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MATHEMATICAL MODELLING AND EXPERIMENTAL DYNAMIC INVESTIGATION OF AN ELEVATED FOUNDATION SUPPORTING VIBRATION MACHINERY

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ABSTRACT

In the last two decades rapid advances in the techniques for the design of engineering structures have been made. With this much progress it is surprising that mathematical modelling and experimental dynamic investigations of elevated foundations supporting vibration machinery has hardly progressed. The main factors contributing to this situation are the tendency for equipment manufacturers to rely on past successful practices, the lack of interest in academic circles for this type of engineering structures and the lack of funds for major studies. Romania, alongside of other countries prefered to consider the worldwide experience in this field instead of developing its own researches. The paper presents the modelling and calibration for the resistant structure of a turbogenerator foundation. Two analytical models have been proposed, one of medium complexity (KONMAN 96) and the other, of high complexity, supported by the program SOLVIA 95. For model calibration, experimental dynamic in situ investigations have been performed on the turbogenerator – foundation – soil system. Some results and general conclusions are outlined.

INTRODUCTION

While the importance of the dynamic analysis of turbogenerator foundations has been a known fact for many years, the study of bibliography shows that research results in this field are far from being satisfactory.

The methods for dynamic analysis of the frame foundation may be divided in two categories: simplified methods and rigorous methods. In the simplified methods a number of assumptions are made and the analysis is carried out on frame-by frame basis. Most published research works have pointed out the following:

- the use of simplified calculation methods by adopting discrete dynamic plane models, with 1DOF, 2 DOF and 3 DOF respectively, for computing the natural frequencies and amplitudes;
- the bending stiffness of the deck slab and of the columns has not always been taken into consideration properly;
- the interaction between the main elements which define the complex dynamic system (between shaft and rotors, between the deck slab, columns and rigid base slab) has been neglected;
- the interaction between the foundation and the soil (when considered) has been inefficiently estimated by approximating several coefficients of elasticity and damping factors specific to the elastic half-space method;
- the influence of the higher eigenmodes of vibration has also been ignored;
- the absence of studies to emphasise the influence of the soil on the turbogenerator foundation response, considering the soil layers and the their lack of isotropic properties.

This elementary approach was based on insufficient theoretical data in the modelling techniques, in the dynamic structural analysis, and also on the limited use of automatic computation. The objective of the analysis was to determine if the proposed foundation will perform satisfactorily under the action of various loads acting according to the design criteria. In rigorous methods, the foundation of a turbogenerator may be modelled as a three-dimensional space frame and analyzed as a multidegree freedom system (nDOF). The need for taking into account the spatial behavior of the turbogenerator foundation in adopting a model to represent the physical parameters of the *machine – foundation – soil system* as accurately as possible, was something many authors have sensed, but the lack of powerful computers and of specific software has only allowed a simplified approach of spatial models. Figure 1 presents an isometric view of a 150MW turbo-generator foundation. The turbogenerator foundation is made of a top slab (or deck) with technological openings (32 m x 16.6 m and variable thickness), which renders it the aspect of a cross and longitudinal beam network, ten elastic columns fixed into the base slab, having square sections and different free heights (H=12.0 m for six columns, H=11.725 m for four columns), and a rigid base slab with the following dimensions: 31.0 m x 11.0 m x 4.0 m. The turbine - generator unit and the auxiliary exciter generator are supported on the top or deck slab with shaft aligned parallel to longitudinal beams, with enough space left under it for the auxiliary equipment. There are beams at intermediate levels and structural walls too, in order to increase rigidity and for technological reasons. It is obvious that the dynamic behavior of such a complex system is influenced by the potential interaction between all its components.

