Anpproaches to Account Energy Losses in Various Parts of "Soil-Structure" Systems in Dynamic Analysis of Civil Structures of NPP

V.Korotkov, D.Poprygin - JSC "ATOMENERGOPROEKT"
D.Volkov-Bogorodsky - IPRIM RAN (Applied Mechanics Institute of Russian Academy of Science)

Abstract: The presentation contains approach, which allows to use modal method of dynamic analysis of civil structures of NPP through the use of Abaqus software. The case is that conventional model of "soil-structure" system consists of two parts. Structure is modeled by beam and plate elements, and soil consists of spring and dashpot elements from ASCE 4-98. While using Modal method of analysis, Abaqus has the option, in which modal composite damping is determined as average weighed characteristic proportional to mass of the finite element. However impedance functions from ASCE 4-98 taken as spring elements has no mass property and dashpot elements are not become active in classic modal method. Therefore modal method used in Abaqus software will provide too conservative results, due to impossibility to take into account very high level of attenuation in soil.

The idea of our approach is to define modal composite damping in system in proportion to strain energy within the mode shape, as independent computer program. This approach allows to take into account soil damping in modal analysis.

In this article we represent approbation on tests of the new method, where we make comparison analysis of the results with the theoretical solution suggested by the authors.

Keywords:"soil-structure" system, modal composite damping, modal method of analysis, response spectra.

1. Introduction

As it is known, while providing dynamic analysis of the NPP civil structures, consideration of a soil base is of great importance. The most conventional method of such consideration is in application of impedance functions from the American standard ASCE 4-98 [1], allowing, with the help of springs and dashpots, to model stiffness and dissipative properties of soils. As a result, there may be investigated a FE model of the "soil-structure" system that includes a reinforced concrete structure, with damping about 4%, and a soil base with spring damping up to 50% and more. We have got, thereby, essentially different damping values in different parts of "soil-structure" systems.

2. Analysis methods

Let us examine how the problem of consideration of inequality of energy losses in various parts of such systems is solved methodically. While using the direct integration method the dissipative properties of soil are accounted with the help of specialized "soil" dashpots, and as for a structure, we apply Rayleigh's damping [2] in it. In case of using modal method of analysis the dashpot-type elements are not activated therefore, it is necessary to treat as follows: to determine dissipative properties of soil as damping of the material (springs), and in a structure the material damping will correspond to a normative value of damping for concrete (around 4%). Finally, modal damping coefficients for α – mode shape should be defined as mass-weighted or stiffness-weighted values according to the following formulae from ASCE 4-98:

$$\xi_\alpha = \frac{\{\phi_\alpha\}^T[\widetilde{M}]\{\phi_\alpha\}}{\{\phi_\alpha\}^T[M]\{\phi_\alpha\}} \quad (1)$$

or

$$\xi_\alpha = \frac{\{\phi_\alpha\}^T[\widetilde{K}]\{\phi_\alpha\}}{\{\phi_\alpha\}^T[K]\{\phi_\alpha\}}, \quad (2)$$

where [M] and [K] – mass and stiffness matrix of the system, $\{\varphi_\alpha\}$– vector of α– form, and $[\widetilde{M}]$ and $[\widetilde{K}]$ – modified mass and stiffness matrices, during formation of which the matrices of each element are multiplied by its dissipation coefficient.

In Abaqus software there is realized only formula (1), that allows to define mass-weighted values of modal damping proportional to mass of the element. However, the "soil" springs do not possess mass therefore, attenuation in the system cannot take soil properties into account per formula (1). In this case a formal use of (1) brings to rather conservative results, and this means that application of Abaqus for solution of dynamic tasks of such a type using the modal method seems to be impossible.

