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DYNAMIC ANALYSIS AND STRUCTURAL DESIGN OF TURBINE GENERATOR FOUNDATIONS

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ABSTRACT

Turbine-generator foundation CAE is presented. Different types of foundations are described. Dynamic behaviors of the foundations and sources of the dynamic loads are discussed.

Modal analysis is required for frequencies separation verification. Very strict limits for amplitude of vibrations at machine bearings shall be checked by harmonic forced vibration analysis. Response spectrum analysis gives estimation of internal forces and displacements due to seismic excitation. Structural design of the turbine generator foundation, made of reinforced concrete, requires series of static analyses on various static and quasi-static loads.

ANSYS/CivilFEM software provides an effective computational environment to perform all types of the analyses at once and to combine their results during the design process. IEC developed CAE is used for in-house foundation design as well as for checking and verification, when design is prepared by the machine manufacturer or by the third part.

Model generation with wide utilization of APDL capabilities is described. Different types of finite elements are used for modeling concrete structures of the foundation, supporting piles, machine parts and their connection to the foundation.

Design procedure in accordance with the relevant International and German, American and Israeli Codes and Standards is discussed. Description of applied loads is presented. Together with ordinary structural and environmental loads, specific machine loads for normal operation condition as well as emergency loads are detailed. Load combinations for ultimate state conditions as per IEC design practice are described.

Numerical results for "Tzafit" gas turbine generator foundation are presented.

INTRODUCTION

Growth of electricity consumption in the world in conjunction with strict environmental requirements inspires during the last years come-back of traditional thermal and combined cycle power plants. The concrete foundation supporting gas- and/or steam turbine(s) and generator takes the central place among the power plant structures.

IEC owns about 60 power units with capacity ranges from tens to 575 MW. During the last decade 10 new units have been constructed, 2 units are currently under construction, 3 units are in stage of detailed design and 3 another units are in stage of conceptual design and technical specifications preparation. All these units have turbine-generator foundations of different types and sizes depending on the capacity and type of power unit. There are four main classes of built foundations:

- Gas Turbine - Generator Foundation (GTGF) for 3 Gas Turbine Units 230-270 MW ("Eshkol", "Alon-Tavor", "Tzafit")
- Steam Turbine – Generator Foundation (STGF) for 2 Combined Cycle Add-On Units 130 MW ("Eshkol", "Alon-Tavor")
- Gas Turbine – Steam Turbine – Generator Foundation (GSTGF) for 5 Single Shaft Combined Cycle Units 350-390 MW ("Gezer", "Hagit", "Haifa")
- Steam Turbine – Generator Foundation (TGF) for 2x575 MW Coal Fired Power Station "Rutenberg-B"

The foundation design may be prepared in IEC Engineering Division or provided by the machine manufacturer or by the third party. In any case, an effective modeling instrument based on ANSYS/CivilFEM software is required for performing analyses and/or for checking and verification of design obtained by alternative CAE.

CONCRETE TURBINE-GENERATOR FOUNDATION

The turbine-generator foundation (TGF) is a complex engineering structure. Different types of foundations are used for different machines depending on their capacity, geometrical sizes and constructional features.

Base Mat Foundation, the simplest type of the TGF, consists of reinforced concrete plate 1.2 … 1.7 m thick. Base mat foundations are usually applied for small gas turbine units with capacity up to 100 MW.

Pedestal Foundation consists of base mat of 1.8 … 2.0 m thickness and several pedestals raised about 3.0 m. Pedestals support gas turbine frame and thick concrete walls of about 5.0 m height support generator. Pedestal foundations are used for large gas turbine units.