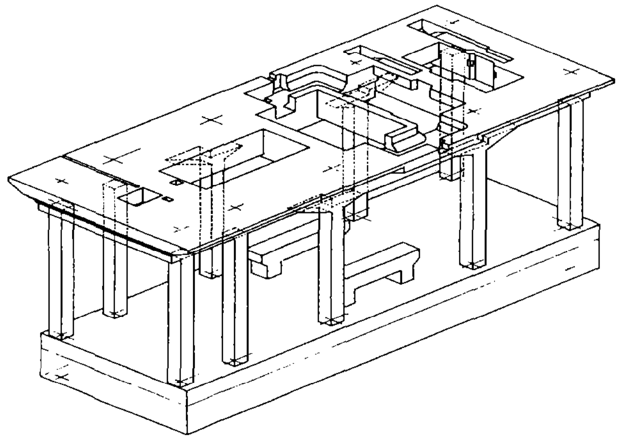


Fig1. Isometric view of the turbogenerator.

MACHINE-FOUNDATION-SOIL SYSTEM MODELLING

The 150MW turbogenerator foundation was modelled using an approach with *finite elements*. The paper will further present two analytical models of the machine-foundation- soil system, one of *medium complexity*, by using and adapting the KONMAN 96 calculation program, and one of *high complexity*, supported by the SOLVIA 95 program.

Developing the calculation model with KONMAN 96 program

The deck slab and the mat discretisation was made with SHELL–type finite elements, following the median plane of effective components and taking into account the technological openings in the foundation deck slab. The ten columns were modelled with finite elements of the BEAM type. In the columns fixing area into the deck slab and mat, the BEAM elements were provided higher rigidities following a repetitive process of increasing the moments of inertia, so that the numerical stability of the problem be not affected. The coincidence between the centre of gravity of the model designed by KONMAN and the centre of the effective structure was verified.

Developing the analytical model with the SOLVIA 95 program

The foundation deck slab and mat discretisation were made with four layers of finite isoparametric elements of the SOLID-3D type each (three points of integration were used for each of the finite elements along the vertical direction), aiming at accurately establishing the bending stiffness (12 points).

In the case of discretisation with four layers and 2x2x2 order of integration, there results a bending stiffness higher than the real one (6 layers are needed in the case of a 2x2x2 order of integration). The conclusion was that in modelling a plate subjected to bending with elements of the SOLID type, a large number of element layers or a larger enough order of integration have to be used, in order to reach a minimum of 10÷12 stress calculation points per plate thickness. Moreover, elements of the SOLID-3D type take into consideration the effect of shearing strain. As both the deck slab and the mat are massive concrete elements, one goal of this analysis was to pinpoint the influence of modelling with elements of the SHELL and of the SOLID-3D type. The differences between the two modelling methods have been highlighted only by higher vibration eigenmodes. The columns of the foundation were initially modelled with finite elements of the BRICK type. It was found that these elements cannot explicitly point out bending stiffness of these columns, other than in the situation when a large number of finite elements is used, both along the cross section and height. Using this type of finite elements might have led to an unjustified increase in the number of equations and that is why finite elements of the BEAM type were used. The connection between the SOLID-3D finite elements (deck slab and mat) and the BEAM finite elements (columns) was made by COUPLING which solves the strain incompatibility between the two categories of finite elements (the link between columns, deck slab and mat). Isoparametric elements of SOLID-3D type are mere decorative (actually the BEAM elements are those that work). It was also checked if, in the case of the calculation model performed with the SOLVIA 95.0 program, the gravity centre of the model was identical with the one of the effective structure.

Table 1 presents the results of the modal dynamic analysis, corresponding to the preliminary models (columns 1 and 2). To be noticed that in the preliminary analysis made by the SOLVIA 95.0 and KONMAN 96 program, the mat was considered rigid.

