Journal of Civil Engineering and Environmental Technology
Print ISSN: 2349-8404; Online ISSN: 2349-879X; Volume 1, Number 4; August, 2014 pp. 30 – 35

http://www.krishisanskriti.org/jceet.html

Dynamic Analysis of Turbo-generator Machine Foundations

Jayarajan P., Kouzer K.M.
M.Dasan Institute of Technology (M-DIT), Ulliyeri, Kozhikode -673620, Kerala
Civil Engineering
Govt.Engineering College
Kozhikode -673005, Kerala

Abstract : **Turbo-generators are power generation machinery used in the power plants. It is the most vital and expensive equipment of a power plant complex and is generally placed inside a power house. The turbo-generator foundation consists of turbine, generator and its auxiliaries mounted on a reinforced cement concrete (RCC) table top structure consisting of the top deck, columns and bottom raft. Considering the difficult natural parameters, enormity of the machines and risk involved in terms of public outcry, analysis and design of turbo-generator foundations still remain one of the most difficult and challenging task in civil engineering profession. A key ingredient to the successful foundation design for a turbo-generator is the careful engineering analysis of the foundation response to the dynamic loads from the anticipated operation of the machine.**

The objective of the dynamic analysis is to check for resonance conditions and to ensure that the amplitude of vibrations is restricted within the acceptable limits set by the machine manufacturer or code of practice. This is achieved through a free vibration analysis to accurately determine the natural frequencies for various modes of vibration and then a harmonic forced vibration analysis to determine the foundation response to loads due to machine unbalance. The paper presents a detailed procedure for the finite element modelling of foundation structure along with supporting soil and dynamic analysis of turbo-generator foundations. To demonstrate the analysis procedures, an example problem of a turbo-generator foundation is also solved using SAP2000 software which provides an effective computational environment to perform all types of analyses.

1. INTRODUCTION

A Turbo-generator (TG) foundation consists of an RCC top deck slab, a supporting structure of beams and columns and a foundation system consisting rafts or piles resting on soil (Figure 1). The top deck supports all the equipments including turbine, generator and other rotary equipments.

The supporting structure transfers the loads from top deck slab to the foundations. The top deck slab is normally built monolithically with the supporting structure For large steam turbine of coal-fired power station the thickness of the top deck slab is about 3.5 m and the base mat thickness may reach 4.0 m. Top of the deck slab is about 16-18 m above the base mat top.

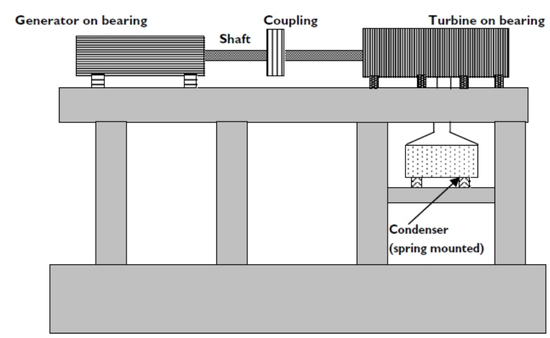

Figure 1. Layout of a TG foundation

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 dynamics. Established methods of obtaining structural models for these foundations, such as, finite element method have proved successful because of the realistic approach used in the analysis considering all the complexities of the parameters. Dynamic effects of the turbo-generators also play a major role on sizing of the foundation wherein conditions like resonance is avoided by varying stiffness and mass of the structure which leads to modifications in foundation sizes.

2. OBJECTIVES

The dynamic behaviour of the supporting structure along with the foundation, play an important role in providing normal operating conditions for the supported turbo-generator. The main source of dynamic forces in the turbo-generator is mass eccentricity, when the mass center of rotating parts does not coincide with the center of rotation. Unbalanced masses of the rotor produce centrifugal forces that lead to vibrations of the turbo-generator foundation.

The analysis of the turbine foundation is normally done in the following four steps.

- Dynamic analysis to calculate the natural frequencies of the system to ensure that it is out of tune to the operating frequency of the machine by ±20%.
- Calculation of the dynamic amplitude to check that the same are within the acceptable limits as prescribed in the code or as pre-defined by the equipment supplier.
- Earthquake analysis if the same is perceived critical for the foundation.
- A pseudo–static analysis to obtain the design moment, shear and torsion induced in the members and to check the stresses induced in the different structural elements like beams, columns and slabs.

The paper focuses on the first two steps of the analysis and accordingly details the various aspects involved in the development of a realistic finite element model required for dynamic analysis. The response of the foundation is then obtained through free vibration analysis (Eigen analysis) and harmonic forced vibration analysis.