In this paper we've realized an approach for determination of modal attenuation coefficients equivalent to realization of formula (2). A sense of the approach is in use of damping in FE system proportionally to elastic strain energy according to the following formula:

$$\xi_\alpha = \Sigma_m \xi_m \varepsilon_{m_\alpha} / \Sigma_m \varepsilon_{m\alpha} \quad (3)$$

In this formula the index *m* - corresponds to FE current number, $\varepsilon_{m\alpha}$ – to the strain energy within α– mode shape, and ξ_m– to damping of material in this FE. Abaqus allows for determination of elastic strain energy for every FE. Besides, the software may be assigned for damping in material for FE various types, excluding the SPRING-type element, as initial information. Taking the above into account there has been developed an independent computer program of modal composite damping per formula (3). In this program the damping in a spring was assigned as input in an interactive regime as additional information. Abaqus provides a possibility for realization of this approach as a plug-in module calculating necessary characteristic and being arranged accordingly in the programming language Python.

It is necessary to note that usage of the formula (3) in this analysis was proposed by Mr. David B. Woyak, a principal engineer of SIMULIA Eastern Region, during probation of AEP specialists in the Providence, USA in 2010.

Workability of the approach is to be tested using test problems. In these tests there is made a comparison of modal coefficients obtained by formulae (1) and (3) with author's proposed theoretical solution based on analysis of the system dynamic coefficient under harmonic resonance action. In this case the system dynamic coefficient will be equal to dynamic coefficient of a non-conservative oscillator which is defined, according to [3], p.44, by the following formula:

$$\beta_{\max} = U_{din} / U_{stat} = 1/2\xi_{theor}, \qquad (4)$$

where U_{din} and U_{stat} – dynamic and static displacements with relevant application of sinus and a value of its amplitude, and ξ_{theor} – theoretical value of modal damping coefficient.

3. Results and discussions

Let us note that the test problems include, in addition to simplified beam elements, a comparative analysis of response spectra in a typical box-type building at various options of definition of modal composite damping in the system.

Let us start to consider the test problems.

Test-1. This test problem deals with a hinge supported beam, length L=10m, cross-section $A=1m^2$ (1×1), Young's modulus $E=2\times 10^7$ kPa, density ρ=2.5 t/m^3. The beam is divided into two equal parts, the left of which has got the damping ratio ξ_1=2%, and the right one ξ_2=7%. It is required to define modal composite damping corresponding to the first tone of oscillations (f) of the beam using formulae (1), (3) and (4). The harmonic load $P=P_0\sin 2\pi f t$, necessary for realization of the formula (4) was applied in the center of the beam span. In this case P_0=1, f =12.5Hz. The considered model is shown on figure 1.

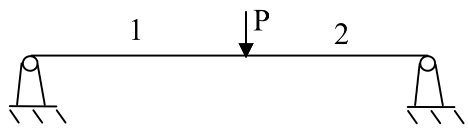

Figure 1. Model of hinge supported beam.

Results of the calculation per formulae (1) and (3) gave exactly similar values of the modal composite damping ξ_1=4.5%. When calculating per the formula (4) we got U_{din}=0.1397mm and U_{stat}=0.125mm, and relevant theoretical damping value comprised ξ_{theor}=4.47% that is practically identical to formulae (1) and (3) calculations. In case of change of the beam second part damping by the very big value ξ_2=50% (like in soil) no quality of results have been changed. Formulae (1) and (3) gave ξ_1=26%, and the formula (4) gave ξ_{theor}=25.8%. Thus, calculation accuracy of the modal composite damping coefficient in two previous calculations is rather high – it is within 1% as compared with theoretical solution, and this error does not change under considerable increase of damping in the second part of the model.

Let's consider next a model with damping in its parts as in the first calculation, and, in this case, increase the Young's modulus by ten times in first part of the beam. The calculation results are following: f=16.62Hz, the formula (1) gives ξ_1=5.249%, the formula (3) – ξ_1=6.606%, and theoretical solution comprises ξ=5.3%. As seen, the relevant errors comprise 1% and 24% as compared with the theoretical solution. Such a result can give rise to doubt in trustworthy of the formula (3) in the modal analysis of composite systems, because this formula error is essential as compared with the theoretical solution. In this regard let us carry out an additional study of the previous problem for definition of the modal composite damping coefficient according to formulae (1) and (2) using the program Solvia (Sweden). Results are as follows: the formula (1) gives ξ_1=5.20% , and the formula (2) - ξ_1=6.60%. As it is seen, the results coincide with high accuracy extent. Therefore, we make a conclusion that calculation results per (3) are equal to results per (2), and since the formula (2) is recommended by the standard ASCE 4-98, then the formula (3) is also acceptable as equivalent to (2). Here, it is necessary to note that accuracy of formulae (2) and (3) is lower than that of the formula (1), as compared with the theoretical solution.

