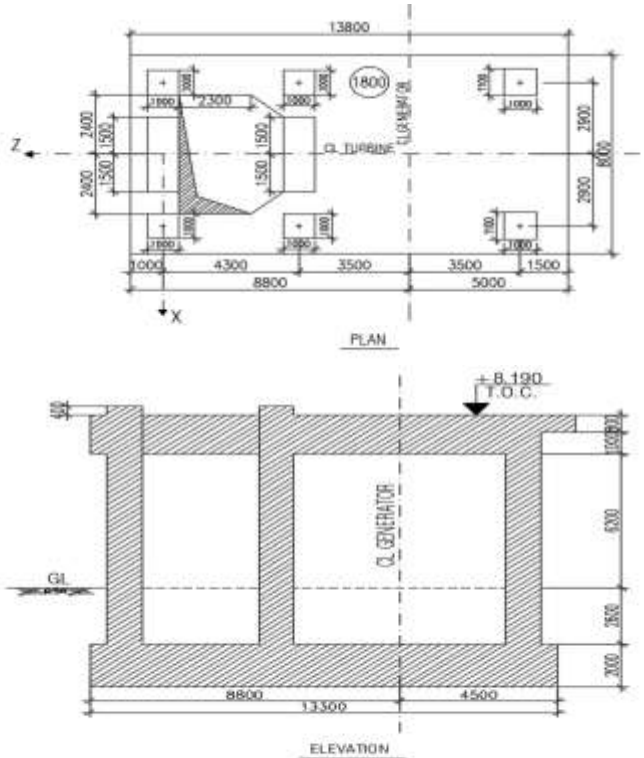

Figure 1: Turbo Generator Foundation Plan and Elevation

2. Frame Sizes

Frame number	Frame 1	Frame 2	Frame 3	
Frame Beam width	1	1	1	m
Frame Beam depth	1.8	1.8	1.8	m
Frame span	9.7	9.7	9.7	m
Beam Moment of Inertia	0.49	0.49	0.49	m^4
Column Moment of Inertia	0.08	0.08	0.11	m^4

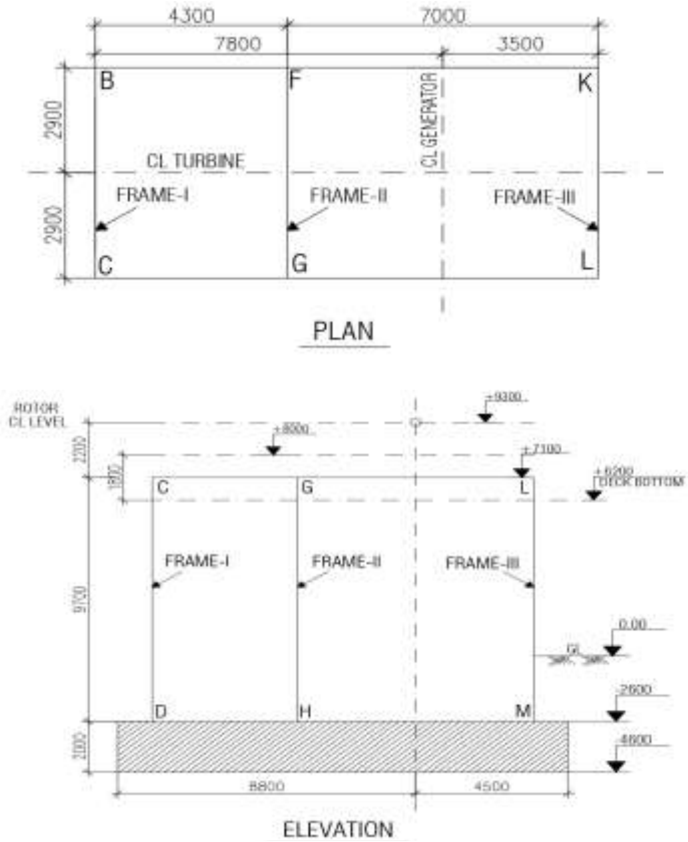

Figure 2: Frames Plane and Elevation (Center Line)

3. Machine Load Data

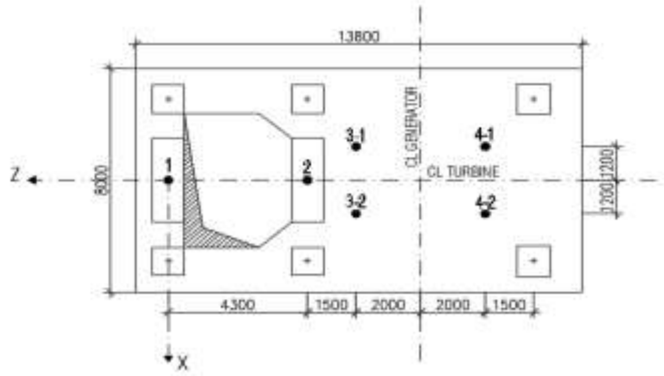

Figure 3: Machine Load Points

Load point	• 1	• 2	• 3	• 4	Total (KN)
Total M/C WT	400	360	200	200	1160KN
Rotor WT	25	35	70	70	200KN
Unbalance					
Lateral/Vertical	5	7	15	15	42KN
Longitudinal	2	3	6	6	17KN
Blade loss force	3	11	__	__	14KN
Short Circuit Torque					2160 KN.m
Machine Speed					50 Hz

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4. Foundation modeling using SAP2000

a) Modeling Procedure

Modeling procedure used in the finite element model using SAP2000 software are:

- The first element used is Shell element to simulate the table top foundation itself with concrete material and defined as Shell-Thick with 1.80 m.
- The second element is Frame element and it is defined as rigid link frame element by giving it a large modulus of elasticity and zero weight, to connect the loading points to the foundation horizontal center line to ensure adequate and smooth load transfer from the loading points to the foundation body. Rigid Frames are also used to connect the turbine supporting points to the turbine Centre of gravity and also to connect generator supporting points to generator center of gravity to ensure that the loading points are connected and acting as one body to simulate the equipment itself.
- The third element is the frame beam to simulate frames beams and columns of foundation with the exact beams and columns dimensions.
- Foundation Basement can be simulated with shell element with springs or solid element but in this case, foundation will be simulated as fixed constraints under each column because there is no need to calculate the stresses on the soil in this study. And the geometry of all foundation is presented in figures 4 & 5.

