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Structural Optimization of Turbine Generator Foundation with Frequency Constraint

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In this paper an efficient method to find optimal design of reinforced concrete columns of the spring mounted turbine generator foundation, subjected to rotating machinery dynamic loads is presented. According to thorough finite element analysis it is observed that columns can be successfully modeled separately, what approves the application of simplified, analytical column models. The design objective is to avoid resonance of the first two natural frequencies of foundation columns with the first harmonic excitation of the generator, while design variables are dimensions of columns cross section. The results of the analyzed example show that the optimization was successfully performed, since optimized dimensions of columns give natural frequencies out of the critical frequency range.

Strukturalna optimizacija temelja turbogeneratora s frekvencijskim ograničenjem

Izvornoznanstveni članak

U radu je prikazana učinkovita metoda za određivanje optimalnog dizajna armirano-betonskih stupova kod elastično temeljenog turbogeneratora, izloženog dinamičkim opterećenjima rotacijskih strojeva. Na osnovi iscrpne konačno-elementne analize opaženo je da se stupovi mogu uspješno modelirati odvojeno od ostatka konstrukcije, što je omogućilo primjenu jednostavnih analitičkih modela stupova. Cilj optimizacije konstrukcije je izbjegavanje rezonancije prvih dviju vlastitih frekvencija stupova s prvim harmonikom uzbude od generatora, dok su optimizacijske varijable dimenzije poprečnih presjeka stupova. Rezultati analiziranog primjera pokazuju da je optimizacija uspješno izvedena s obzirom da se uz optimizirane dimenzije postižu vlastite frekvencije izvan rezonantnog područja.

1. Introduction

The turbine generator industry invests great effort in the design of machines in order to increase their efficiency and reliability. Such requirements have led to a demand of high quality, reliable machine foundation which has to provide safe and continuous machine operation. Prior to final design of a new or revised foundation, extensive calculations have to be performed in order to ensure smooth machinery operation at the nominal condition as well as to verify resistance in a case of unfavorable and unpredictable dynamic loads such as seismic load [1-2], turbine blade loss load [3-4] or generator short circuit load [5].

There are many types of foundations [1,6] but when considering industrial turbine generators most of them are spring mounted foundation, table or frame foundation and raft or block foundation. In this paper spring mounted foundation is considered. Spring mounted foundation is normally low tuned i.e. have natural frequency lower than operating speed frequency. Therefore a vibration analysis of the foundation becomes necessary. Complete foundation together with turbine generator simplified model should be analyzed in detail providing information regarding dynamic behavior of foundation and its structural components.

The diversity of the optimum structural design problem considering dynamic behavior is well presented and classified in [7]. According to this Ref. optimum design for dynamic problems are classified in two main categories: natural frequency (NF) analysis and dynamic response (DR) analysis. Dynamic optimization of a turbine frame foundation can be formulated and solved by sequential linear programming [8]. Multi-objective formulation included minimization of the structural weight and forced vibration amplitude.

In the paper [9], problem of determining optimal joint position and cross-sectional parameters of linearly elastic space frames with imposed stress and natural frequency constrained is considered. Optimal design is attained by a sequence of quadratic programming problems.

Symbols/Oznake

a	- dimension of cross section (z - direction), m - dimenzija poprečnog presjeka (z - smjer)	k_{sz}	- stiffness of the spring in z direction, N/m - krutost opruge u z smjeru
a_{lb}	- lower bound of the design variable a, m - donja granica optimizacijske varijable a	L	- length of the column, m - duljina stupa
a_{ub}	- upper bound of the design variable a, m - gornja granica optimizacijske varijable a	m	- mass of the prismatic column - masa prizmatičnog stupa
b_{lb}	- lower bound of the design variable b, m - donja granica optimizacijske varijable b	m_{diff}	- difference between the entire mass of the column and the mass of the prismatic part of the column stupa - razlika između ukupne mase stupa i mase prizmatičnog dijela
b_{ub}	- upper bound of the design variable b, m - gornja granica optimizacijske varijable b	Δf	- desired deviation of the natural frequency from the resonant frequency - traženo odstupanje vlastite frekvencije od rezonantne frekvencije
a_n	- numerical constant - numerička konstanta	Δf_{alow}	- allowable deviation between results of simplified analytical model and final verification numerical simulation - dopušteno odstupanje rezultata pojednostavljenog analitičkog modela i konačnih rezultata dobivenih numeričkom simulacijom provjere
$a_{x\text{-}cor}$	- correction coefficient - korekcijski koeficijent	ρ	- density, kg·m^{-3} - gustoća
b	- dimension of cross section (x - direction), m - dimenzija poprečnog presjeka (x - smjer)	μ	- unit mass per length - masa po jedinici duljine
E	- modulus of elasticity, GPa - modul elastičnosti	ω_x	- natural frequency of the column for the x axis - vlastita frekvencija stupa za x os
f	- frequency - frekvencija	Ω	- rotating speed, s^{-1} - brzina vrtnje
$f_{x\text{-}an}$	- analytically calculated frequency - analitički izračunata frekvencija		
$f_{x\text{-}Nastran}$	- numerically calculated frequency - numerički dobivena frekvencija		
I_x	- cross-sectional moment of inertia for x axis - moment inercije poprečnog presjeka		
k_x	- stiffness of the column in x direction, N/m - krutost stupa u x smjeru		
k_{sx}	- stiffness of the spring in x direction, N/m - krutost opruge u x smjeru		