3. INPUT DATA

The dynamic analysis of a turbine foundation requires critical machine input data from turbine & generator manufacturer and soil properties from geotechnical specialists. A check list required for the Turbine foundation design is given below.

- Overall dimensions of the machine
- The anchor bolt locations, diameter and length of bolts including their anchoring details.
- The height at which the centre line of the shaft of the machine is located from top of concrete deck slab.
- Operating speed of the machine.
- The loads and locations of valves and pipes to supported on deck slab.
- Dynamic loads generated during the operation of the machine.
- Cut outs in the top deck including its size and location.
- Different load combinations for which the turbine foundation has to be designed specially from mechanical considerations like short circuit moments, breaking of impeller and thermal differential etc.
- Performance criteria in terms of frequency ratio and amplitude of vibration.
- Allowable bearing capacity of the soil
- Dynamic shear modulus, Poisson's ratio and mass density of soil.

Once the above check list is satisfied, the engineer can proceed for the preliminary sizing of various members of the foundation to be checked later by a detailed dynamic analysis.

4. PRELIMINARY SIZING OF TURBINE FOUNDATION

The guidelines given below can be used to obtain preliminary sizing of turbine foundations to be used for dynamic analysis.

- The overall dimensions of the top deck slab shall be finalized taking into consideration the sizes of machines, the space requirements for its operation and maintenance.
- All columns should be sized in such a way that they are almost equally stressed under vertical loads. As a rule of thumb, the columns shall have load carrying capacity of about six times the actual vertical load and shall be placed not less than 3.6 meters center to center.
- The depth of the longitudinal and the transverse beam shall be one fifth the clear span with the width equal to the width of the column.
- The turbine frame should in principle act as a rigid shear frame as such the flexural stiffness of the top deck beams shall be two times the flexural stiffness of the columns.
- The bottom of the raft shall not be placed above the level as suggested by the geotechnical consultant where the thickness (t) of the slab shall not be less than, $t = 0.07L^{4/3}$, where L is the average distance between columns.
- The mass of the top deck plus mass of half the length of the column shall not be less than the mass of the supported turbine and its auxiliaries on the top deck.
- The total mass of the frame plus the raft shall not be less than three times the mass of the machine.
- The stress induced in soil shall not exceed 50% of the allowable bearing capacity of the soil. For foundations supported on piles the most heavily loaded pile shall not carry 50% of its allowable load.

- The center of rigidity of the columns shall coincide with the CG of the equipment plus the top half of the structural loads both in the transverse and longitudinal direction.

The preliminary sizes obtained as per the above guidelines can also be used to perform the hand calculations before a detailed dynamic analysis. For the detailed hand calculations [1] can be used.

5. FINITE ELEMENT METHOD

Finite element method is the most commonly accepted analysis tool for the design of turbine foundations as it enables the modelling of machine, foundation and soil in one go, which brings behaviour of the machine-foundation system closer to that of the prototype, resulting in improved reliability. However, it shall be noted that the accuracy of analysis results depends on many factors such as the modelling techniques, element types and the model refinement.

6. MODELLING OF TG FOUNDATIONS

A frame foundation comprises base raft, set of columns and top deck consisting of (longitudinal and transverse) beams and slabs. The top deck is made of RCC with required openings, depressions, raised pedestals, and extended cantilever projections. There are many ways of representing the model of a frame foundation using the beam elements, shell elements, solid elements, or a combination of all of these each with its associated limitations. A typical conceptual model of a turbine foundation resting on a bottom raft supported by soil is shown in Figure 2.Some important considerations to be kept in mind for the modelling of various components of TG foundations are given below.

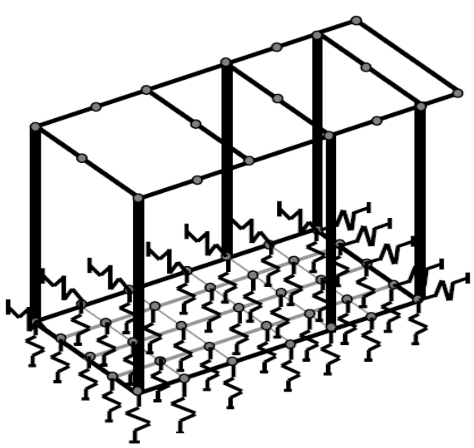

Figure 2. 3D model – turbine frame foundation

6.1. The Super structure

The obvious choice for the super structure is to model it as a space frame where the beams and columns are idealized as beam elements having six degrees of freedom at each node. But for modeling a turbine foundation frame there is a difference with normal building frames where the beams and columns are modeled at their centre lines. In the case of Turbine foundations , as the columns are of large dimensions (1500-2000mm) and design bending moment in beams are required at the face of columns, the beam column junction should consist of three nodes instead of one connected by rigid links as shown in Figure 3. For the beam elements as the span by depth ratio is significant it is preferable to consider the shear deformation of the girder during the analysis.

