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SPECIFICITY OF DYNAMIC ANALYSIS OF REINFORCED CONCRETE FOUNDATIONS UNDER TURBOGENERATORS

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In dynamic analysis of reinforced concrete turboset foundation updated numerical methods analysis should be used: FEM (Finite Element Method) and SEM (Spectral Element Method). This second one adopted to frame foundation analysis is presented in details. The advantage of this method for turbodet foundation dynamic analysis is proved. Numerical example of calculation is presented too.

Key words: turbogenerators foundations, spectral element method, natural frequencies of founadtion

1. Introduction – data from the past

Growing energy consumption demands of the country and technological progress require application of steam turbo-generators of bigger and bigger power. At the beginning of the 1950's the power of the biggest turbo-generator in Poland was 30 MW – but in the eighties turbo-generators of the power 500 MW were already installed. The dimensions of the projection of their reinforced concrete frame foundations were about 12/50 m and their total height 18 m. Some dimensions of the foundation bars reach up to 2 m. In some cases the neighbouring columns were joined with vertical walls and at the bottom a thick stiff plate constituted the foundation; there fore the dynamic analysis of these structures was difficult, and this analysis is the basis of design under the occurring there dynamic loads Rausch (1936, 1959), Kłoś (1949), Kisiel (1957), Buzdugan (1972), Lipiński (1969, 1985).

Both the above mentioned Lipiński monographs as well as the national standards; e.g., polish, german, russian and another, allow for application of