In this paper, optimization of the foundation reinforced concrete columns of the elastically suspended turbine generator, subjected to rotating machinery dynamic loads, is performed. The design objective is to avoid resonance of the natural frequency of foundation columns with first harmonic excitation of the generator, while design variables are dimensions of columns cross section. In order to identify the problem, the simulation of the model was performed in software for finite element analysis, MSC Nastran, while afterwards the optimization of columns with a simplified model was done in computing software Matlab. The results show that the optimization is successfully performed, since the optimized dimensions of the columns give natural frequencies out of the critical frequency range.

2. Problem identification

The turbine generator, which is investigated, consists of the steam turbine and the generator, which are connected through the reduction gears. They are laid on the steel foundation plate which is supported by six reinforced concrete columns. Reinforced concrete with the mark C30/37 is defined according to Eurocode 1 [10]. A finite element model of the structure was made in the software for the finite element analysis – MSC Nastran (Figure 1). In order to simplify the entire model, the turbine and the generator are modeled as homogenous bodies with a density calculated from known masses and approximate dimensions. Mass of the turbine and reduction gear is 60 000 kg, mass of the generator is 40 500 kg and of the plate is 25 000 kg.

The main problems which can be encountered in this kind of structures, during normal operation, are excessive vibrations caused by unbalance forces, $F_u = u\Omega^2$, where u is the unbalance (kgm) and Ω is the rotating speed of the machine (Figure 1), or by misalignment of the shafts which connect turbine or generator with the reduction gear. In order to avoid excessive vibrations, natural frequencies of columns must not coincide neither

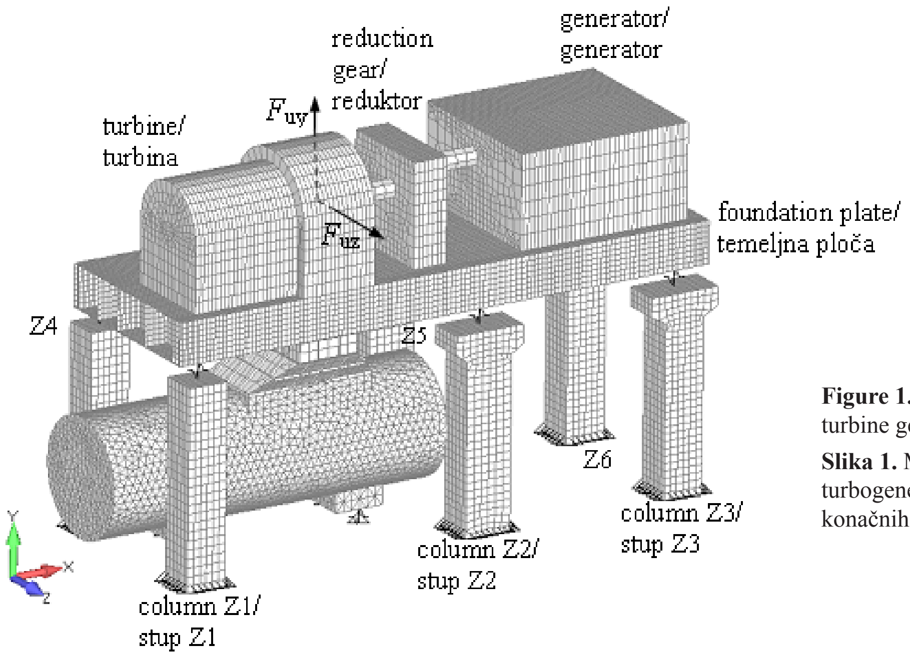


Figure 1. Finite element model of the turbine generator foundation system

Slika 1. Model sustava temelja turbogeneratora napravljen pomoću metode konačnih elemenata

with the operating speed of the turbine (6044 min^{-1}, 100.73 Hz) or generator (1500 min^{-1}, 25 Hz) nor with their higher harmonic (Figure 2). In order to ensure that natural frequencies of the columns are out of the critical frequency range, i.e. out of the range close to operating speeds, optimization of dimensions is performed. The optimization is performed only for columns Z1, Z2 and Z3 since they are the same as columns Z4, Z5 and Z6, respectively.