Table 1

Eigenmode	PRELIMINARY MODEL		CALIBRATED MODEL	CALIBRATED MODEL WITH INTERACTION	
	KONMAN 96	SOLVIA 95	KONMAN 96	KONMAN 96	SOLVIA 95
	f(Hz)	f(Hz)	f(Hz)	f(Hz)	f(Hz)
0.	1.	2.	3.	4.	5.
1	9.7005E-01	1.00339E+0	2.0020E+00	1.6013E+00	1.67525E+00
2	9.9239E-01	1.00375E+0	2.2599E+00	1.9071E+00	1.88555E+00
3	1.0938E+00	4.60364E+0	2.8880E+00	2.2722E+00	4.68988E+00
4	1.1498E+01	1.19728E+01	1.1600E+01	4.5853E+00	4.82004E+00
5	1.3321E+01	1.41744E+01	1.3688E+01	4.7979E+00	4.95985E+00
6	1.3960E+01	1.51360E+01	1.4098E+01	4.9309E+00	4.97863E+00
7	1.5384E+01	1.67581E+01	1.5775E+01	5.4690E+00	5.90503E+00
8	1.9307E+01	1.68409E+01	1.9863E+01	7.7479E+00	7.13140E+00
9	1.9663E+01	1.94147E+01	2.0264E+01	9.7111E+00	9.30306E+00
10	2.1462E+01	1.95781E+01	2.2905E+01	1.3366E+01	1.30738E+01
11	2.2415E+01	1.97031E+01	2.3046E+01	1.7391E+01	1.61133E+01
12	2.2708E+01	1.97162E+01	2.3268E+01	1.8475E+01	1.62594E+01
13	2.2830E+01	1.97204E+01	2.4178E+01	1.9861E+01	1.74652E+01
14	2.2877E+01	1.97294E+01	2.5651E+01	2.0828E+01	1.92599E+01
15	2.2947E+01	1.97350E+01	2.6013E+01	2.1898E+01	1.96865E+01
16	2.3014E+01	1.97371E+01	2.6138E+01	2.2832E+01	2.01060E+01
17	2.3037E+01	1.97376E+01	2.6361E+01	2.3121E+01	2.04102E+01
18	2.3046E+01	1.97404E+01	2.8470E+01	2.3168E+01	2.22209E+01
19	2.3086E+01	1.97766E+01	3.6710E+01	2.4247E+01	2.23164E+01
20	2.3325E+01	1.99210E+01	3.7947E+01	2.5549E+01	2.24939E+01

CALIBRATION OF THE CALCULATION MODEL THROUGH DYNAMIC EXPERIMENTAL INVESTIGATION

As the turbogenerator structural system is an extremely complicated one, and there are lots of elements under the floor which actually cannot be modelled, and also considering the author's intention to develop an *advanced calculation model* to take into account the *interaction* between the foundation and the soil, the calibration of the calculation model with the results obtained following experimental research with instrumental measuring of vibration in the "machine-foundation-soil" system was considered necessary. Experimental investigations on the ensemble made of turbogenerator, foundation and soil were carried out under operating conditions, at the designed parameters. Detailed dynamic measurements performed on turbomachinery foundations under operating conditions play a significant role in the evaluation of various methods of dynamic computation and obtaining data on the dynamic behavior of the foundations. The measurements referred to velocity time variation along three orthogonal directions: cross, longitudinal and vertical. 15 sensor mountings were made along the 10 turbogenerator equipment bearings. The location map of vibration logging points is shown in Fig.2. The velocity values measured simultaneously were processed in time and frequency domain, and with the help of the Fourier amplitude spectrums the frequency content of the recorded movements was established. An example of the numerical processing carried out is presented in Fig.3.

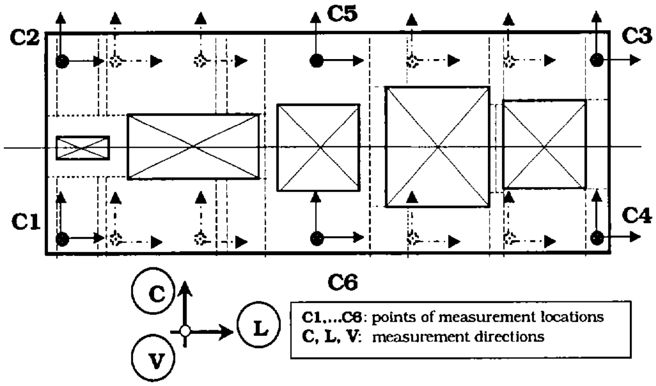


Fig. 2 Location map of vibration logging points

The fundamental eigenfrequencies corresponding to the measuring directions and the eigenfrequency associated to the torsion phenomenon were obtained.

- Cross direction $f_{I,C} = 2.0$ Hz
- Longitudinal direction $f_{I,L} = 2.2$ Hz
- Vertical direction $f_{I,V} = 8.0$ Hz
- Torsion $f_{I,TORS} = 3{,}6$ Hz

Differences between amplitudes at the deck slab extremities were noticed, which can be explained by the floor geometry and the location of the excitation source.