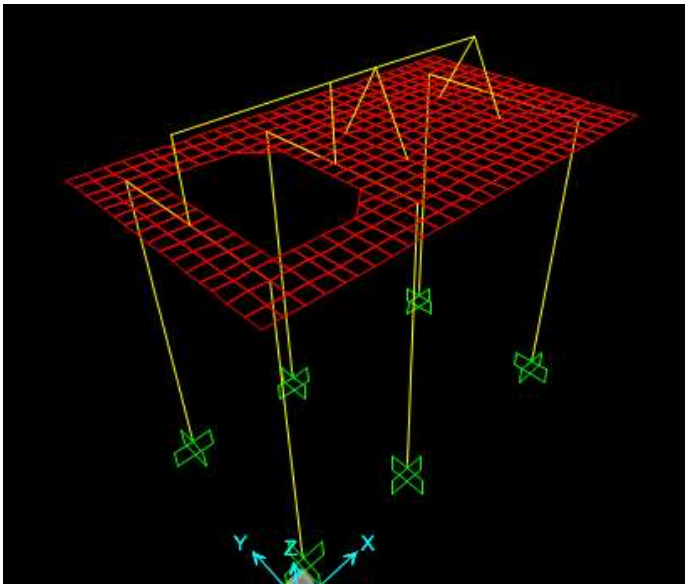

Figure 4: Model Geometry using Shell-Beam Element Method

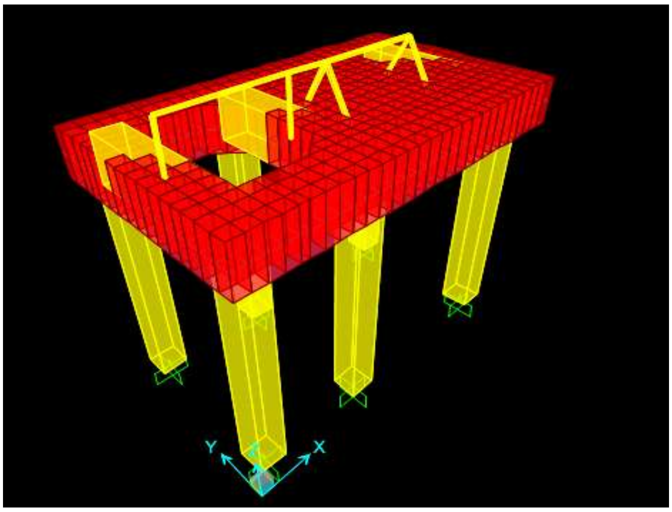

Figure 5: Model Geometry (Extruded View)

b) Material Properties

• Concrete Grade	M25
• Mass density of concrete	2.50 t/m3
• Elastic Modulus E	3.00E+07 kN/m2
• Poisson's ratio	0.15
• Shear Modulus G	1.30E+07 kN/m2

c) Load Definition

The loads on the foundation used in the model are based on machine load data mentioned before in part 3.

d) Time History Function Definition

According to DIN 4024-1(the German institute for standardization) the natural frequencies of the foundation with equipment must not occur within the following ranges:

For 50 Hz application exclusion ranges of 37.5 Hz to 64 Hz for the first natural frequency and 42.5 Hz to 56.5 Hz for higher natural frequencies.

A step of 2.5 Hz was selected to define time history frequencies which started from 37.5 Hz to 65 Hz for Steady state condition. And from 2.5 Hz to 37.5 Hz for startup and shut down condition.

e) Dynamic Load Cases

- Time History load cases definition: In phase and Out of phase cases are considered (at each frequency).
- Load Cases generation concept are as follows: Load cases are the basic cases with Arrival time of T = 0.0 and all load points starting their cycle at the same time.

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Notes:

- All load combinations are generated with all Loads at the defined load points with positive sign and negative sign separately.
- The considered damping is the damping of the whole system (Equipment + Foundation system)
- Damping is assumed as 0.05.

f) Mass Source Definition

Mass Source = Equipment Own Weight (represented in mass joints) + Foundation Own Weight.

g) Load Combinations Generation

Dynamic analysis load combination is the envelope of all defined Time history load cases.

h) Analysis (Free Vibration Analysis)

Natural Frequencies for various modes is listed in Table I. First eight mode shapes are presented to show natural frequencies for transitional, torsional and vertical modes of vibration.

TABLE I
Frame natural frequencies (HZ)

Modal Periods And Frequencies						
OutputCase	StepType	StepNum	Period	Frequency	CircFreq	Eigenvalue
Text	Text	Unitless	Sec	Cyc/sec	rad/sec	rad2/sec2
MODAL	Mode	1	0.375295	2.6646	16.742	280.29
MODAL	Mode	2	0.366129	2.7313	17.161	294.5
MODAL	Mode	3	0.287812	3.4745	21.831	476.59
MODAL	Mode	4	0.04174	23.958	150.53	22659
MODAL	Mode	5	0.032601	30.674	192.73	37145
MODAL	Mode	6	0.031537	31.708	199.23	39693
MODAL	Mode	7	0.026669	37.497	235.6	55508
MODAL	Mode	8	0.02583	38.714	243.25	59170

III. VALIDATION OF TURBO GENERATOR FRAME FOUNDATION RESULTS OBTAINED BY FEM

The previous results are validated by comparison with previous published bookBhatia (2008) as shown in table II. The obtained results in this study will be used to determine the damping effect on foundation in the next sections.