and afterwards calculation of correction coefficients with the purpose of defining the most accurate analytical model for optimization in MATLAB. Thereafter, the verification simulation with the optimized dimensions in MSC Nastran is performed and accordingly, if the deviation of the numerical from analytical results is not satisfactory, the correction of analytical model is made. The procedure is repeated for each column. Finally, the simulation of the entire model of the turbine generator

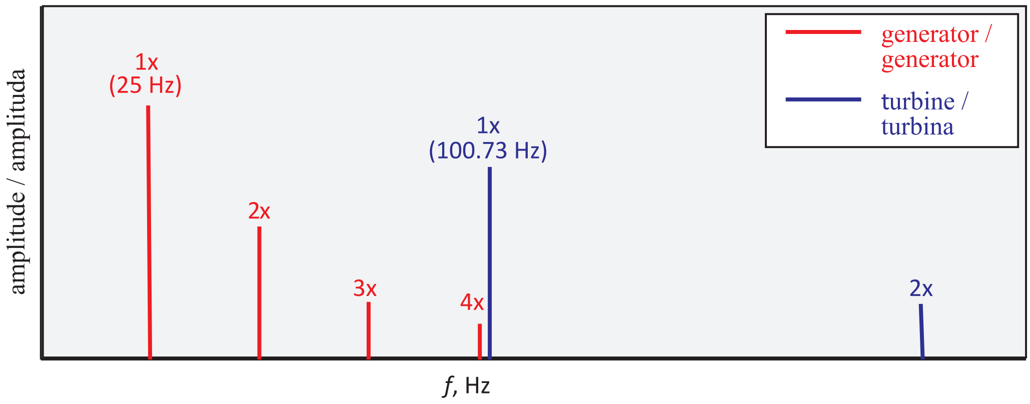


Figure 2. Operating speeds of the turbine and the generator and their higher harmonics

Slika 2. Frekvencije nominalne brzine turbine i generatora te njihovi viši harmonici

3. A detailed procedure of the optimization process

The starting point in the procedure is the problem identification, which is explained in the first section. In the block diagram (Figure 3) a detailed procedure of the foundation columns optimization is presented. After problem identification it follows the definition of the finite element (FE) and analytical model of columns foundation with all optimized columns is performed. In next chapters the each step of the process is explained in more detail.

3.1. Finite element model of columns

For columns Z1, Z2 and Z3 the finite element model was build and natural frequencies, for three different boundary conditions, were obtained. In the first case, columns are clamped at the bottom side (Figure 4). In the second case, at the top of the column a spring k_s is set up (Figure 5). Upper node of the spring element was assumed to be fixed. In the third case, columns are incorporated in the entire model (Figure 1). The third case was assumed to be most realistic. The simulation was performed for the initial dimensions, with the data given in Table 1, while the results of the simulation are shown in Table 2.