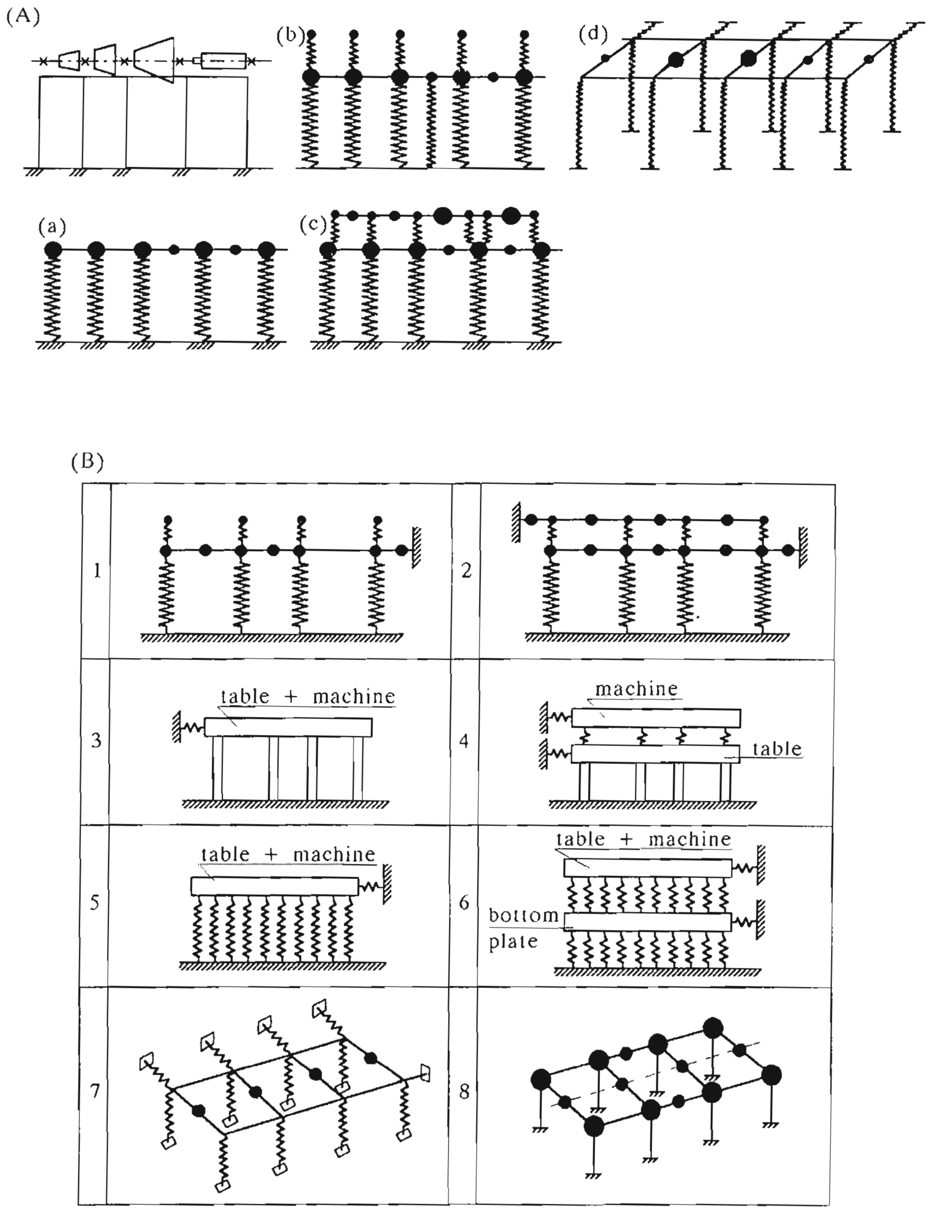


Fig. 1. (A) Models of foundation (a) various approaches used in the literature, e.g., Ciesielski et al. (1971), Kitagawa and Yuko (1989), Wrana (1997a). (B) Various model of foundation (b) used in the literature (Buzdugan, 1972; Major, 1980) and in polish practice (Buzdugan, 1972; Major, 1980; Lipiński, 1969; Ciesielski et al., 1998)

simplified models of bar structures and division of the whole special foundation structure into particular flat transversal frames. Concentrated masses in the discrete structure model, in view of their symmetry brought about solutions for the systems with several degrees of freedom; however even, making use of symmetry and anti -symmetry of the system, only determination of basic and some initial harmonic frequencies and vibration shapes was possible Examples of the adopted early physical models are shown in Fig.1 (cf Lipiński, 1969; Buzdugan, 1972). For the applied dimensions and stiffness of the structure the natural frequencies reache 20 to 30 Hz, whereas, when the basic excitation (rotation frequency of the blades of the turbine) is 50 Hz. Analysis was limited only to checking the dynamic limit state condition of the bar sections taking into consideration the stiffness parameters (i.e. amplitude of transverce vibrations of the upper foundation plate). Practically the data decisive for diagnosis of the foundation work were obtained from dynamic measurements, cf Ciesielski (1968, 1971). Harmonic analysis of the measurement results showed explicitly that besides the maximum response to excitation, i.e at frequencies 50 and 100 Hz, there occur also sub-resonance, at other frequencies, however that could not be determined accurately enough by the available analytical means.

Again, the experimental methods were then the only basis for correction of dynamic systems and elimination, of the appearing of sub-resonance.

2. New possibilities of analysis and diagnostics of foundation structures for turbo-generators

There are three factors that have recently changed the situation of designing, construction and diagnostics.

(A) Computerisation and rapid development of numerical methods creating new calculation possibilities also in application to dynamic analysis of structures.

(B) New equipment, apparatus, and measurement possibilities as well as new methods of measurement result evaluation applying informatics, theory of systems, and other new theories (e.g. fuzzy sets, artificial neural nets etc.)

(C) New material and structural possibilities, including application of advanced vibro-insulation systems controlling automatically dynamic properties of the structure (so called intelligent structures). In the following only the first one of the mentioned (A) is considered i.e. numerical methods. The clauses (B) are also important; these by use of computers, permit better recognition of material properties, e.g. elastic, dynamic, damping properties, fatigue, rheological changes, corrosion and degree of efficiency due to exploitation. This can be done on the way of identification of properties adopted in possibly simple dynamic models of structures. In turn, the structural possibilities e.g. application of special dampers and regulators of the structure response (cf Lipiński, 1985; Ciesielski, 1992; Ciesielski and Wrana, 1998) enable optimal shaping of the structure under given conditions. Soil structure interaction has been already also recognised better, first of all due to investigation results of soil dynamic properties (cf Buzdugan, 1972; Major, 1980), and to investigations of vibration propagation in the ground cf Ciesielski and Stypuła (1997).