Tabletop Foundation consists of elevated concrete plates and beams supported by columns and walls that transfer the loads to the base mat. This type of foundation is usually used as STGF. For relatively small steam turbine of add-on units the thickness of the top plate is about 1.5 m and base mat thickness is 2.0 m (Fig. 1). For large steam turbine of coal-fired power station the thickness of the top plate is about 3.5 m and the base mat thickness may reach 4.0 m. Top of the table in this case is about 16 … 18 m above the base mat top. Vibration isolators consisting of springs and dampers located at the top of columns below the table plate are sometimes used to separate fundamental and operation frequencies and, consequently, to prevent transmission of dynamic loads on supporting structures in normal operation conditions.

Combined Foundation presents the combination of pedestal and tabletop foundations placed on common base mat of approximately 2.5 … 3.0 m thick. Foundations of this type are used for single-shaft combined cycle units when gas turbine, generator and steam turbine have a common rotor axis.

In all types of TGF the base mat may rest directly on soil or may be supported by piles. An adequate model of soil/piles in terms of equivalent spring coefficients and damping parameters is very significant for the dynamic analysis of the TGF. Usually these parameters are to be provided by a geotechnical consultant. Theoretical background and practical recommendations for soil parameters estimation are presented in [1 – 3].

Figure 1: Table-Top Steam Turbine-Generator Foundation

Dynamic behaviors of the foundation play an important role in providing normal operating conditions for the supported turbo-machine. The main source of dynamic forces in the turbo-machine is mass eccentricity, when center mass 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 rotating turbo-machine foundation. At each bearing of the rotor (both at turbine and at generator) the harmonic forces in any direction perpendicular to longitudinal rotation axis are

$$F_i(t) = P_i \sin(\omega t)$$

$$P_i = m_i e \omega^2$$

where

m_i = proportional part of rotating mass, supported by *i*-th bearing;
e = mass eccentricity;
$\omega = 2\pi f$ = circular operating frequency of the turbine-generator;
f = operating frequency ($f_0 = 50\,\text{Hz}$ at nominal turbine speed).

Very strict limits for amplitude of vibrations at machine bearings shall be checked by harmonic forced vibration analysis.

Israel is a relatively strong earthquake area. TGF is a structure that supports heavy and high elevated equipment. Therefore seismic forces are very significant for a proper and safe design of the TGF. Dynamic response spectrum analysis gives an estimation of internal forces and displacements due to seismic excitation.

The structural design of the turbine-generator foundation made of reinforced concrete requires series of static analyses on various static and quasi-static loads.

MODEL DESCRIPTION

ANSYS/CivilFEM software provides an effective computational environment to perform all types of the analyses at once and to combine their results during the design process. It is IEC practice to use ANSYS for analysis and design of complex engineering structures. Following this tradition, a special application for turbine generator foundation has been developed after the concrete chimney ANSYS-based CAD [4]. This application is used for in-house foundation design as well as for checking and verification, when design is prepared by the machine manufacturer or by the third party.

Model generation widely utilizes APDL capabilities. 3-D grid of K-points serves as basis for automatic generation process. Each one of the planar objects (base mat, pedestals, vertical walls and top plate) is modeled as a carpet of Areas. Selection and Boolean operations on the Areas are extensively used for sculpturing particular planar object to its realistic configuration, taking into consideration openings, reentering and salient angles etc. Planar object is modeled at its middle plane. Due to significant thickness of the base mat discontinuities of model exist. For example, vertical wall or pedestal starts from the top of the base mat when the mat is located below at a distance of half-thickness (Fig. 2). This distance may reach 1/4 … 1/3 of the wall height. The same situation is with the top of piles located at the bottom of the base mat. To account these eccentricities the RIGID REGION between nodes of separate objects coinciding in horizontal plane are applied after the mesh generation.