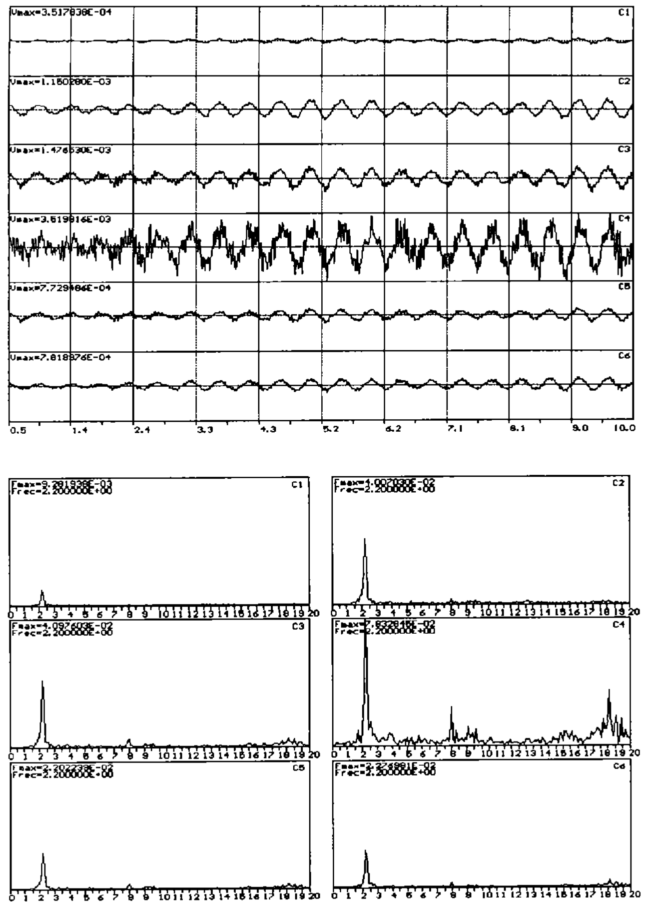


Fig.3 Time domain and amplitude Fourier spectra

Differences between amplitudes at the deck slab extremities were noticed, which can be explained by the floor geometry and the location of the excitation source. From those presented so far, one can notice that there are some differences between the fundamental eigencharacteristic values obtained through analysis – using the preliminary model – and those obtained experimentally. In order to explain the existence of such differences, the hypotheses the preliminary calculation model was based on were verified, along with a qualitative evaluation consisting of an on-the-whole and detailed examination of the turbogenerator equipment and its foundation.