TABLE II
Validation Table showing Frame natural frequencies

Frame Natural Frequencies (Hz)			
Mode	Solid Model Analyzed by K.G. Bhatia example	Beam Plate Model Using SAP 2000	Observation
1	2.95	2.6646	Less than 10%
2	3.02	2.7313	Less than 10%
3	3.67	3.4745	Less than 10%
4	26.48	23.958	Less than 10%
5	32.36	30.674	Less than 10%
6	33.2	31.708	Less than 10%
7	35.57	37.497	Less than 10%
8	36.4	38.714	Less than 10%

The above table is the validation table between solid model analyzed by Bhatia (2008) and beam plate model analyzed by SAP2000 and the observation shows that results are in the same range and not exceed 10% between the two models.

IV. EFFECT OF PASSIVE DAMPING DEVICES ON DYNAMIC RESPONSE OF T.G FOUNDATION USING FINITE ELEMENT MODEL

Use of damping devices in the foundation of critical structures has attracted considerable attention in the recent years, Lin Su et al., (1989) and K. Spanos et al., (2015). The most types can be used as damping devices for turbo-generator foundation are:

- Pure friction base isolation
- Laminated Rubber Bearing
- Resilient-friction base isolator (R-FBI)
- Electric de France system (EDF)
- Friction Pendulum Bearings (FPS)
- Lead Rubber Bearings (LRB)

In this study Lead rubber bearing is chosen for the following reasons:

- Rubber bearings isolators provide isolation and depending on the rubber compound it is also provide damping at resonance.
- Rubber used in LRB is a combination of the two (damping + isolation). Their stiffness forms part of the isolation process and their damping removes some Vibrational energy.
- Damping in LRB is reducing the response at the resonant frequency, while isolation is reducing response due to shifting of the frequency away from the resonant frequency.

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- Lead-core in LRB is used to provide an additional means of energy dissipation and initial rigidity against vibration.

The above reasons make lead rubber bearing one ofthe most suitable damping device for Turbine pedestals.

1. Dynamic response for Turbo Generator Foundation without using passive supplemental damping devices

This section introduces the design data and dynamic properties for foundation without supplemental damping devices (LRB) to compare the results in the next section.

a) Mode Shape and Frequencies

The following table III, shows the modes and frequencies for Machine foundation without using LRB.

TABLE III

Mode shapes Periods and Frequencies without using LRB

Modal Periods And Frequencies without using Lead Rubber Bearings						
Output Case	Step Type	Step Num	Period	Frequency	Circ. Freq	Eigenvalue
Text	Text	Unitless	Sec	Cyc/sec	rad/sec	rad2/sec2
MODAL	Mode	1	0.375295	2.6646	16.742	280.29
MODAL	Mode	2	0.366129	2.7313	17.161	294.5
MODAL	Mode	3	0.287812	3.4745	21.831	476.59
MODAL	Mode	4	0.04174	23.958	150.53	22659
MODAL	Mode	5	0.032601	30.674	192.73	37145
MODAL	Mode	6	0.031537	31.708	199.23	39693
MODAL	Mode	7	0.026669	37.497	235.6	55508
MODAL	Mode	8	0.02583	38.714	243.25	59170

b) Velocity Check

The maximum velocity at the concrete top edge of the supports points is 1.06 mm/s (r.m.s), as shown in table IV.

TABLE IV

Joint Velocities without using LRB

Joint Velocities without using Lead Rubber Bearings - Absolute									
Joint	OutputCase	CaseType	StepType	U1	U2	U3	R1	R2	R3
Text	Text	Text	Text	mm/sec	mm/sec	mm/sec	rad/sec	rad/sec	rad/sec
P1	Env. Dyn. Loads	Combo.	Max	0.03745	5.77	0.2	0.000145	0.00012	0.0001876
P1	Env. Dyn. Loads	Combo.	Min	-0.0375	-5.77	-0.2	-0.00015	-0.0001	-0.000187
P2	Env. Dyn. Loads	Combo.	Max	0.01598	5.98	0.57	0.000194	0.00011	0.0001872
P2	Env. Dyn. Loads	Combo.	Min	-0.016	-5.98	-0.57	-0.00019	-0.0001	-0.000187
P3-1	Env. Dyn. Loads	Combo.	Max	0.22	6.06	0.72	0.000203	0.00011	0.0001864
P3-1	Env. Dyn. Loads	Combo.	Min	-0.22	-6.06	-0.72	-0.0002	-0.0001	-0.000186
P3-2	Env. Dyn. Loads	Combo.	Max	0.22	6.06	0.72	0.000203	0.00011	0.0001864
P3-2	Env. Dyn. Loads	Combo.	Min	-0.22	-6.06	-0.72	-0.0002	-0.0001	-0.000186
P4-1	Env. Dyn. Loads	Combo.	Max	0.22	6.26	1.06	0.000211	9.7E-05	0.0001865
P4-1	Env. Dyn. Loads	Combo.	Min	-0.22	-6.26	-1.06	-0.00021	-1E-04	0.000186
P4-2	Env. Dyn. Loads	Combo.	Max	0.22	6.26	1.06	0.000211	9.7E-05	0.000186
P4-2	Env. Dyn. Loads	Combo.	Min	-0.22	-6.26	-1.06	-0.00021	-1E-04	-0.000186

c) Displacement Check

The max. Displacement at the concrete top edge of the supports points is 7.3×10^{-3} mm, as shown in table V.