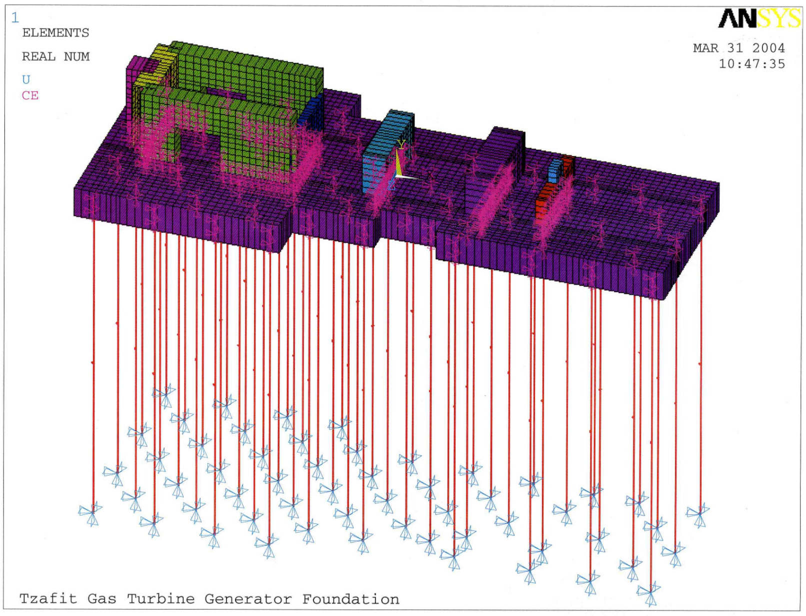

Figure 2: Finite Element Model Generation

Different types of finite elements are used for modeling concrete structures of the foundation. Element SHELL63 is used for planar objects, BEAM44 is used for columns and beams. Different material properties (concrete grade B-30 for base mat and concrete grade B-40 for elevated structures) as well as different real constants (plate thickness) are used for different objects. Special attention in meshing process is paid to establish consistent local coordinate systems for elements. It is important for right interpretation of analyses results.

The 3–D spring elements COMBINE14 are used for modeling piles supporting base mat. The node at the top of the pile is connected by RIGID REGION to coplanar node at the midplane of the base mat.

The 3-D elements MASS21 without rotary inertia are used for modeling additional masses obtained from the weight of machine parts and other equipment. Due to the fact that machine to foundation mass ratio is about 1:3 … 1:5, differences between fundamental frequencies with and without additional masses may be around 15%.

Non-structural nodes modeling machine bearing location at rotational axis elevation are connected to the foundation by RIGID REGION.

DESIGN PROCEDURE

Codes and Standards

Turbo-generator foundations are unique because they may be subjected to significant dynamic loads during operation in addition to ordinary structural design and environmental loads. Therefore normative design documents shall cover all load types and shall establish dynamic and static design criteria.

International Standard [5] limits unbalanced mass eccentricity and defines balance quality grade in terms of product $e\omega$. For gas and steam turbines balance quality grade G2.5 is to be applied which means that $e\omega = 2.5$ mm/s.

International Standards [6, 7] and German normative [8] establish dynamic design criteria in terms of permissible bearing vibration displacement amplitude or bearing root-mean-square vibration velocity. For turbine with nominal operating frequency 50 Hz bearing displacement amplitude is limited by 12.5 μm (Zone Boundary A/B).

The only standard specifically addressed to machine foundation design is German Standard [9]. The American Report [10] gives a good overview of all aspects of concrete turbine-generator foundation design but it has no normative status.

The design of reinforced concrete structures shall be in accordance with requirements of Israeli Standard [11], when seismic and wind loads are defined by [12] and [13] respectively.

Modal Analysis

Dynamic behaviors of the foundation shall be firstly verified by modal analysis. All modes with frequencies up to $1.2 f_0 = 60$ Hz shall be extracted. Usually 30 … 40 modes are enough. First 2 … 4 modes present rigid body translational (in horizontal plane) or translational-rotational modes. Vertical translational mode is usually combined with flexural modes. Only about 10 first modes have significant participation factor.

Frequency separation criteria shall be verified. For low-tuned foundation the fundamental frequency shall be less than $0.8 f_0 = 40$ Hz. If this condition is not met the resonance may occur and the foundation should be resized.