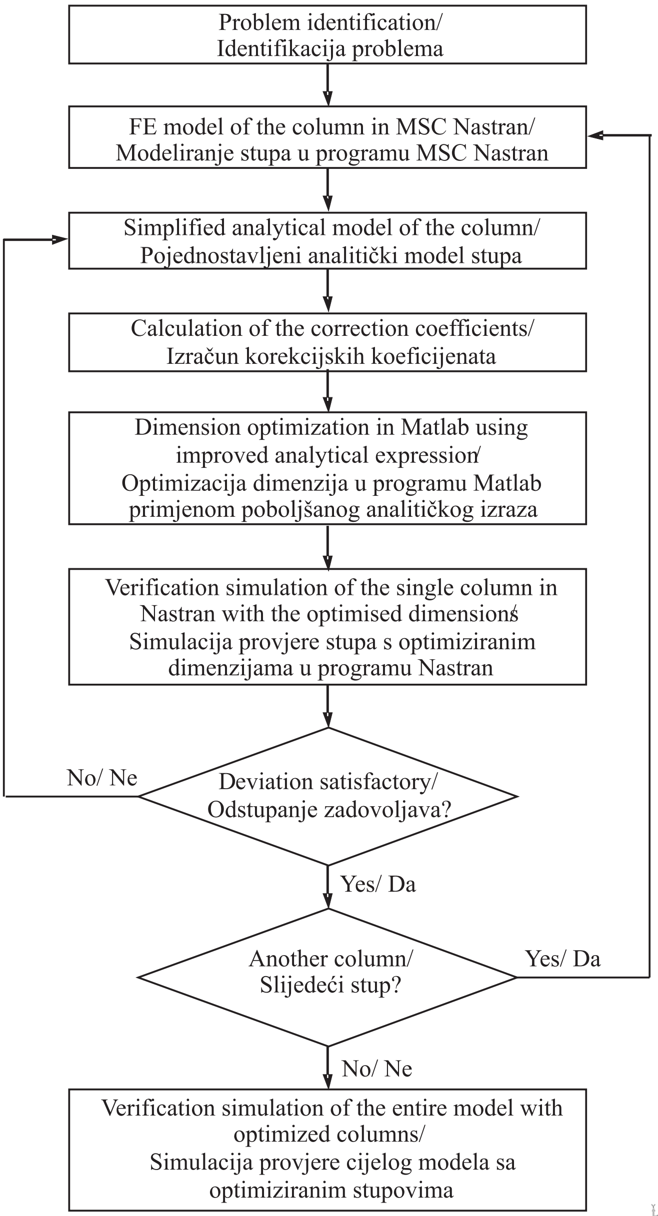


Figure 3. Block diagram of the optimization process

Slika 3. Blok dijagram postupka optimizacije

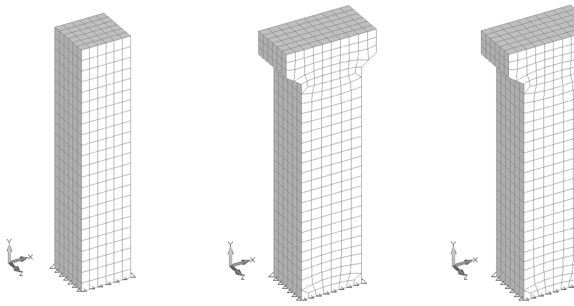


Figure 4. First boundary condition: columns clamped at the bottom

Slika 4. Prvi rubni uvjet: stupovi ukliješteni na dnu

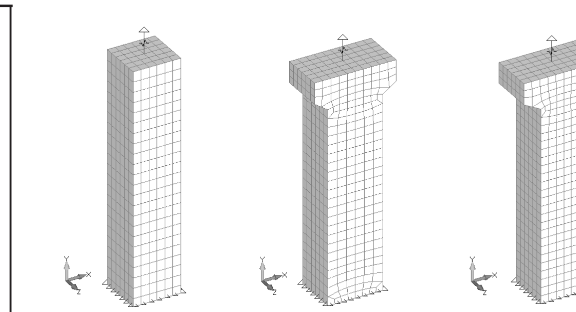


Figure 5. Second boundary condition: columns clamped at the bottom with the spring on top

Slika 5. Drugi rubni uvjet: stupovi ukliješteni na dnu s oprugom na vrhu

The first and the second column mode represent 1. flexural flexible modes for *x* and *z* axis, respectively. The third mode is torsional mode, whereas the fourth and the fifth represent 2. flexural flexible modes, as can be seen in the Figure 6. Since the frequency of the first and the second mode is close to the operating speed of the generator (25 Hz) there is a possibility that the resonance occurs. Therefore, the special attention in the optimization process is given to the avoidance of the resonance of first two column modes.

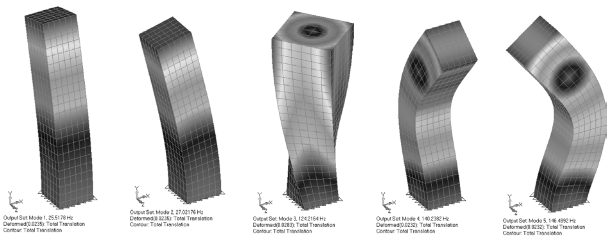


Figure 6. Modes of vibration of the column Z1

Slika 6. Vlastite forme vibriranja stupa Z1

Table 1. Initial characteristics of columns

Tablica 1. Početne karakteristike stupova

Column/Stup	Z1	Z2	Z3
density/gustoća, ρ, kg/m^3	2500	2500	2500
modulus of elasticity/modul elastičnosti, E, GPa	32	32	32
length of the column/duljina stupa, L, m	4,21	4,21	4,21
dimension of cross section (x - direction) b/ dimenzija poprečnog presjeka (x - smjer) b, m	0,85	1	0,85
dimension of cross section (z - direction) a/ dimenzija poprečnog presjeka (z - smjer) a, m	0,8	0,8	0,8
cross-sectional moment of area for x axis/ moment inercije poprečnog presjeka, I_x, m^4	0,03627	0,04267	0,03627
stiffness of the spring (x - direction)/ krutost opruge (x - smjer), k_{sx}, MN/m	10,30	14,18	14,18
stiffness of the spring (z - direction)/ krutost opruge (z - smjer), k_{sx}, MN/m	10,30	14,18	14,18

Table 2. Natural frequencies of columns Z1, Z2 and Z3 for the three different cases