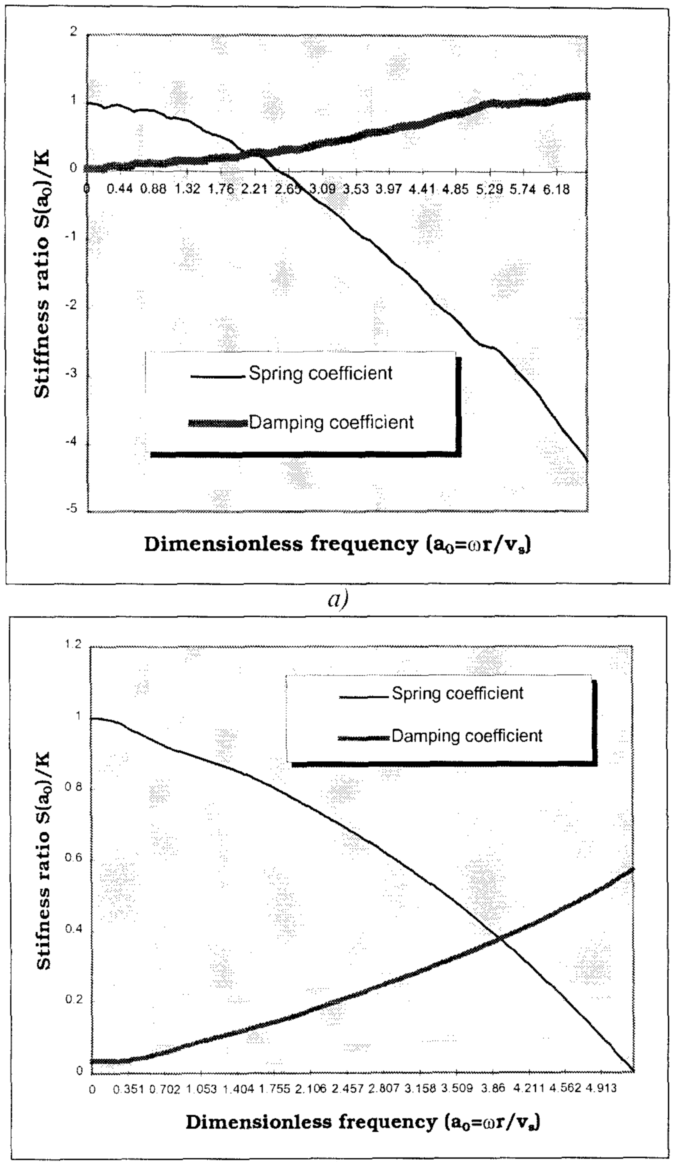
Following calibration, the use of two completely different models (KONMAN, SOLVIA) led to an extremely accurate agreement between the results obtained. In this respect, 40 vibration eigenmodes were computed, and eigenfrequencies, modal participation factors and vibration eigenshapes were compared. For the calibration of the calculation model the idea that experimental investigations, correctly and properly read and analysed can indicate how close calculation is to reality was accepted. Experimental verification should be understood only as a check up of the condition that calculated amplitudes are comparable with the real ones, and comparing frequencies is relevant in practice only to fundamental eigenfrequencies of vibration.

Following analysis, the conclusion reached was that fundamental eigenfrequency values obtained experimentally are the closest to real values, as there are numerous elements impossible to model which were not taken into account when designing the preliminary calculation model. Based on the experimental research results and direct observation on the real configuration of the turbogenerator – foundation system, the dynamic model was calibrated by increasing column stiffness up to the point when fundamental eigenfrequencies close to those obtained experimentally and the same transversal amplitude ratios were obtained (column 3 in Table 1). Columns 4 and 5 in Table 1 present the first 20 eigenfrequencies, taking into account the interaction with the soil (an extremely deformable one).

The soil behaviour is significantly influenced by the level and history of deformations caused by seismic waves. Elements which characterise soil non-linearity effects can be grouped into two categories:

a) the class of parameters which define the soil damage level, with direct reference to modifications of its rigidity in dynamic load condition;
b) the class of parameters which define the soil damping level, through its hysteretic modifications, equivalent to the energy dissipation phenomenon in continuous dynamic rating.

The evaluation of the *degraded* properties of the foundation soil depends on the level of deformations induced by seismic action and it can be made by means of a specialised computer program. Within the application which is the topic of this chapter, a deconvolution was performed, followed by a convolution of the seismic signal at the free surface of the soil to the base rock and backwards, resulting in a *determination of the strain level in each soil layer*. The convolution process consists of a determination of the acceleration variation at the basic rock level, depending on the acceleration registered at the free surface of the soil, through the inverse transfer function. The deconvolution of the earthquake on March 4th 1977 (the N-S component) at the free surface to the base rock, allowed through its reconvolution for the re-establishing of specific acceleration variation characteristics which might occur in the respective location. Following this process, the dynamic shearing moduli and damping factors characteristic to each soil layer are in a permanent change. Successive iterations and corrections were performed, till differences between the filtered signal and original one became unsignificant (less than 10%). Thus the dynamic shearing moduli and the damping factors (hysteretic damping, material) *corrected* for each soil layer which corresponds to the level of shearing deformation induced by the seismic move taken into account (input data for impedance calculus), were obtained. The analysis performed is known under the name of *free field analysis*. Figure 4 presents charts indicating dynamic spring coefficients and damping factor variations with frequency, for different overall impedance components (extremely deformable soil).



a)

b)

Fig 4. Dynamic stiffness coefficients in frequency domain
a) Dynamic impedance (lateral translation).
b) Dynamic impedance (coupled translation and rotation).