TABLE V

Joint Displacementwithout using LRB

Joint Displacements without using Lead Rubber Bearings									
Joint	OutputCase	CaseType	StepType	U1	U2	U3	R1	R2	R3
Text	Text	Text	Text	mm	mm	mm	Radians	Radians	Radians
P1	Env. Dyn. Loads	Combo.	Max	0.000388	0.271579	0.0029	1.37E-06	8.5E-07	1E-05
P1	Env. Dyn. Loads	Combo.	Min	-0.00039	-0.27158	-0.0029	-1.4E-06	-8E-07	1E-05
P2	Env. Dyn. Loads	Combo.	Max	0.000379	0.301132	0.003834	1.51E-06	8E-07	1E-05
P2	Env. Dyn. Loads	Combo.	Min	-0.00038	-0.30113	-0.00383	-1.5E-06	-8E-07	1E-05
P3-1	Env. Dyn. Loads	Combo.	Max	0.012527	0.311244	0.004412	1.64E-06	8.1E-07	1E-05
P3-1	Env. Dyn. Loads	Combo.	Min	-0.01253	-0.31124	-0.00441	-1.6E-06	-8E-07	1E-05
P3-2	Env. Dyn. Loads	Combo.	Max	0.012527	0.311244	0.004412	1.64E-06	8.1E-07	1E-05
P3-2	Env. Dyn. Loads	Combo.	Min	-0.01253	-0.31124	-0.00441	-1.6E-06	-8E-07	1E-05
P4-1	Env. Dyn. Loads	Combo.	Max	0.012476	0.338194	0.007353	1.78E-06	6.9E-07	1E-05
P4-1	Env. Dyn. Loads	Combo.	Min	-0.01248	-0.33819	-0.00735	-1.8E-06	-7E-07	1E-05
P4-2	Env. Dyn. Loads	Combo.	Max	0.012476	0.338194	0.007353	1.78E-06	6.9E-07	1E-05
P4-2	Env. Dyn. Loads	Combo.	Min	-0.01248	-0.33819	-0.00735	-1.8E-06	-7E-07	1E-05

d) Frequency Range Check (case 1)

For first natural frequency with participation mass >5% As per DIN 4024-1

Operating frequency/range	First natural frequency
50 Hz (3000 RPM) / -X% + Y%	50Hz – (20+X)% to 50Hz + (25+Y)%

X and Y depend on the local grid code and/or machine vendor requirements.
Typical values would be: X=5 and Y=3.

For a 50 Hz application that would mean exclusion range of 37.5 Hz to 64 Hz, for the first natural frequency.

From Sap2000 model output Modal Cases No. (1, 2, 4, 5&7) have a mass participation ratio >5% as shown in table VI marked in red and some of them are in safe frequency range as shown in frequency table III. Butmode number 7 is in the excitation value (frequency = 37.49) which mean that it is in the danger range which lead to maximize the size and geometry of foundation to be in the safe frequency range but it is better to use a smart economic solution with using damping devices and compare the values in the next pages.

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TABLE VI
Participation Mass Ratio for Each Mode shape

Modal Participating Mass Ratios									
Case	StepType	StepNum	Period	UX	UY	UZ	SumUX	SumUY	SumUZ
Text	Text	Unitless	Sec	Unitless	Unitless	Unitless	Unitless	Unitless	Unitless
MODAL	Mode	1	0.375295	0.999902	9.195E-19	0.000003019	0.999902	9.19E-19	0.000003019
MODAL	Mode	2	0.366129	9.526E-19	0.981225	0	0.999902	0.981225	0.000003019
MODAL	Mode	3	0.287812	0	0.018553	0	0.999902	0.999778	0.000003019
MODAL	Mode	4	0.04174	0.000026	0	0.823779	0.999928	0.999778	0.823782
MODAL	Mode	5	0.032601	0.000053	0	0.092986	0.999981	0.999778	0.916768
MODAL	Mode	6	0.031537	0	0.000216	0	0.999981	0.999994	0.916768
MODAL	Mode	7	0.026669	0.000008286	0	0.077524	0.999989	0.999994	0.994291
MODAL	Mode	8	0.02583	5.892E-20	0.000001659	0	0.999989	0.999996	0.994291

e) Frequency Range Check (case 2)

For higher natural frequency with participation mass (5% > participation mass >1%) As per DIN 4024-1

Operating frequency/range	Higher natural frequencies
50 Hz (3000 RPM) / -X% + Y%	50Hz – (10+X)% to 50Hz + (10+Y)%

For a 50 Hz application that would mean exclusion range of 42.5 Hz to 56.5 Hz for higher natural frequencies.

From Sap2000 model. Output Modal Case No. (3) is a (5% > participation mass >1%) as shown in table VI. And Frequency as shown in table IIIis in the safe frequency range.

4. Dynamic response for Turbo Generator Foundation with using supplemental passive damping devices

This section introduces the design data and dynamic properties foundation with supplemental damping devices (Lead Rubber Bearing).

a) Calculate the stiffness of each bearing

Total weight of (machine + foundation system) (W) = 5374 KN

Consider No. of isolators = 6 isolators (isolator in the top of each column)

∴ Load per isolator = $\frac{5374}{6}$ = 896 KN

Consider target of isolation efficiency η = 90%

Considering isolating damping as 10% which means that ζ = 0.1

∴ From the graph (Isolation frequency VS. frequency ratio) Bhatia (2008), the frequency ratio (β) = 3.6

∴ Required isolator frequency (P) = $\frac{\omega}{\beta} = \frac{314.16}{3.6}$ = 87.26 rad/s

As ω = $\frac{2\pi N}{60}$ = 314.16 rad/sec

∴ Required isolator deflection δ,calculated as follows:

∵ $P = \sqrt{\frac{g}{\delta}}$,

∴ $(P^2) = \frac{g}{\delta}$,   Then, $\delta = \frac{9810}{87.26\text{^}2}$ = 1.2 mm

∴ Stiffness of isolator (Vertical) = Ky = $\frac{896}{1.2}$ = 750 KN/mm

∴ Stiffness of isolator (Lateral) = Kx = Kz = 0.6 x 750 = 450 KN/mm

And the following figures 6&7, shows location of LRB above foundation columns and its simulation using SAP2000 FE model.