Tablica 2. Vlastite frekvencije stupova Z1, Z2 i Z3 za tri različita slučaja

Column/ Stup	Mode No./ Forma br.	Case 1/ Slučaj 1:	Case 2/ Slučaj 2:	Case 3/ Slučaj 3:	$\frac{f_2 - f_1}{f_1} \times 100\%$	$\frac{f_3 - f_2}{f_2} \times 100\%$
Z1	1	25,518	28,128	28,200	10,23%	0,26%
	2	27,022	29,491	29,560	9,14%	0,23%
	3	124,216	124,216	120,297	0,00%	-3,15%
	4	140,238	140,659	140,302	0,30%	-0,25%
	5	146,489	146,883	146,401	0,27%	-0,33%
Z2	1	23,395	26,186	26,255	11,93%	0,26%
	2	28,768	31,045	31,109	7,92%	0,21%
	3	104,519	104,519	101,236	0,00%	-3,14%
	4	133,916	134,273	134,022	0,27%	-0,19%
	5	152,059	152,330	151,608	0,18%	-0,47%
Z3	1	22,447	25,578	25,633	13,95%	0,22%
	2	23,682	26,647	26,701	12,52%	0,20%
	3	97,937	97,937	94,851	0,00%	-3,15%
	4	131,316	131,681	131,411	0,28%	-0,21%
	5	131,905	132,229	131,868	0,25%	-0,27%

From the Table 2. it is seen that the natural frequency of the first mode of the column with the spring, in comparison with the cantilever column, raised up for 3 Hz (14 %), while the same column natural frequencies changes additionally for only 0,3%, when analyzed as integral part of the entire turbine generator system.

Consequently, the column structural optimization with frequency constraint will be performed for the 1. flexural flexible mode for *x* axis in *yz* flexural plane and boundary conditions explained and presented in the Figure 5 which corresponds to calculated natural frequencies given in Table 2, column Case 2. This boundary condition ensures negligible error of the natural frequencies for the local column model with respect to most realistic conditions for the entire turbine generator foundation system and therefore enables localized column structural optimization.

3.2. Analytical model of columns and calculation of correction coefficients

In order to perform optimization in MATLAB column finite element model is reduced to the simple analytical model. According to Den Hartog [11], the analytical expression for the first flexural natural frequency in *yz* flexural plane of the clamped uniform cantilever beam is equal to

$$\omega_{\mathrm{x}} = a_{\mathrm{n}} \sqrt{\frac{EI_{\mathrm{x}}}{\mu L^3}} , \tag{1}$$

where E is the modulus of elasticity, $I_{\mathrm{x}} = ba^3/12$ is the cross section area moment of inertia of the column for x axis, a is the height of the column cross section (z - direction), b is the width of the cross section (x - direction), L is the length of the beam, μ is the unit mass per length and a_{n} is a numerical constant which is equal to $a_1 = 3{,}52$ for the first flexural mode.

Since the frequency calculated from the analytical equation (1), $f_{\mathrm{x\text{-}an}} = \omega_{\mathrm{x}}/2\pi$ differs from the numerically obtained frequency in software MSC Nastran, $f_{x\text{-Nastran}}$, correction coefficients, $a_{\mathrm{x\text{-}cor}}$ are obtained for each column, using the expression

$$a_{\mathrm{x\text{-}cor}} = 3{,}52 \frac{f_{\mathrm{x\text{-}Nastran}}}{f_{\mathrm{x\text{-}an}}} . \tag{2}$$

For initial dimensions of columns, Z1, Z2 and Z3 (Table 1) values of correction coefficients are 3.79, 3.53 and 3.45, respectively. Finally, the analytical expression for the natural frequency of the column Z1 in Figure 5, is obtained as:

$$\omega_{\mathrm{x}} = \sqrt{\frac{k_{\mathrm{x}} + k_{\mathrm{sx}}}{m}} , \tag{3}$$

where $m = \rho abL$ is the mass of the column with the quadratic shape and the density ρ, k_{x} is the stiffness of the column and k_{sx} is the stiffness of the spring in the x-direction, which are in parallel connection. Since the stiffness of the column is equal to

$$k_{\mathrm{x}} = a_{\mathrm{n}}^2 \frac{EI_{\mathrm{x}}}{L^3} , \tag{4}$$

where $a_{\mathrm{n}} = a_{\mathrm{x\text{-}cor}}$ is the correction coefficient, the analytical expression for the natural frequency (3) for the column Z1 can be rewritten in the form

$$\omega_{\mathrm{x}} = \sqrt{\frac{a_{\mathrm{x\text{-}cor}}^2 \dfrac{Eba^3}{12L^3} + k_{\mathrm{s}}}{\rho abL}} . \tag{5}$$

Since the columns Z2 and Z3 do not have quadratic shape their natural frequency is obtained by using the expanded form of the expression (5):

$$\omega_{\mathrm{x}} = \sqrt{\frac{a_{\mathrm{x\text{-}cor}}^2 \dfrac{Eba^3}{12L^3} + k_{\mathrm{s}}}{\rho abL + m_{\mathrm{diff}}}} , \tag{6}$$

where m_{diff} is the difference between the entire mass of the column and the mass of the prismatic part of the column, m.