The comparative analysis revealed a bigger variation (depending on frequency) of the two categories of parameters, in the case of deformable founding soils, as compared to the rigid ones. This situation is typical for interaction phenomena and studies on machine foundations should be taken into account. The model calibration entailed a large number of runs, in each case eigenfrequencies, modal participation factors and eigenshapes being analysed. Thus a calibrated calculation model (physical and mathematical) was obtained, compatible with the one corresponding to the actual system consisting of turbogenerator and foundation.

Figures 5 and 6 show the first two eigenmodes of vibration obtained both with the KONMAN 96 and SOLVIA 95.0 computer programs.

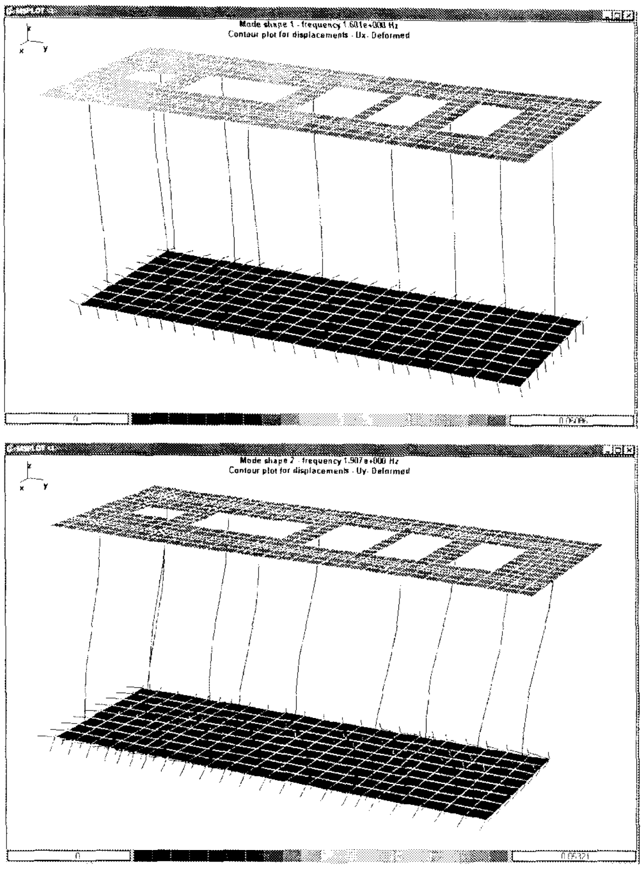


Fig. 5 Mode shapes 1 and 2 (KONMAN 96)

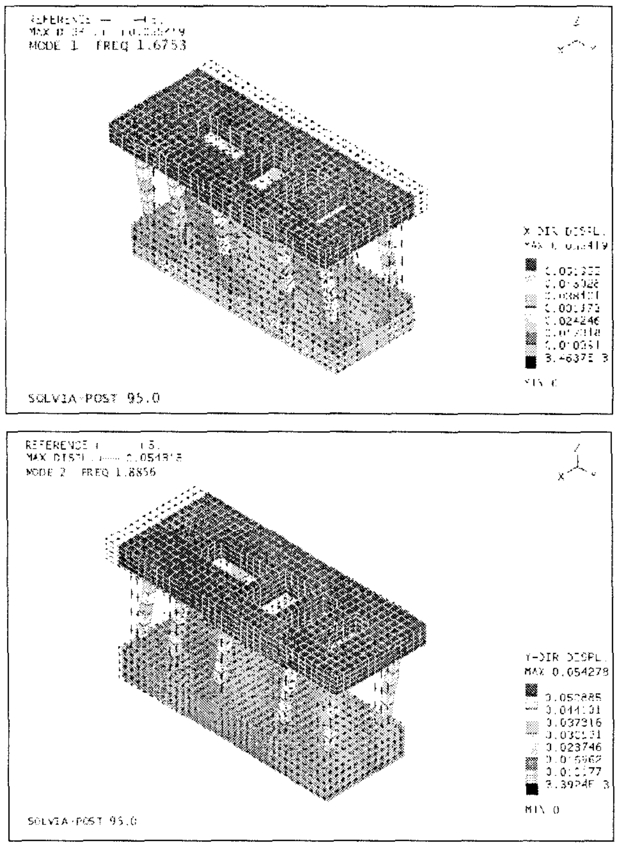


Fig. 6 Mode shapes 1 and 2 (SOLVIA 95.0)