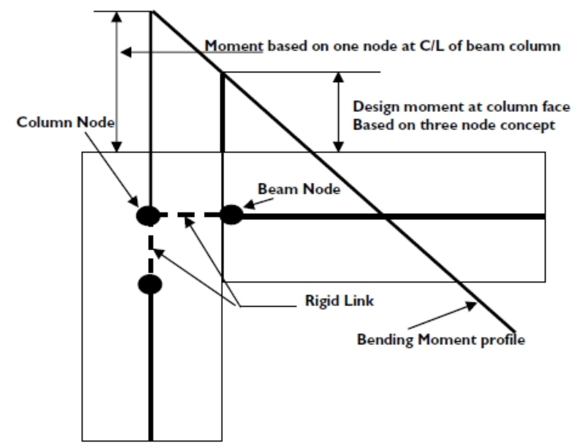

Figure 3. Beam column junction with rigid link

The mathematical model for the superstructure shall also not be complicated with the addition of minute details such as haunches, depressions, raised blocks etc. which increases the problem size without any significant gain in the accuracy of results. Only those elements that contribute significantly to the stiffness and mass, like large openings, sizeable depressions, etc., must be accounted for and modeled in detail, whereas the elements like pockets, small notches, etc. could easily be ignored while modelling.

6.2. The Foundation Raft

The foundation raft usually consists of a slab of about 2000/2500 mm thick resting on soil or pile. While the raft can be modeled using plate bending elements, beam elements supported on soil springs or even 8-noded brick element, the engineer needs to be aware of the limitations in each case. While the use of Kirchoff-type of plate based on the thin plate theory neglect the contribution of transverse shear acting along the edge of plate (dominant in the case of thick rafts), Mindlin-type of thick plate considers shear contribution along the edge. However such thick plate elements suffer from many other technical problems such as sensitivity to geometrical meshing.

Brick elements could also be a good choice for modeling the turbine raft. From convergence point of view brick elements are stable. However it has been observed that the eight nodded brick element usually have poor approximation capability and higher order elements having 16 or 24 nodes are usually used for efficient solution. Besides this brick element suffers from one serious lacunae in terms of design. Brick elements in most of the commercially available software give output in terms of normal and shear stress parameters whereas for the turbine raft design we are basically looking for output in terms of moment, shear and torsion. The back calculation of these design parameters from the computer output is extremely tedious. In terms of ease of use as well as convergence of results, beam elements do make a very attractive choice for modelling the turbine raft.

6.3. The Soil

The basic soil parameter which needs to be known to mathematically model the soil is dynamic shear modulus (G_s). The soil being a continuum itself can either be modelled based on FEM as 3D brick elements, 2D plane strain elements or discrete springs. For the particular case of turbine foundation analysis, the common practice is to model the soil as frequency independent linear springs based on Richart or Wolf's springs. In this approach, the soil is represented by a set of three translational springs, attached at each node at the base of the foundation in contact with the soil. Approximate formulae for computation of dynamic stiffness of rigid foundations (frequency dependent & independent) can be found in [2,7].

In case soil is modelled as a continuum, it becomes necessary to confine it to a finite domain and accordingly the extent of soil domain to be modelled becomes an important issue. Though there is no definite answer to this, experience shows that soil domain equal to three to five times the lateral dimensions in plan on either side of the foundation and five times along the depth should work out to be reasonably good. If the soil profile indicates the presence of layered media, appropriate soil properties are assigned to the respective soil layers.

6.4. The Machine

Machine is relatively rigid compared to the foundation and soil. While modeling the machine, the broad objective is to represent the machine in such a way that its mass is truly reflected, and CG of the overall mass of the model matches with that of the prototype. Thus, modeling of the machine with rigid links or rigid-beam elements is considered good enough. Machine mass is considered lumped at appropriate locations so as to correctly simulate the CG location. This should be cross-checked with the mass distribution given by the supplier/manufacturer. [3] provides guidelines for advanced modelling of machine including the rotor and stator.