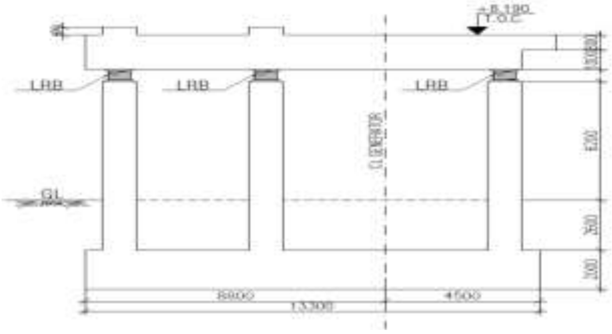

Figure 6: LRB above Columns Locations on TG Foundation

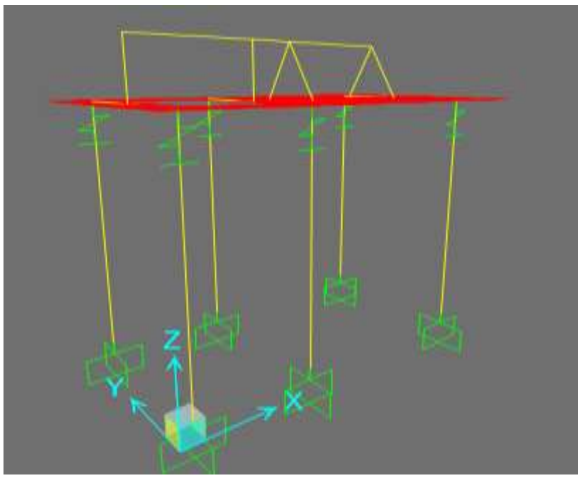

Figure 7: Simulating LRB in Sap2000 model

b) Mode Shape and Frequencies

The following table VII, shows the modes and frequencies for Machine foundation with using Damping devices (lead rubber bearings).

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TABLE VII

Mode shapes Periods and Frequencies with using LRB

Modal Periods And Frequencies with using Lead Rubber Bearings						
OutputCase	StepType	StepNum	Period	Frequency	CircFreq	Eigenvalue
Text	Text	Unitless	Sec	Cyc/sec	rad/sec	rad2/sec2
MODAL	Mode	1	0.092456	10.816	67.959	4618.4
MODAL	Mode	2	0.088432	11.308	71.051	5048.2
MODAL	Mode	3	0.073603	13.586	85.366	7287.4
MODAL	Mode	4	0.037828	26.436	166.1	27589
MODAL	Mode	5	0.029289	34.142	214.52	46020
MODAL	Mode	6	0.028425	35.181	221.05	48861
MODAL	Mode	7	0.024844	40.252	252.91	63963
MODAL	Mode	8	0.024456	40.89	256.92	66006

c) Velocity Check

The max. Velocity at the concrete top edge of the supports points is 1.00 mm/s (r.m.s), as shown in table VIII.

TABLE VIII

Joint Velocities withusing LRB

Joint Velocities with using Lead Rubber Bearings									
Joint	OutputCase	CaseType	StepType	U1	U2	U3	R1	R2	R3
Text	Text	Text	Text	Mm/s	Mm/s	Mm/s	Rad/s	Rad/s	Rad/s
P1	Env. Dynamic Loads	Combination	Max	0.03124	1.97	0.19	0.0001114	0.00012	2E-04
P1	Env. Dynamic Loads	Combination	Min	-0.03124	-1.97	-0.19	-0.000111	-0.00012	-2E-04
P2	Env. Dynamic Loads	Combination	Max	0.01624	2.13	0.41	0.0001383	0.000115	2E-04
P2	Env. Dynamic Loads	Combination	Min	-0.01624	-2.13	-0.41	-0.000138	-0.00011	-2E-04
P3-1	Env. Dynamic Loads	Combination	Max	0.29	2.16	0.59	0.0001443	0.000115	2E-04
P3-1	Env. Dynamic Loads	Combination	Min	-0.29	-2.16	-0.59	-0.000144	-0.00011	-2E-04
P3-2	Env. Dynamic Loads	Combination	Max	0.29	2.16	0.59	0.0001443	0.000115	2E-04
P3-2	Env. Dynamic Loads	Combination	Min	-0.29	-2.16	-0.59	-0.000144	-0.00011	-2E-04
P4-1	Env. Dynamic Loads	Combination	Max	0.28	2.21	1	0.0001467	9.66E-05	2E-04
P4-1	Env. Dynamic Loads	Combination	Min	-0.28	-2.21	-1	-0.000147	-9.7E-05	-2E-04
P4-2	Env. Dynamic Loads	Combination	Max	0.28	2.21	1	0.0001467	9.66E-05	2E-04
P4-2	Env. Dynamic Loads	Combination	Min	-0.28	-2.21	-1	-0.000147	-9.7E-05	-2E-04

d) Displacement Check

The max.Displacement at the concrete top edge of the supports points is 5.3x10^{-3} mm, as shown in table IX.