3. Physical and mathematical models of turbo-generator foundations

The applied structures are bar systems. Hence the models consist of prismatic, reinforced concrete bar segments whose cross sections can differ from rectangular ones – due of technological procedure there may occur other shapes, incissions, weakenings, cracks, changes of reinforcement, finally with so called bevels increasing the stiffness of joints in nodes. Additionally, though rather exceptionally there may occur changes of material properties. Classical models (Fig.1), can be presented for materials adapted to the possibilities of computer numerical analysis. These are finite element methods (FEM), finite difference method (FDM), boundary element method (BEM) and others.

The FEM applied to foundation dynamics (see, e.g., Kruszewski, 1984), requires for turbo-generator foundations some hundred or some thousand degrees of freedom (DOF). There are numerous programmes for dynamic analysis of such structures (cf e.g. Wrana, 1997b). Recently the spectral element method (SEM) has been introduced to dynamic analysis.

This method is described by Wrana (1999). There are applied the shape function which depend on the number of DOF but mainly on the natural frequency ω_n^2. The dynamic stiffness K_d occurring in the equation can be determined for bars according to the elementary Bernoulli or Thimoshenko models (cf e.g. Langer and Bryja, 1993). An example of comparison between the results of foundation dynamic analysis using the Bernoulli and Timoshenko models, respectively, is given by Ciesielski and Wrana (1998). These differences prove to be very small. Recently a proposition has been presented of introducing an "enlarged model" of a beam in which a new model of the cross section deformation that takes into account changes of the angle of slide at the height of the section (Wrana, 1999). This model was applied practically in dynamic analysis to turbo-generators (Wrana, 1999).

4. Application of the spectral element method (SEM) to dynamic analysis of turbo-generator foundations

In the spectral element method (SEM) the matrix of dynamic stiffness $\mathbf{K}_d(x, y, z, \omega_n)$ is constructed (so called spectral stiffness), in which a continuos mass distribution is taken into consideration whereas in the finite element method there is applied only

$\mathbf{M}_L$	–	matrix of concentrated masses
$\mathbf{M}_c$	–	matrix of "consequent masses"
(x, y, z, ω_n)	–	coordinates of the system and a "consequent" vibration frequency.

The elements dynamic stiffness matrix $\mathbf{K}_d(x, y, z, \omega_n)$ are called spectral elements, and the shape functions of this element (dependent on the frequency ω) are called spectral shape functions.

Wrana (1999) showed that application of spectral shape functions to the problems of bar structure dynamics brings about a solution to the problem of the "strong" type not the "weak" type as in the case of FEM application. It is possible to obtain an accurate solution since in bar structures there is a finite number of boundary conditions.

For solving the problems of dynamics the SEM can be more useful than the FEM. The FEM bases on the shape function which depends only on the shape and number of DOF in the element and satisfies the requirements of the so called "weaker" variant of the problem. Whereas, the SEM employs the shape functions which not only depend on the DOF number in the element, but satisfy also the equation of the "strong" problem.

Hence, in the problems of dynamics they depend on natural frequency ω_n^2 and so they are called shape spectral functions. In Table 1 a comparison between characteristics of the eigenvalue problem to the FEM and SEM approaches, respectively is given

Table 1. Eigenvalues: frequencies and vibration modes of the spatial frame

Structure Ω	Element Ω_e	FEM	SEM
Structure 1D Eigenvalues of beam Ω Ω_e $\mathbf{K}_d(\omega^2)\boldsymbol{\Phi} = \mathbf{0}$ $\mathbf{K}_d$ – dynamic stiffnes matrix of the beam ω – eigenfrequency $\boldsymbol{\Phi}$ – eigenvibration shape	Ω_e $\mathbf{K}_{de}(\omega_e^2)\boldsymbol{\Phi}_e = \mathbf{0}$ $\mathbf{K}_{de}$ – dynamic stiffnes matrix of element e ω_e – eigenfrequency (element) $\boldsymbol{\Phi}_e$ – eigenvibration form (element)	$\max \omega^2 \leqslant \max \omega_e^2$ $(\omega_e^2)_i$ $i = 1, 2, ..., e$ e – DOF number of element $(\omega^2)_i$ $i = 1, 2, ..., E$ E – DOF number of structure Ω eigenshape functions N do not depend on ω^2	$\max \omega^2 = \max \omega_e^2$ $(\omega_e^2)_i$ $i = 1, 2, ..., \infty$ $(\omega^2)_i$ $i = 1, 2, ..., \infty$ application of shape spectral functions $N(\omega^2)$, see Wrana (1999)