Harmonic Forced Vibration Analysis

This analysis is required to verify dynamic design criteria for vibration due to rotor unbalance forces in normal operation conditions. Sometimes the manufacturer provides unbalance loads P_i^0 for nominal frequency f_0 at each bearing of turbine and generator explicitly. In other cases P_i shall be calculated on the basis of balanced quality grade.

Harmonic analysis is provided in frequency range $0.8 f_0 \le f \le 1.2 f_0$, i.e. between 40 and 60 Hz. Unbalance forces are to be adjusted for operating frequency. Quadratic adjustment

$$P_i(f) = P_i^0 \left(f / f_0\right)^2$$

shall be used when unbalance loads are defined explicitly, and the linear adjustment

$$P_i(f) = P_i^0 f / f_0$$

is applied in case of balanced quality grade usage.

These rotor unbalance loads may be acting with random distribution of relative phase angle. Hence four cases are taken into consideration:

- Vertical unbalance forces applied in-phase;
- Vertical unbalance forces applied counter-phase;
- Horizontal unbalance forces applied in-phase;
- Horizontal unbalance forces applied counter-phase.

Damping ratio is assumed 0.02 as recommended in [9].

Response Spectrum Analysis

The evaluation of the seismic effect on TGF is based on the dynamic response spectrum analysis. The design spectrum for all mode shapes and periods is derived from the spectral amplification factor curves for horizontal seismic action, corresponding to appropriate type of soil, as required in Israeli Standard [12] (Fig. 3). Notwithstanding its relatively small area, Israel has zones that significantly differ one from another from seismological point of view. The expected horizontal ground acceleration varies from about 0.1g at Mediterranean Sea shore to 0.3g near the Jordan Valley which is a part of the Syrian-African fault line.

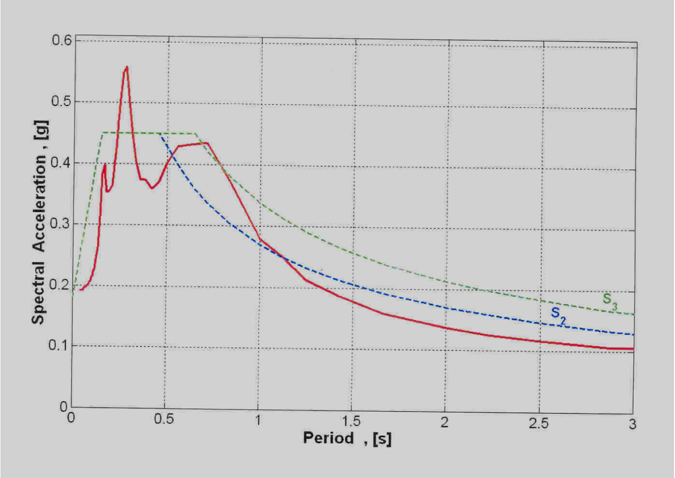

Figure 3: SI 413 Spectrum (for Soil Types S2, S3) vs. Site-Specific Response Spectrum

Additional magnification of ground acceleration known as site effect depends on local geological structure. Due to the vital importance of power station normal functioning IEC order seismological survey and seismic hazard assessments at each one of the new designed power units. Site-specific response spectrum obtained as a result of the experimental survey [14] is used in TGF design in addition to spectrum defined by Standard (Fig. 3).

SRSS method is used for the mode shapes combination.

Design Loads

The following static and quasi-static loads shall be taken into account in structural design of the turbine-generator foundation.