TABLE IX

Joint Displacement with using LRB

Joint Displacements with using Lead Rubber Bearings									
Joint	OutputCase	CaseType	StepType	U1	U2	U3	R1	R2	R3
Text	Text	Text	Text	mm	mm	mm	rad	rad	rad
P1	Env. Dyn. Loads	Combination	Max	0.000195	0.023947	0.0022	7.148E-7	5.592E-7	3.097E-6
P1	Env. Dyn. Loads	Combination	Min	-0.000195	-0.023947	-0.0022	-7.148E-7	-5.592E-7	-3.097E-6
P2	Env. Dyn. Loads	Combination	Max	0.000074	0.034712	0.002856	8.078E-7	5.074E-7	3.085E-6
P2	Env. Dyn. Loads	Combination	Min	-0.000074	-0.034712	-0.002856	-8.078E-7	-5.074E-7	-3.085E-6
P3-1	Env. Dyn. Loads	Combination	Max	0.00366	0.038489	0.003623	8.46E-7	5.081E-7	3.058E-6
P3-1	Env. Dyn. Loads	Combination	Min	-0.00366	-0.038489	-0.003623	-8.46E-7	-5.081E-7	-3.058E-6
P3-2	Env. Dyn. Loads	Combination	Max	0.00366	0.038489	0.003623	8.46E-7	5.081E-7	3.058E-6
P3-2	Env. Dyn. Loads	Combination	Min	-0.00366	-0.038489	-0.003623	-8.46E-7	-5.081E-7	-3.058E-6
P4-1	Env. Dyn. Loads	Combination	Max	0.003642	0.048154	0.005383	8.759E-7	3.966E-7	3.042E-6
P4-1	Env. Dyn. Loads	Combination	Min	-0.003642	-0.048154	-0.005383	-8.759E-7	-3.966E-7	-3.042E-6
P4-2	Env. Dyn. Loads	Combination	Max	0.003642	0.048154	0.005383	8.759E-7	3.966E-7	3.042E-6
P4-2	Env. Dyn. Loads	Combination	Min	-0.003642	-0.048154	-0.005383	-8.759E-7	-3.966E-7	-3.042E-6

e) Frequency Range Check (case 1)

For first natural frequency with participation mass >5% As per DIN 4024-1

Operating frequency/range	First natural frequency
50 Hz (3000 RPM) / -X% + Y%	50Hz – (20+X)% to 50Hz + (25+Y)%

X and Y depend on the local grid code and/or machine vendor requirements.
Typical values would be: X=5 and Y=3.

For a 50 Hz application that would mean an exclusion range of 37.5 Hz to 64 Hz, for the first natural frequency.

From Sap2000 model output Modal Cases No. (1, 2, 3, 4&5) have a mass participation ratio >5% as shown in table X marked in red and their Frequencies shown in the frequency table VII. And as shown the lead rubber bearing lead all the frequencies to be in the safe frequency range, also mode number 7 now is out of (mass ratio > 5%) and that is shows how lead rubber bearing significantly affect the dynamic responses of turbo-generator foundation.

TABLE X

Participation Mass Ratio for Each Mode shape with using LRB

Modal Participating Mass Ratio									
Case	StepType	StepNum	Period	UX	UY	UZ	SumUX	SumUY	SumUZ
Text	Text	Unitless	Sec	Unitless	Unitless	Unitless	Unitless	Unitless	Unitless
MODAL	Mode	1	0.092456	8.251E-17	0.831689	0	8.25E-17	0.831689	0
MODAL	Mode	2	0.088432	0.999866	6.253E-17	0.000003212	0.999866	0.831689	0.000003212
MODAL	Mode	3	0.073603	1.281E-18	0.167704	0	0.999866	0.999393	0.000003212
MODAL	Mode	4	0.037828	0.000022	0	0.805786	0.999888	0.999393	0.805789
MODAL	Mode	5	0.029289	0.000039	0	0.076139	0.999928	0.999393	0.881928
MODAL	Mode	6	0.028425	1.881E-19	0.000165	0	0.999928	0.999558	0.881928
MODAL	Mode	7	0.024844	0.000007328	2.014E-19	0.0108868	0.999935	0.999558	0.990796
MODAL	Mode	8	0.024456	1.059E-17	0.000424	2.511E-20	0.999935	0.999983	0.990796

f) Frequency Range Check (case 2)

For higher natural frequency with participation mass (5% > participation mass >1%) As per DIN 4024-1

Operating frequency/range	Higher natural frequencies
50 Hz (3000 RPM) / -X% + Y%	50Hz – (10+X)% to 50Hz + (10+Y)%

For a 50 Hz application that would mean an exclusion range of 42.5 Hz to 56.5 Hz for higher natural frequencies.

From Sap2000 model. Output Modal Case No. (7) is in a (5% > participation mass >1%) as shown in table X. And the corresponding Frequency as shown in table VII is in the safe frequency range.

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V. COMPARISON BETWEEN DYNAMIC RESPONSES WITH/WITHOUT LRB

The previous results showed the great effect of using LRB in changing the behavior of dynamic responses for machine foundation as it leads the machine and foundation to be at the safe dynamic frequencies range without maximize the size of table top of machine foundation and also it leads to decrease the velocity and displacements of foundation and under is the comparison between the results.

a) Time/Frequency Chart without using LRB

The below chart figure 8, shows the Time vs. Frequency without using LRB

Figure 8: Time vs. Frequency without using LRB

b) Time/Frequency Chart with using LRB

The below chart figure 9 shows the Time vs. Frequency with using LRB

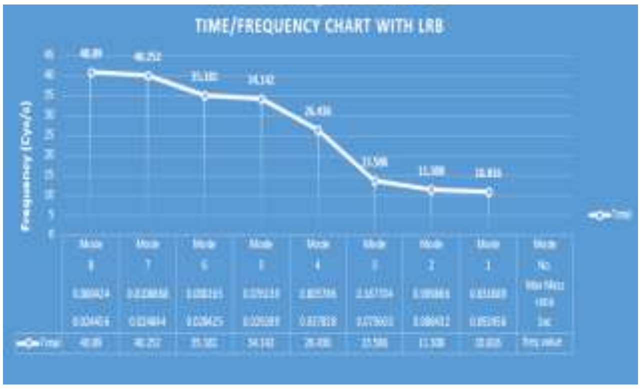

Figure 9: Time vs. Frequency with using LRB

c) Velocity comparison Chart with/without using LRB

The below chart figure 10, shows the Velocity of T.G foundation with/without using LRB at machine resting points