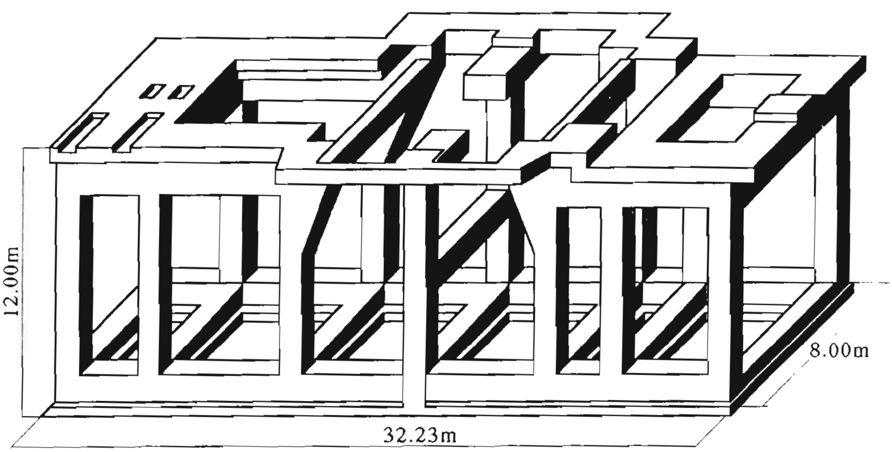
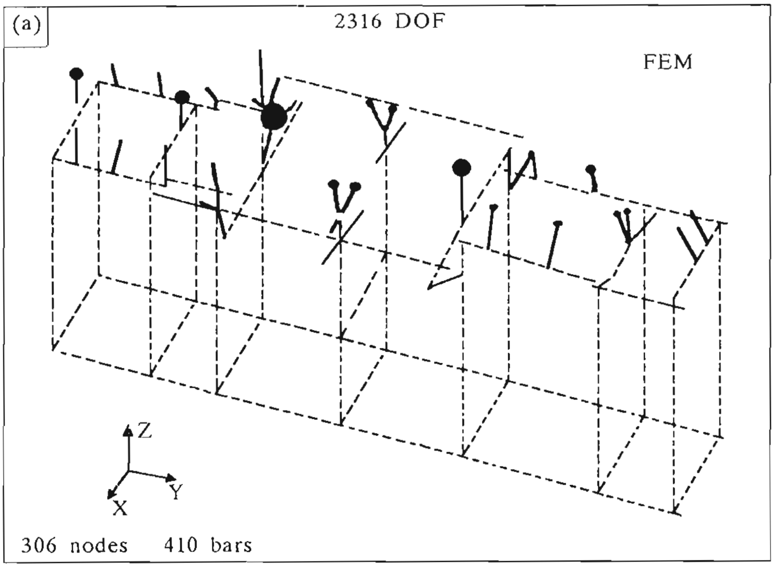