Ordinary Structural Loads

- ***SW*** - self weight of structures
- ***DL*** - dead loads due to the weight of the turbo-machine and equipment
- ***LL*** - live loads
- ***PL*** - piping loads
- ***TE*** - thermal expansion or friction forces
- ***T*** - temperature

Normal Operation Loads

- ***ST*** - shaft thrust
- ***NT*** - normal torque
- ***NP*** - pressure
- ***CV*** - condenser vacuum loads

Emergency Loads

- ***UF*** - rotor unbalance forces
- ***CB*** - compressor loss-of-blade
- ***TB*** - turbine loss-of-bucket
- ***SC*** - generator short circuit or faulty synchronization
- ***SP*** - shutdown pressure
- ***FP*** - failure pressure

Installation Loads

- ***ER*** - erection loads
- ***CS*** - construction loads or shrinkage

Environmental Loads

- ***EQ*** - seismic loads
- ***WL*** - wind loads
- ***SN*** - snow loads
- ***SL*** - site-specific loads, for example – swelling

Not all loads listed above are defined for each foundation. In fact the applied loads depend on turbine type, machine configuration and manufacturer and on the site conditions. So, loads ***CV*** and ***FP*** are specific for the steam turbine and do not exist in gas turbine.

Thermal Expansion loads can be developed at the turbine-generator supports from mechanical resistance to the thermal movement of the turbine-generator. It is a self-balanced system of forces with a net resultant force equal to zero, producing only internal forces in the foundation.

Shaft Thrust is an axial load on the foundation produced from the flow momentum change through the gas turbine.

Normal Torque is generally applied to the foundation as a couple of vertical static forces.

Condenser Vacuum is the load from the vacuum pull of the condenser on the steam turbine.

Unbalance Forces are static equivalent forces which correspond to the maximum allowable rotor vibration amplitudes (Zone Boundary C/D). This load is calculated as a function of the rotor weight and usually assumed as 5…7 times of the rotor support reaction at each bearing. Separate load steps are produced for in-phase, as well as for alternating counter-phase unbalanced forces applied in vertical and in horizontal directions.

Loss of Blade (Bucket) of the turbine may produce a large dynamic forces rotating with the rotor. This load is normally defined by the turbine manufacturer as an equivalent static load.

Short Circuit moment is bi-harmonic function of time with descending amplitude

$$M(t) = A_0 e^{-t/a_0} \sin(\omega t) - A_1 e^{-t/a_1} \sin(2\omega t) + A_2 e^{-t/a_2}$$

Equivalent quasi-static load, equal to the maximum of the time-dependent short circuit moment, may be used for structural design purposes. According to [9] a dynamic load factor of 1.7 should be used for the static equivalent short circuit moment.

Shrinkage effect is considered by a uniformly temperature drop from the ambient temperature for all the elements above the top of the base mat. Shrinkage shall be taken into account because the pedestals and walls are concreted later than the base mat.

It should be noted that some design loads produce several load steps differ by direction of the load action.

Load Combinations

Following load combinations for ultimate state conditions are used for structural design in accordance with requirements of the Israeli Concrete Code [11].

1.2 (***SW*** + ***DL***)

1.4 (***SW*** + ***DL***) + 1.6 ***LL*** + 1.6 ***TE*** + 1.6 (***ST*** + ***NT*** + ***NP***)
1.4 (***SW*** + ***DL***) + 1.6 ***LL*** + 1.6 ***TE*** + 1.6 (***ST*** + ***NT*** + ***NP***) + 1.6 ***SL***
1.4 (***SW*** + ***DL***) + 1.6 ***LL*** + 1.6 (***TE*** + ***T***) + 1.6 (***ST*** + ***NT*** + ***NP***)