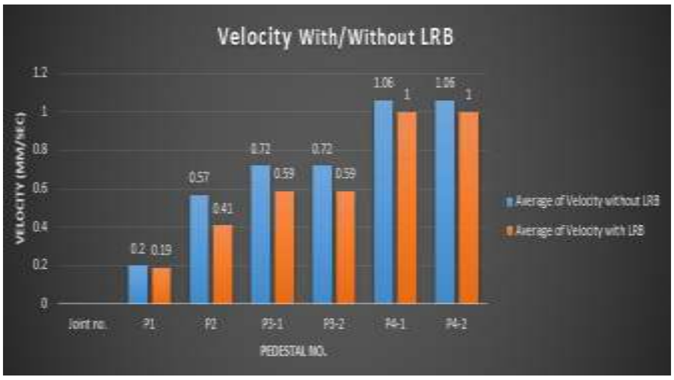

Figure 10: Velocity comparison with and without using LRB

d) Displacement comparison Chart with/without using LRB

The below chart figure 11, shows the Displacement of T.G foundation with/without using LRB at machine resting points

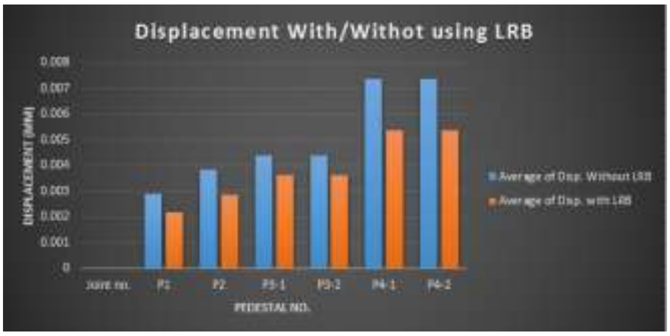

Figure 11: Displacement comparison with and without using LRB

VI. STUDY THE DYNAMIC RESPONSE OF T.G FOUNDATION AFTER DECREASING TOP DECK MASS USING LEAD RUBBER BEARINGS

This section studies the effect of LRB in reducing the mass of the table top foundation, which means use more economic sections with less mass and dimensions in the power plants. Through this study,the good response appears when top deck of the foundation decreased by 20%. And this percentage can be changed according to the mass and loadsof each foundation.Which mean that LRBleads to use machine foundation with less area and more economic concrete sections. And under is theresults after reducing 20% of foundation top deck.

a) Mode Shape and Frequencies

The following table XI, shows the frequencies for each mode shape after reducing 20% of top deck masswith using Damping devices (lead rubber bearings).

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TABLE XI

Mode shapes Periods and Frequencies with LRB after reducing 20% of top deck mass

Modal Periods and Frequencies with LRB after reducing 20% of top deck mass						
OutputCase	StepType	StepNum	Period	Frequency	CircFreq	Eigenvalue
Text	Text	Unitless	Sec	Cyc/sec	rad/sec	rad2/sec2
MODAL	Mode	1	0.085597	11.683	73.405	5388.2
MODAL	Mode	2	0.082164	12.171	76.471	5847.8
MODAL	Mode	3	0.068931	14.507	91.152	8308.8
MODAL	Mode	4	0.036645	27.289	171.46	29398
MODAL	Mode	5	0.028171	35.498	223.04	49747
MODAL	Mode	6	0.026963	37.088	233.03	54304
MODAL	Mode	7	0.025245	39.612	248.89	61948
MODAL	Mode	8	0.025024	39.961	251.08	63043

b) Frequency Range Check (case 1)

For first natural frequency with participation mass >5% As per DIN 4024-1

Operating frequency/range	First natural frequency
50 Hz (3000 RPM) / -X% + Y%	50Hz – (20+X)% to 50Hz + (25+Y)%

X and Y depend on the local grid code and/or machine vendor requirements.
Typical values would be: X=5 and Y=3.

For a 50 Hz application that would mean an exclusion range of 37.5 Hz to 64 Hz, for the first natural frequency.

From Sap2000 model output with using supplemental lead rubber bearings we found that Modal Cases No. (1, 2, 3 & 4) which marked with red in table XII have a mass participation ratio >5% and Frequencies are in the safe frequency range. Which means that lead rubber bearings lead all of these frequencies to be in the safe frequency range and out of the excitation range after reducing 20% of top deck foundation.

TABLE XII

Participation Mass Ratio for Each Mode shape with using LRB after reducing 20% of top deck mass

Modal Participating Mass Ratios									
Case	StepType	StepNum	Period	UX	UY	UZ	SumUX	SumUY	SumUZ
Text	Text	Unitless	Sec	Unitless	Unitless	Unitless	Unitless	Unitless	Unitless
MODAL	Mode	1	0.085597	1.3E-16	0.831629	0	1.3E-16	0.83163	0
MODAL	Mode	2	0.082164	0.999832	1.012E-16	1.038E-06	0.999832	0.83163	1.038E-06
MODAL	Mode	3	0.068931	1.32E-18	0.16763	0	0.999832	0.99926	1.038E-06
MODAL	Mode	4	0.036645	0.000012	0	0.753806	0.999844	0.99926	0.753807
MODAL	Mode	5	0.028171	0.000038	4.971E-20	0.025109	0.999882	0.99926	0.778915
MODAL	Mode	6	0.026963	7.33E-19	0.000157	2.597E-20	0.999882	0.99942	0.778915
MODAL	Mode	7	0.025245	0.000011	0	0.0198274	0.999892	0.99942	0.977189
MODAL	Mode	8	0.025024	2.66E-17	0.000555	1.207E-18	0.999892	0.99997	0.977189

c) Frequency Range Check (case 2)

For higher natural frequency with participation mass (5% > participation mass >1%) As per DIN 4024-1

Operating frequency/range	Higher natural frequencies
50 Hz (3000 RPM) / -X% + Y%	50Hz – (10+X)% to 50Hz + (10+Y)%

For a 50 Hz application that would mean exclusion range of 42.5 Hz to 56.5 Hz for higher natural frequencies.