Fig. 2. Foundation of 200 MW turboset



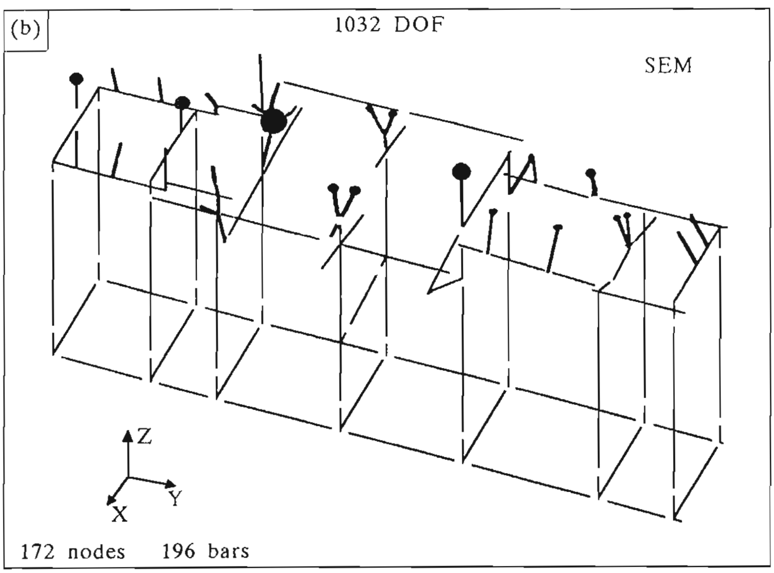


Fig. 3. FEM and SEM meshes (to Fig.2)

5. Example of dynamic analysis of a reinforced concrete frame foundation of turbo-generator by means of the SEM

The foundation of a turbo-generator 200 MW is considered and presented in Fig.2. Dynamic analysis of harmonically excided vibrations of frequency 50 Hz due to the turbo-generator in operation (turbo-generator of alternating current) has been carried out. The structure of the foundation is similar to a spatial frame with bars of large cross sections. Interaction between the lower grate with soil as a two parameter Winkler base (ground) of constant elasticity $K_{ground} = 50000\,\mathrm{KN/m^3}$ is concidered. Fig.3 shows the FEM and SEM meshes, respectively for enlarged model bars. The considered foundation was subjected to investigations "in situ" by the team of Institute of Structure of Mechanics of the University of Technology in Cracow. The difference between the measured amplitudes of displacements and those from calculation lies within the range of the admissible error of measurement apparatus which confirm the usability of the presented method.

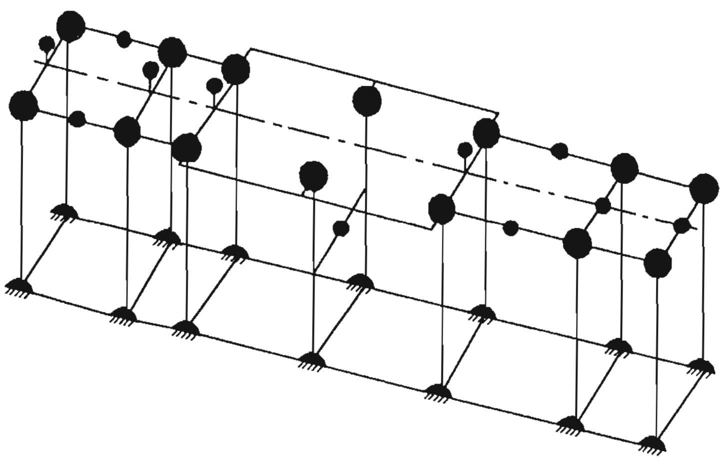


Fig. 4. Classical model (to Fig.2) of foundation of the 200 MW turboset

Fig.4 shows a discrete classical model, applied in other our works.

Fig.5 shows the foundation of the turbo-generator 200 MW modelled with bars of a spatial frame.

The FEM mesh consists of 410 bars and 386 nodes of 2316 DOF, where a considerable number of bars are the so called off-sets, stiff, mass free bars, joining the bar axes. Whereas the SEM mesh consists of 196 bars and 172

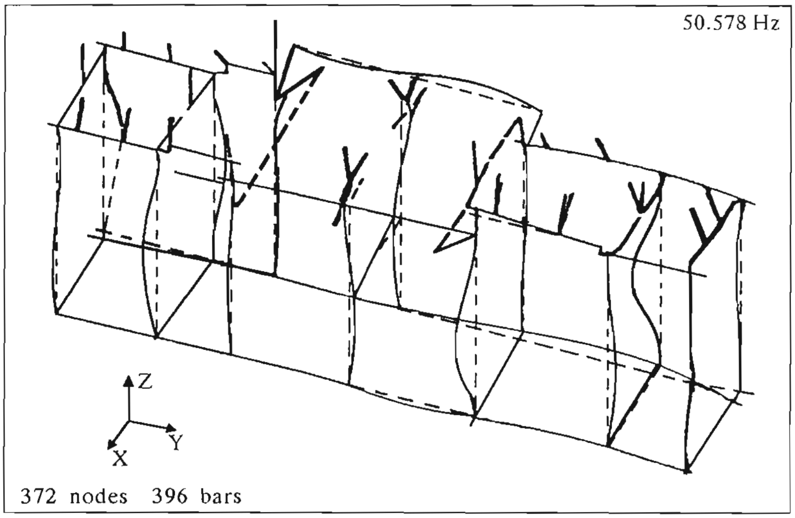


Fig. 5. Form of vibration by $f_w = 50.578\,\mathrm{Hz}$ cloasest to exciting frequency $f_f = 50\,\mathrm{Hz}$