7. DYNAMIC LOADS

The main dynamic loads acting on the turbine foundation during its operation are caused by the unbalance of the rotating parts with a frequency corresponding to the operating speed. These loads are normally provided by the machine manufacturer. In case these loads are not available, they may be calculated via the balance quality grade of the rotor.

The balance quality grade "G" is the product of the maximum permissible eccentricity "e" (mm) and the maximum angular velocity of the rotor "ω" (rad/s) as shown in Figure 4. In industry, balance quality grades are usually determined in accordance with ISO 1940-1 [6]. They are separated from each other by a factor of 2.5. For turbines and generators, the intended balance quality grade is usually G=2.5 mm/s. The resultant unbalanced load F(t) (N) is calculated with the rotating mass "m" (kg) and the balance quality grade "G" (mm/s) as follows.

$$F(t) = m\, e\, \omega^2$$

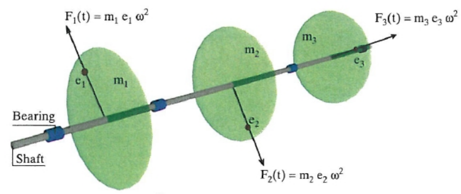

Figure 4. Scheme of unbalance loads

8. DYNAMIC ANALYSIS

Dynamic analysis of turbine foundation is done after modelling, mass lumping at appropriate locations and application of dynamic loads are completed. The dynamic analysis is performed in two stages, namely free vibration analysis to obtain all natural frequencies and forced vibration analysis to obtain peak response of the foundation under dynamic loads. Detailed procedure for performing dynamic analysis of different structural systems can be found in [4]. The number of significant modes to be considered for the analysis shall be based on modal mass participation factor. The number of modes that excite at least 95-99% of the mass should be considered in the analysis. Further the highest natural frequency calculated should be at least ten percent higher than the operating frequency of the machine [5].

9. EXAMPLE

A table top framed foundation shall be constructed for the proposed turbo-generator with the following data.

Operating frequency of machine = 4500 rpm.
Centre line axis of shaft =1.950m above the top deck
All columns = 1200 x 1000 mm
Top of deck slab = EL 108.000 (100.000-GL)
Bottom of foundation raft = EL 96.750
Thickness of foundation raft = 1500 mm
Thickness of top deck slab = 1000 mm

Shear modulus of soil (from geotechnical report) G_s = 545.5 MPa (as per client specification dynamic analysis shall also be performed for 0.75*G_s & 1.25*G_s). Various details including the mass of rotor part for individual machines along with the corresponding maximum expected unbalance loads are obtained from vendor drawing.

9.1. Finite Element Modelling

The table-top foundation structure for turbine is analyzed using SAP2000 (Version 14) software [8]. SHELL (thick) elements which include the effects of transverse shear deformation are used for modeling of base raft & deck slab. Reinforced concrete columns & Tie Beams are modeled using FRAME element. To consider the effect of rigidity of column from mid-plane of raft to top-surface of raft and from soffit of top-deck slab to mid plane of top-deck slab, element OFFSETS are modeled. Soil is modeled using SPRING element in horizontal X, Y direction and in vertical Z direction at every node of the base raft bottom. The SAP2000 3D model for the foundation structure is shown in Figure 5.

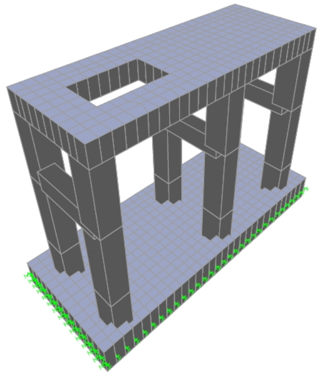

Figure 5. SAP 2000-TG foundation 3D model

The machine lumped masses are modeled at its mass centers as provided in vendor drawing. To connect these masses to the top-deck slab joint BODY CONSTRAINT facility is used. The self weight of foundation structure is modeled using consistent mass approach. SAP2000 will internally convert the masses on account of self weight of elements as a lumped mass at every nodes based on contributory length/area. The weights of various machine components are applied at mass centers described in vendor drawing using "JOINT LOAD" command which are then automatically converted to mass in SAP2000.

9.2. Dynamic Analysis Results

From the results of free vibration analysis, it is found that almost 100% of structure mass is excited (modal participating mass ratio=1) in all directions on considering the first twenty natural modes of vibration. Further all natural frequencies of vibration are well below the operating speed of 75 Hz avoiding the resonance. The SAP2000 free vibration analysis results for the TG foundation are presented below in Table-1. The mode shape of the structure corresponding to mode-1 is shown in Figure 6.