1.4 (***SW*** + ***DL***) + 1.6 ***LL*** + 1.6 ***TE*** + 1.6 (***ST*** + ***NT*** + ***NP***) + 1.6 ***UF***
1.4 (***SW*** + ***DL***) + 1.6 ***LL*** + 1.6 ***TE*** + 1.6 (***NT*** + ***NP***) + 1.6 ***SP***

$$1.4\,(\boldsymbol{SW}+\boldsymbol{DL}) + 1.6\,\boldsymbol{LL} + 1.6\,\boldsymbol{TE} + 1.6\,(\boldsymbol{ST}+\boldsymbol{NT}) + 1.4\,\boldsymbol{CB}$$
$$1.4\,(\boldsymbol{SW}+\boldsymbol{DL}) + 1.6\,\boldsymbol{LL} + 1.6\,\boldsymbol{TE} + 1.6\,(\boldsymbol{ST}+\boldsymbol{NT}) + 1.4\,\boldsymbol{TB}$$
$$1.4\,(\boldsymbol{SW}+\boldsymbol{DL}) + 1.6\,\boldsymbol{LL} + 1.6\,\boldsymbol{TE} + 1.6\,(\boldsymbol{ST}+\boldsymbol{NT}) + 1.4{*}1.7\,\boldsymbol{SC}$$

$$1.4\,(\boldsymbol{SW}+\boldsymbol{DL}) + 1.2\,\boldsymbol{LL} + 1.2\,(\boldsymbol{ST}+\boldsymbol{NT}+\boldsymbol{NP}) + 1.2\,\boldsymbol{W}$$
$$1.4\,(\boldsymbol{SW}+\boldsymbol{DL}) + 1.4\,\boldsymbol{W}$$
$$1.2\,(\boldsymbol{SW}+\boldsymbol{DL}) + 1.4\,\boldsymbol{W}$$

$$1.0\,(\boldsymbol{SW}+\boldsymbol{DL}) + 1.0\,\boldsymbol{LL} + 1.0\,\boldsymbol{TE} + 1.0\,(\boldsymbol{ST}+\boldsymbol{NT}+\boldsymbol{NP}) + 1.0\,\boldsymbol{EQ}$$
$$1.0\,(\boldsymbol{SW}+\boldsymbol{DL}) + 1.0\,\boldsymbol{EQ}$$

$$1.4\,\boldsymbol{SW} + 1.6\,\boldsymbol{CS}$$
$$1.2\,(\boldsymbol{SW}+\boldsymbol{DL}) + 1.6\,\boldsymbol{SL}$$

Load factor consistent with a live load applies for normal operation loads and for emergency loads that may occur from time to time during the machine life. Load factor consistent with a dead load applies for emergency loads of catastrophic character ***CB***, ***TB, SC*** that have a very low probability of occurrence during the life of the machine. In contrast to normal operation loads, the emergency loads are not considered acting concurrently with other emergency loads and with accidental environmental loads.

The required amount of reinforcement is calculated by CivilFEM standard procedure.

CALCULATION EXAMPLE

"Tzafit" gas turbine generator foundation (Fig. 4) is of pedestal type. The base mat of 2.0 m thickness has a length of 38.0 m and width varies from 11.0 to 16.0 m. Three pedestals supporting gas turbine frame and exhaust diffuser have a height of 2.85 m and thickness varies from 0.75 to 2.0 m. Five connected vertical walls supporting generator have a height of about 4.7 m and thickness varies from 0.6 to 1.6 m. Center line of the rotor is located at elevation 5.4 m above top of the base mat. The base mat is supported by 55 piles of 0.8 m diameter and of 22 m length arranged in diamond grid.