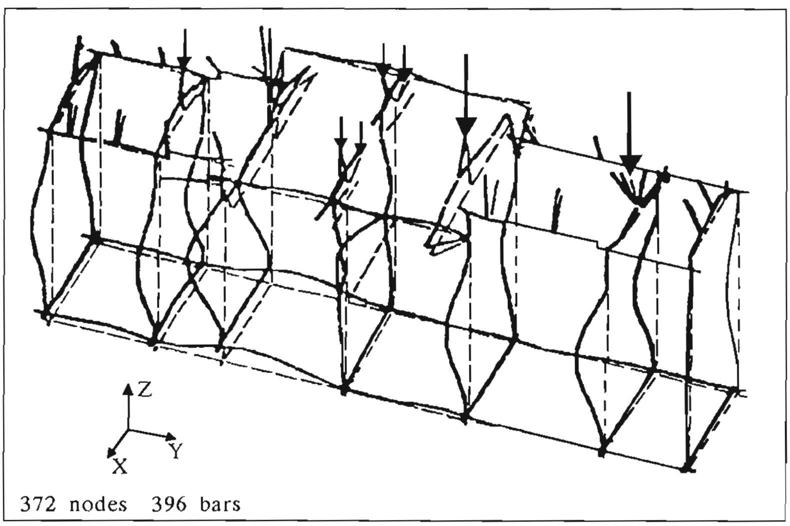


Fig. 6. Forced vibration excited by vertical loading

nodes of 1032 DOF; this is the minimum number of bars and nodes resulting from a big number of off-sets of a complex shape of structure.

Table 2 shows the list of natural frequencies of the foundation. In calculation the effects of longitudinal forces from constant masses and dead load of the structure were considered (geometrical matrix). From the results it can be seen that the eigenvalue (natural) spectrum is very dense, e.g. in the interval 45 Hz to 55 Hz there are 15 frequencies.

The natural shape corresponding to natural frequency $f = 50.578$ Hz was presented in Fig.5 as an example. Fig.6 shows the calculation results for vibrations due to components of vertical xcitation. Calculation results of 100 lowest natural frequencies of the FEM model of 2316 DOF and the SEM one of 1032 DOF differ only by the error of numerical rounding up, whereas the whole calculation is less complicated. The obtained spectrum of frequency and shapes of vibration permit technical intervention (e.g. change of bars cross sections) in order to limit the sizes of vibration amplitudes.

Table 2. Natural frequencies of the foundation

No.	Frequency [Hz]	No.	Frequency [Hz]
1	2.6371	71	45.1900
2	2.3310	72	45.9177
3	2.3407	73	46.0431
4	4.2846	74	47.3404
5	4.9510	75	47.5103
6	5.8196	76	48.1264
7	6.8126	77	48.7983
8	6.9073	78	49.0883
9	6.9178	79	49.3795
10	7.5769	80	50.5785
11	8.9177	81	51.1298
12	9.2967	82	51.3279
13	9.4999	83	52.9013
14	9.7971	84	53.9176
15	10.3438	85	54.7061
16	10.8105	86	55.3486
⋮	⋮	⋮	⋮

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Specyfika obliczeń dynamicznych żelbetowych fundamentów pod turbozespoły

Streszczenie

Analiza dynamiczna fundamentów pod turbozespoły wymaga, na obecnym poziomie techniki, obliczeń zaawansowanymi metodami numerycznymi. W pracy przedstawiono problem doboru modeli dynamicznych dla żelbetowych fundamentów ramowych dla metody elementów skończonych (FEM) i metody elementów spektralnych (SEM). Podano przykłady obliczeń.

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