From Sap model output. Modal Cases No. (5&7) are in a (5% > participation mass >1%) as shown above in table XII, and the corresponding Frequencies are in safe frequency range.

d) Time/Frequency Chart with using LRB after reducing 20% of top deck

The below chart figure 12 shows the Time Vs. Frequency with using LRB isolator with reduction 20% in the top deck concrete mass.

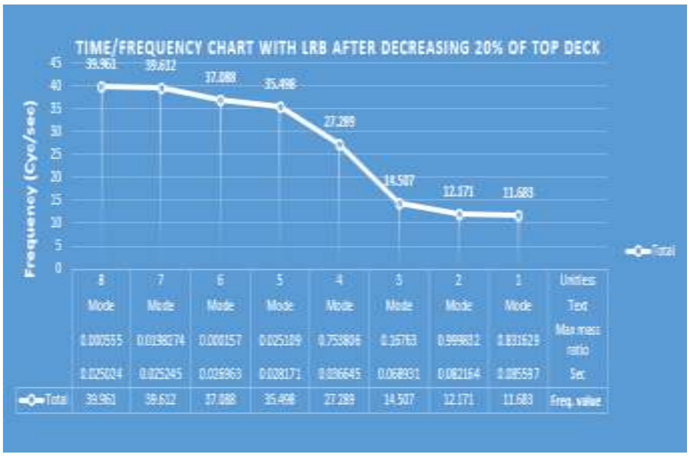

Figure 12: Time vs. Frequency with using LRB after reducing 20% of top deck

e) Velocity Check after reducing 20% of top deck

The max. Velocity at the concrete top edge from all support points is 1.16 mm/s (r.m.s).

f) Displacement Check after reducing 20% of top deck

The max. Displacement at the concrete top edge from all support points is 5.3x10-3 mm.

So from the previous results, tables and charts,lead rubber bearings (passive supplemental devices) not only lead the dynamic properties of Turbo-Generator foundation to be in the safe frequency range, but also lead to decrease the mass and

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dimensions of foundation with safe dynamic responses, which means use more economic foundation concrete sections with less mass and dimension and good dynamic properties. And figure 13 shows the Turbo-Generator foundation after decreasing the top deck of foundation with 20%.

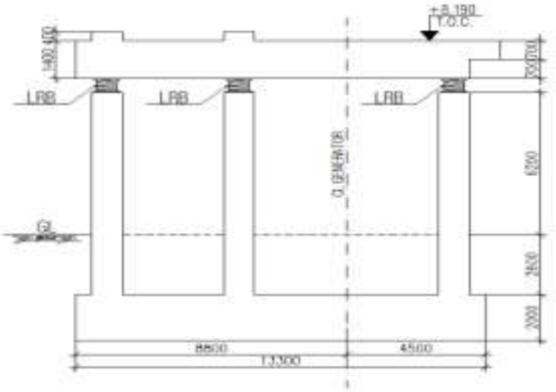

Figure 13: T.G Foundation after decreasing Top Deck with 20% and still in the Safe Range

V. SUMMARY

The purpose of this paper is to highlight the effect of supplemental damping devices in changing the dynamic behavior of turbo-generator foundation. Study of T.Gframe foundation is introduced. And to model such large framed foundation a SAP2000 finite element model is built using shell and frame elements. The main analysis performed to compare the dynamic behavior of foundation with and without using damping devices are: (1) Frequency analysis, (2) harmonic analysis.

Frequency analysis is performed to determine the natural frequency of the foundation and the percentage of masses captured by the modes of vibration and the frequencies corresponding to it. This analysis done for two cases with and without using damping devices (LRB) to compare the results. In addition to that, the frequency analysis is used in study to check if the foundation natural frequency is outside the machine operating frequency with +/-20% margin in each case.

Harmonic analysis is performed to determine the response of the foundation to the dynamic unbalanced loads that applied from the machine to the foundation during all machine operation time to compare the results with and without damping devices (LRB).

Study the effect of damping devices in decreasing masses of the foundation therefor reduce the construction cost is introduced for more economic foundation.

VI. CONCLUSION

Based on the results of this study the following can be concluded:

Frequency Analysis: Using supplemental damping devices (LRB) has a significant effect on changing the fundamental frequency, changes in the natural frequency values are observed due to using lead rubber bearing which lead the turbo-generator foundation locate in the safe frequency range by changing the dynamic response for the foundation from being set in resonance condition to be out of the resonance condition which lead the foundation to be in the safe dynamic range.

Harmonic Analysis: using of supplemental damping devices (LRB) reflect in changing the displacements, velocities and amplitudes with good results to ensure that using damping devices improve the dynamic responses of turbo-generator machine foundation in both frequency analysis and harmonic analysis.

Also results shows that decreasing 20% of top deck of the foundation with using LRB still setting the foundation in the safe range with good dynamic responses which means that using damping devices in machine foundations is more economic and more efficient for machine stability.

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