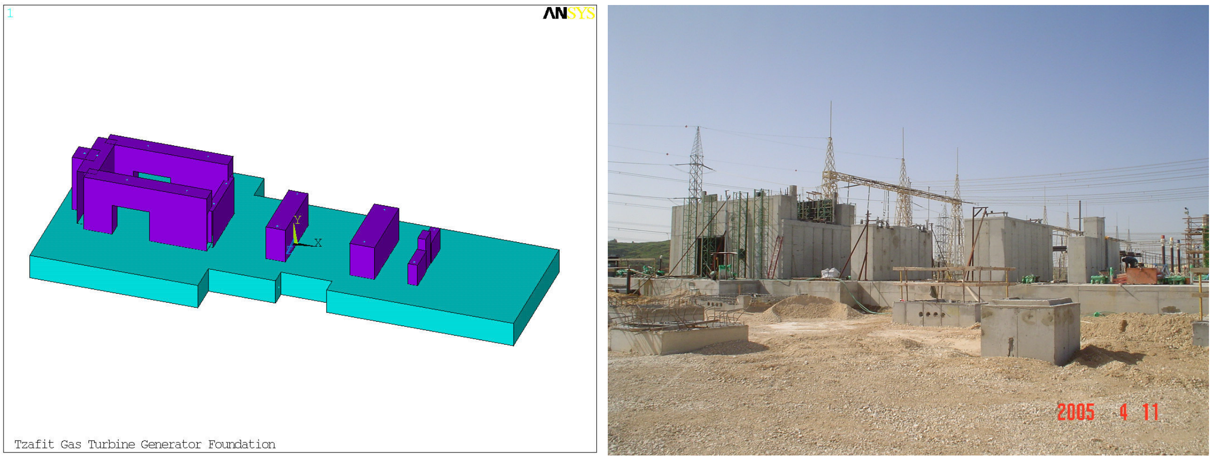

Figure 4: "Tzafit" Gas Turbine Generator Foundation

Equipment weight is about 950 tons when foundation self-weight is approximately 3000 tons, that provides machine-to-foundation mass ratio less than 1:3.

Finite-element model consists of 4200 SHELL63 elements, 165 COMBIN14 elements and 50 MASS21 elements (Fig. 5). Total number of 37 modes has been extracted. First 3 modes are the rigid body modes in horizontal plane with frequencies 2.76 to 3.10 Hz. It gives a good correlation with the single-degree-of-freedom model frequency estimation of 2.90 Hz. The first significant flexural mode (5th mode in full set) is presented on Figure 6.