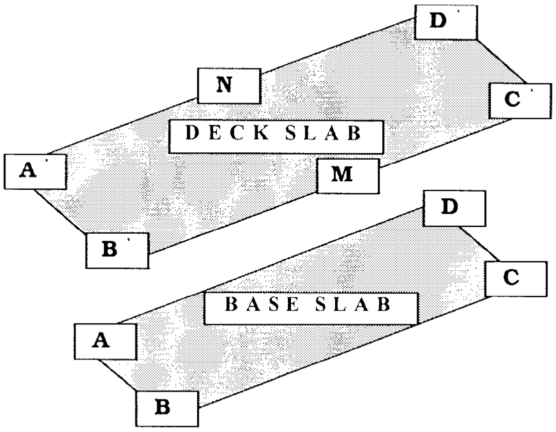


Fig. 7 Characteristic points on the base and deck slabs

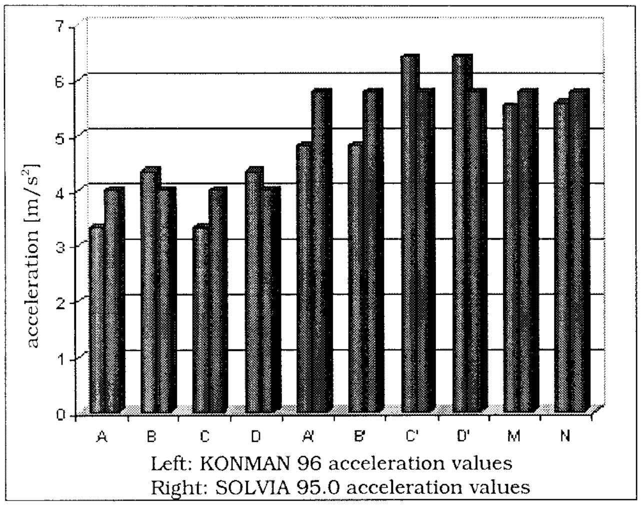


Fig. 8 Comparative values of acceleration

In the characteristic points denoted in Fig. 7, the compatibility of the results (displacements and accelerations) obtained for two different strong motions (along two orthogonal directions), with both programs, was pointed out. As a result, the graph in Fig. 8 was performed for acceleration values.

CONCLUSIONS

a. Both calculation models led to similar results in as far as important vibration eigenmodes are concerned (eigenmodes with significant participation factors). The effective results refer to eigenfrequencies and eigenshapes, and modal participation factors.

b. In high frequencies (inherent modes with low participation) insignificant differences between results occur, which might be explained by the behaviour of SHELL type finite elements, as compared to the SOLID-3D ones.

c. Both modelling with finite elements of the SOLID-3D type and the SHELL type can lead to satisfactory results, provided bending stiffness is well defined when elements of the SOLID-3D type are used (several layers of finite elements and a higher order of integration, so that a minimum 10÷12 stress calculation points be established per plate thickness).

d. Theoretic studies highlighted the influence of modelling foundations for turbo-generators with different types of finite elements on dynamic response, estimated by means of numerical analyses.

e. An important contribution to the calibration of models based on the KONMAN and SOLVIA computer programs was the way in which different categories of equipment, frame structures and other categories of structural elements were approached. Calibration of the models based on vibration measurements emphasised the influence of technological equipment and frame structures on the machine-foundation system dynamic characteristics and rendered them justification and credibility.

f. The results obtained in developing calculation models, through theoretical and experimental research, have led to practical conclusions in modelling, namely:
   - technological equipment and elements placed under the foundation deck slab, considered *non-structural,* can seriously increase the fundamental frequency of the machine-foundation system;
   - an improper modelling with finite elements of the SOLID-3D type can end up in overestimated values of bending stiffness, both for columns and foundation deck slab.

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