3.3. Dimension optimization in MATLAB

Optimization is performed in the software MATLAB using an Optimization Toolbox [12], which includes routines for many types of optimizations, such as unconstrained nonlinear minimization, constrained nonlinearminimization, linear and quadratic programming, nonlinear least squares and curve fitting, etc. This techniques are used to find a set of design parameters x that can in some way be defined as optimal. The objective function, $f(x)$ to be minimized or maximized might be subject to constraints in the form of equality constraints, inequality constraints and/or parameter bounds.

In this work, the optimization problem is to find optimal dimensions of the column cross section under the condition that its first two flexural natural frequencies do not coincide with the operating speed of the generator (25 Hz). The objective function is the natural frequency of the column for x axis, defined in (5) and (6) and subjected to condition that both first flexural natural frequencies are greater than upper allowed or smaller than lower allowed frequency. The optimization process is divided into two parts. If the natural frequency of the column, ω_{x}, is greater than the operating speed of the generator the objective is to minimize the natural frequency, subject to conditions

Table 3. Lower and upper bounds of design variables

Tablica 3. Donja i gornja granica optimizacijskih varijabli

Column/Stup	a_{lb}, m	a_{ub}, m	b_{lb}, m	b_{ub}, m
Z1	0,7	0,9	0,7	1
Z2	0,7	0,9	0,7	1,2
Z3	0,7	0,9	0,7	1,2

that both 1. flexural frequencies are greater than 25 Hz + $\Delta f + \Delta f_{alow}$, where Δf = 2,5 Hz i.e. 10 % of the service excitation frequency [13], is the desired deviation (half bandwidth) of the (higher order, flexible) foundation natural frequency from the resonant excitation frequency and Δf_{alow} = 0.5 Hz presents allowable deviation between results of simplified analytical and final verification numerical simulation. In contrary, the objective is to maximize ω_x subjected to conditions that both 1. flexural frequencies are less than 25 Hz – Δf – Δf_{alow}. The analogous procedure is implemented for each of the columns Z1, Z2 and Z3. Upper and lower bounds of design variables *a* and *b* are shown in Table 3, where indexes *lb* and *up* refer to lower bound and upper bound, respectively. They are selected in order to respect the existing dimensions of the space in which the turbine generator has to be placed. Initial guesses of design variables are equal to initial dimensions of columns (Table 1).

According to the nature of the optimization problem, function *fmincon*, which finds a constrained minimum or maximum of a nonlinear function of several variables starting at an initial estimate, is applied. Output files from the optimization process in Matlab, which show a gradual change of the objective function across the iteration steps, are given for each column in Tables 4 – 6, while the optimized dimensions are shown in Table 7.

Table 4. Output file for column Z1

Tablica 4. Izlazna datoteka za stup Z1

Iter	F-count	f(x)	Feasibility	First-order optimality	Norm of step
0	3	1.807037e+002	0.000e+000	1.696e+001	
1	6	1.759625e+002	0.000e+000	4.636e+000	2.252e-002
2	9	1.759294e+002	0.000e+000	6.282e-002	7.985e-004
3	12	1.759292e+002	0.000e+000	3.458e-004	2.614e-004
4	15	1.759292e+002	0.000e+000	3.231e-006	5.158e-005

Table 5. Output file for column Z2

Tablica 5. Izlazna datoteka za stup Z2

Iter	F-count	f(x)	Feasibility	First-order optimality	Norm of step
0	3	1.649456e+002	1.098e+001	9.999e-001	
1	6	1.760964e+002	0.000e+000	1.672e-001	5.765e-002
2	9	1.759317e+002	0.000e+000	5.710e-003	1.442e-003
3	12	1.759292e+002	0.000e+000	7.880e-005	3.048e-004

Table 6. Output file for column Z3

Tablica 6. Izlazna datoteka za stup Z3

Iter	F-count	f(x)	Feasibility	First-order optimality	Norm of step
0	3	1.600215e+002	1.591e+001	9.999e-001	
1	6	1.762444e+002	0.000e+000	3.152e-001	1.010e-001
2	9	1.759367e+002	0.000e+000	1.115e-002	1.790e-003
3	12	1.759301e+002	0.000e+000	1.115e-002	4.324e-003
4	15	1.759292e+002	0.000e+000	1.523e-003	9.575e-004
5	18	1.759292e+002	0.000e+000	1.102e-005	8.762e-005

Table 7. Optimized dimensions of columns cross section

Tablica 7. Optimizirane dimenzije poprečnog presjeka stupova

Column/Stup	*a*, m	*b*, m
Z1	0,78	0,85
Z2	0,86	1,00
Z3	0,88	0,91

For the verification, the simulation of the entire model of the turbine generator foundation with optimized dimensions of columns cross section is performed, what gives first flexural natural frequencies of the columns Z1, Z2 and Z3 in planes *yz* and *xy* as shown in Table 8. Coresponding normal modes are shown in Figures 7-12.