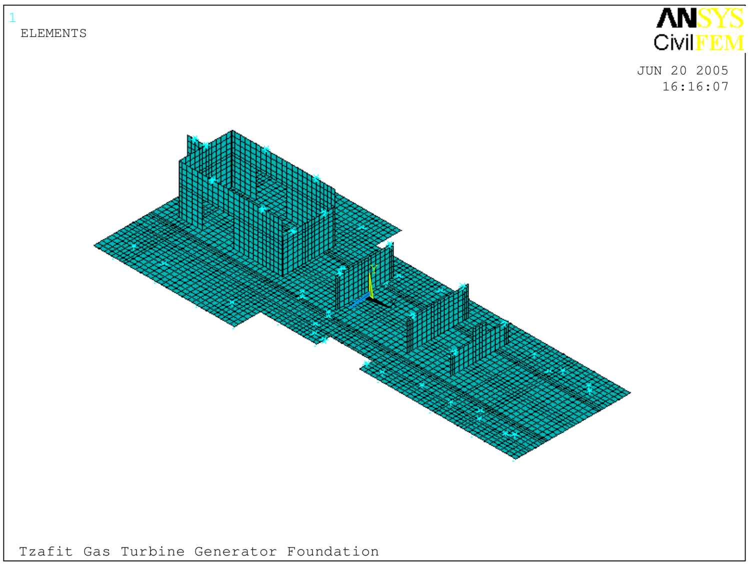

Figure 5: "Tzafit" GTGF Finite Element Model

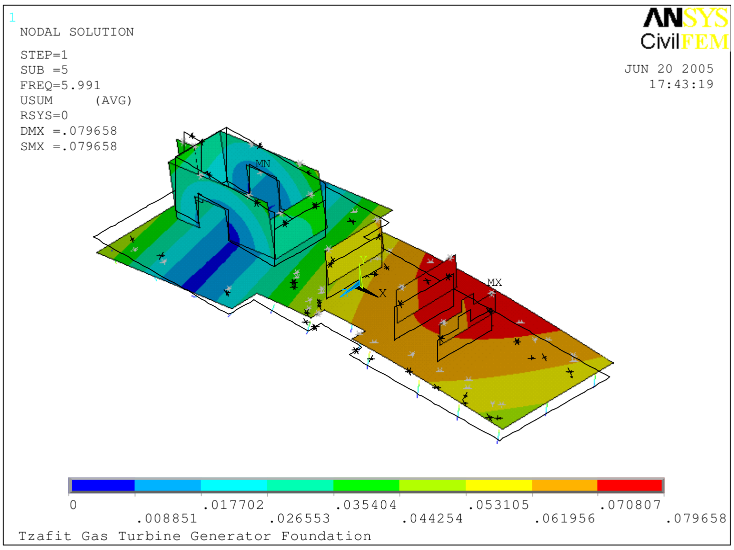

Figure 6: "Tzafit" GTGF 5th Natural Mode of Vibration

Rotor unbalance forces $P_1 = P_2 = 4.3$ tons at the generator collector-end (P_1) and turbine-end (P_2) bearings and $P_3 = P_4 = 6.6$ tons at the turbine forward- (P_3) and aft- (P_4) bearings have been provided by manufacturer. Results of dynamic analysis for horizontal loads applied in counter-phase are presented on Figure 7.

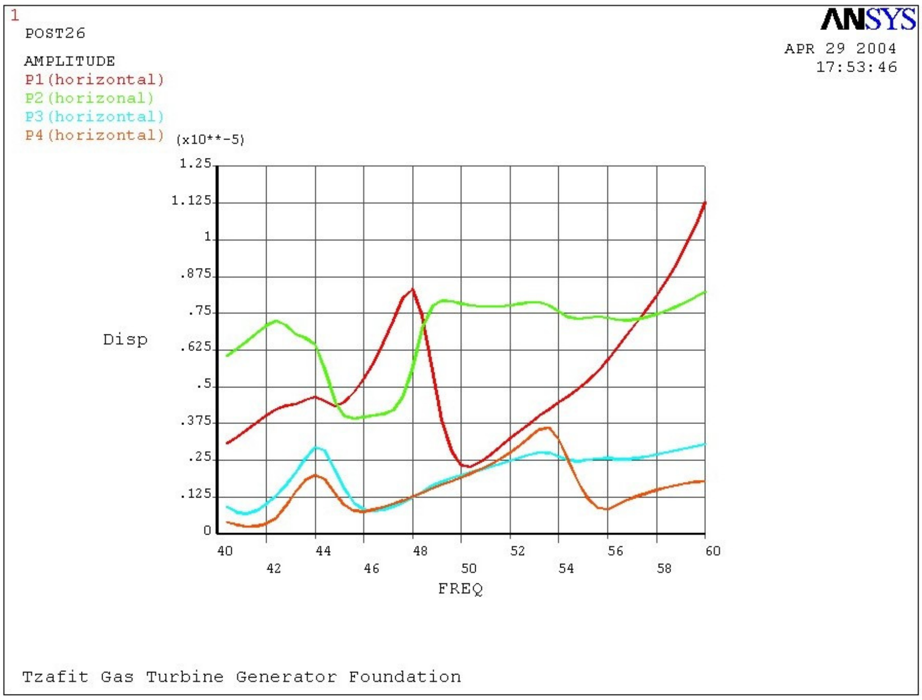

Figure 7: "Tzafit" GTGF Vibration Amplitudes at Bearing under Horizontal Unbalance Forces applied in Counter-Phase. Damping 0.02.

CONCLUSIONS

ANSYS/CivilFEM software provides an efficient tool for dynamic analysis and structural design of the turbine-generator foundations. Analyses features and design procedure have been described in details. Developed turbine-generator foundation CAE is extensively used in IEC design practice. Example of the real project has been presented.

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