Table 1. Natural frequencies of TG foundation

Mode	Period	Frequency	Mode	Period	Frequency
Unitless	Sec	Cyc/sec	Unitless	Sec	Cyc/sec
1	0.359784	2.7794	11	0.038376	26.058
2	0.293487	3.4073	12	0.037156	26.913
3	0.190491	5.2496	13	0.036482	27.41
4	0.056111	17.822	14	0.035171	28.433
5	0.050078	19.969	15	0.034407	29.064
6	0.045124	22.161	16	0.033592	29.769
7	0.042564	23.494	17	0.030508	32.778
8	0.04189	23.872	18	0.029769	33.592
9	0.04057	24.649	19	0.026308	38.011
10	0.038636	25.883	20	0.022919	43.631

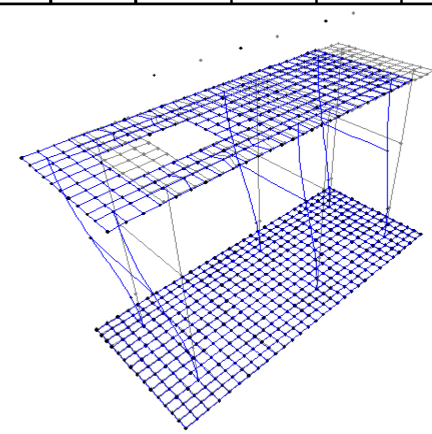

Figure 6. Foundation mode shape - first mode

To perform the forced vibration analysis, the machine unbalance load provided by the equipment manufacturer is applied on the SAP2000 model at bearing locations through TIME HISTORY function. The displacement plot of a typical bearing represented by joint 2001 in Y direction is given in Figure 7. The maximum amplitude of 75 microns is within the manufacturer specified limit of 80 microns. The steady state response analysis available in SAP2000 can be used to obtain the variation in peak foundation responses over a range of frequencies.

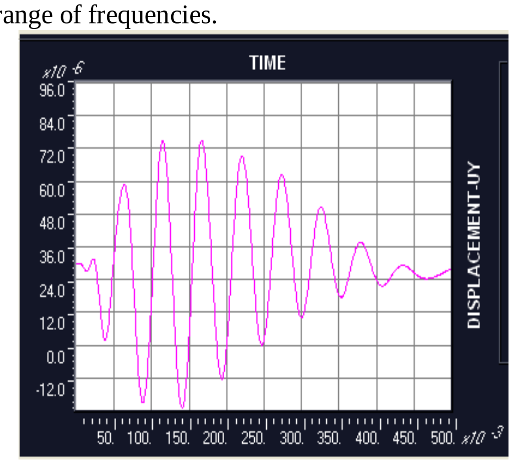

Figure 7. Forced response of node- 2001

10. CONCLUSIONS

The dynamic analysis of turbine foundations needs attention to detail both in modelling and interpretation of the results. The paper highlights various issues related to the mathematical modelling of structure, machine and soil for dynamic analysis of the foundation system. Finite element method provides an efficient tool for the modelling and dynamic analysis of turbo-generator foundations. SAP2000 provides a real computational environment for the modelling of structure, machine and soil in a single model and to perform the free and forced vibration analysis.

11. REFERENCES

[1] Alexander Major, Vibration Analysis and Design of Foundations for Machines and Turbines, Collet's, Collet's Holdings Limited, London, 1962.

[2] Artur Pais, Eduardo Kausel, "Approximate Formulas for Dynamic Stiffness of Rigid Foundations", Department of Civil Engineering, MIT, Cambridge, USA..

[3] Bhatia K.G., "Foundations for Industrial Machines and Earthquake Effects", *ISET Journal of Earthquake Technology, Paper No.495,Vol.45,No.1-2,March-June* 2008, pp. 13-29.

[4] Biggs, J.M., Introduction to Structural Dynamics, McGraw-Hill, New York, 1964.

[5] IS 2974(Part 3):1992, Indian Standard design and construction of machine foundations- Part 3: Foundations for rotary type machines (Medium and high frequency), Bureau of Indian Standards, New Delhi.

[6] ISO 1940-1 (1993) Mechanical Vibration – Balance Quality Requirements of Rigid Rotors – Part 1: Determination of Permissible Residual Unbalance.

[7] Kameswara Rao N.S.V, Foundation Design: Theory and Practice, John Wiley & Sons(Asia) Pte Ltd.

[8] SAP2000 v14, Structural Analysis Program, Computers and Structures Inc., Berkeley, California. www.csiberkeley.com.