Table 8. Natural frequencies obtained from verification simulation of the entire turbine generator foundation model with optimized columns cross-section dimensions

Tablica 8. Vlastite frekvencije cijelog modela temelja turboagregata dobivene kontrolnom simulacijom s optimiziranim dimenzijama poprečnih presjeka stupova

Column/ Stup	Mode No./ Forma br.	Plane/ Ravnina	*f*, Hz
Z1	1	yz	27,58
	2	xz	29,55
Z2	1	yz	27,52
	2	xz	31,02
Z3	1	yz	27,6
	2	xz	28,14

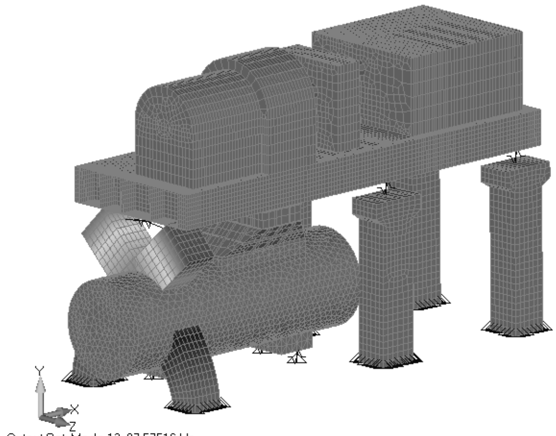
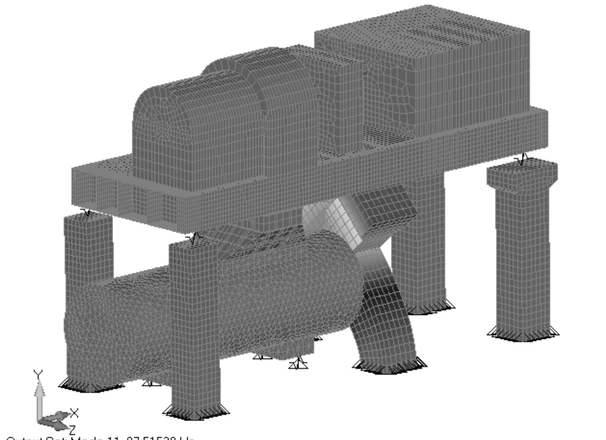


Figure 7. Normal mode of the column Z1 in the flexural plane *yz* obtained by verificaton simulation

Slika 7. Vlastita forma stupa Z1 u ravnini savijanja *yz* dobivena provjerom



Slika 8. Vlastita forma stupa Z2 u ravnini savijanja *yz* dobivena provjerom

Figure 8. Normal mode of the column Z2 in the flexural plane *yz* obtained by verificaton simulation

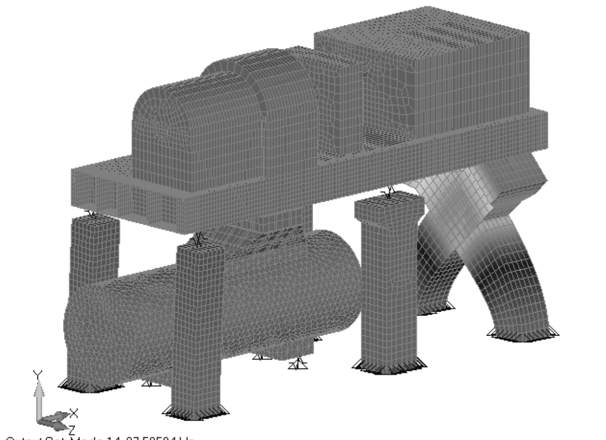


Figure 9. Normal mode of the column Z3 in the flexural plane *yz* obtained by verificaton simulation

Slika 9. Vlastita forma stupa Z3 u ravnini savijanja *yz* dobivena provjerom

Table 8 shows that first natural frequencies of optimized columns Z1, Z2 and Z3 (Figures 7, 8 and 9) for normal modes in the flexural plane *yz,* deviate for less than 0,5 Hz from the objective frequency f_x (28,0 Hz), while the deviation of some natural frequencies in plane *xy* (Figures 10, 11 and 12) is greater than 0,5 Hz. The obtained results are as expected, since the objective function in the optimization process was only the natural frequency for *x* axis, subjected to constraint that both first flexible natural frequencies are greater than allowed.

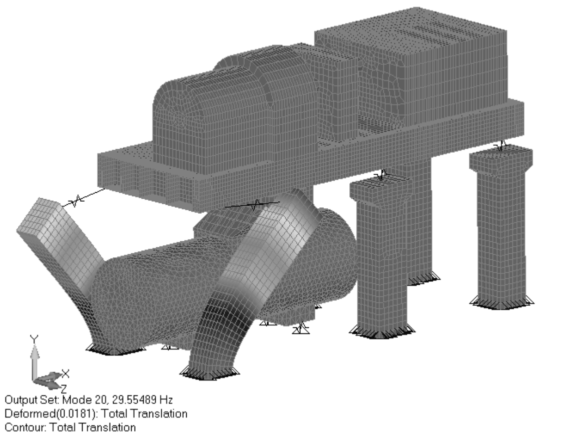


Figure 10. Normal mode of the column Z1 in the flexural plane *xy* obtained by verificaton simulation

Slika 10. Vlastita forma stupa Z1 u ravnini savijanja *xy* dobivena provjerom

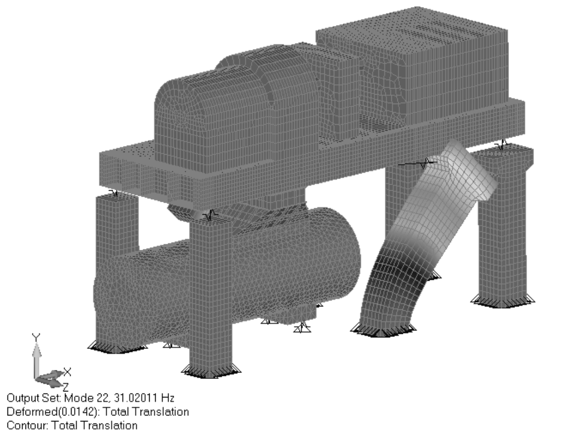


Figure 11. Normal mode of the column Z2 in the flexural plane *xy* obtained by verificaton simulation

Slika 11. Vlastita forma stupa Z2 u ravnini savijanja *xy* dobivena provjerom

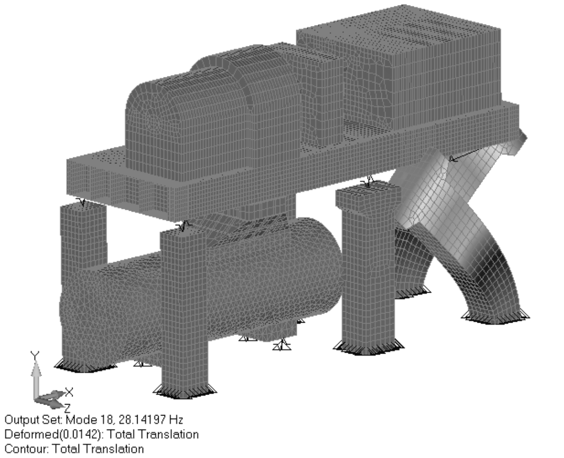


Figure 12. Normal mode of the column Z3 in the flexural plane *xy* obtained by verificaton simulation

Slika 12. Vlastita forma stupa Z3 u ravnini savijanja *xy* dobivena provjerom

6. Conclusion

In this paper, a method for finding an optimal design of structural columns of the spring mounted turbine generator foundation subjected to dynamic loads is presented. According to thorough finite element analysis and comparisons of local column models with the global turbine generator foundation model it is concluded that each column can be modeled separately, using the simplified analytical model. From the analyzed example of turbine generator foundation it is observed that springs which are set up on top of the columns in the horizontal x and z directions give natural frequencies which are very similar to corresponding natural frequencies of the global turbine generator foundation, i.e. this is the most influential effect which has to be included in the analytical model. Tuning of the analytical model of columns with the corresponding finite element model is performed by calculation of correction coefficients.

As a critical excitation operating speeds of the turbine (100.73 Hz) and the generator (25 Hz) caused by unbalance and their higher harmonics, caused by shaft misalignment, are examined.

In consideration of natural frequencies of the initial design of the turbine generator foundation model possible resonances of the first two natural frequencies of columns with first harmonic of the generator were identified. Therefore, this became the design objective, while design variables were dimensions of columns cross section.

Results showed that natural frequencies of the optimized columns lay out of the critical frequency range, what proves the accuracy of the applied procedure. Furthermore, the proposed method is suitable not only for the design optimization of the analyzed example but of an every structure subjected to frequency constraints, which can be represented with a similar analytical model.

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