Further, having increased damping in the second part of the model up to 50%, and having repeated calculations we shall get the following results: the formula (1) gives ξ_1=33.19%, the formula (3) - ξ_1=46.22%, and theoretical solution – ξ_{theor}=34%, and error is 2% and 35%. As it is seen, the formula (1) error is practically unchangeable, and the formula (3) error – increases under considerable increase of damping in one of the beam parts. Table 1 represents a dependence of modal damping from damping in the beam materials. In this Table ξ_{Abaqus}(%) - damping corresponding to the formula (1), and ξ_{ε}- to the formula (3).

Table 1. (U_{sat}=0.7049mm) dependence of modal damping from damping in the beam materials

ξ_1(%), ξ_2(%)	ξ_{Abaqus}(%)	ξ_{ε}(%)	$U_{din}(mm)$	ξ_{theor}(%)	Error(%)	
2,2	2.0	2.0	1.712	2.0	0	0
2,7	5.25	6.61	0.654	5.3	1	24
2,10	7.20	9.38	0.477	7.4	3	27
2,20	13.70	18.58	0.250	14.0	2	33
2,30	20.20	27.80	0.170	20.7	2	34
2,40	26.70	37.01	0.128	27.3	2	36
2,50	33.20	46.22	0.104	34.0	2	35
2,60	39.70	55.43	0.086	40.6	2	37
2,70	46.19	64.65	0.075	47.2	2	37

It is seen from the Table that as far as damping increases in one of the beam materials, calculation error of the modal damping, corresponding to the formula (3), increases.

Test-2. Let's consider a system with two degrees of freedom, which models the reactor building vertical oscillations. The system contains a spring and a dashpot modeling soil properties. The spring rigidity K_z=5×10^8kN/m, attenuation value – Bz=1.4×10^7kN/m ×s/m(70%). The building was modeled with a beam element, length *L=60m*, cross-section area – *A*= 870m^2, Young's modulus 2×10^7 *kPa*, dummy density – ρ=3.72t/m^2, and damping ratio in the beam is 4% of critical value. Such a model realizes frequency of vertical oscillations of the first tone corresponding to the real value – *f* =6.33Hz. The model also possesses the real mass *m*=125280*t*. In point 1 we shall apply harmonic force with the amplitude P_0=*ma*=21465kN, and shall carry out calculations using SIM-architecture. This system model is given in figure 2.

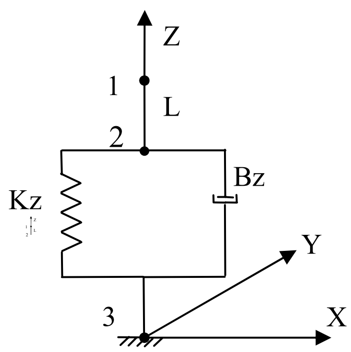

Figure 2. Model of the system

Results of the calculations are given in Table 2. In the Table the first column deals with damping in the beam that comprises 4%, and attenuation of "soil" dashpot, varying from 0% to 70%. Then the Table presents damping values received by formulae (3) (ξ_ε) and (4) (ξ_{theor}), as well as calculation error. As it is seen from the Table, at low damping values in the "soil" dashpot the calculation of the modal damping coefficient in the system according to the formula (3) is conservative. Then, as far as the "soil" dashpot attenuation increases the calculation error essentially increases, and not conservatively.

Table 2. (U_{stat}=1.1158mm) Dependence of the system modal damping on soil attenuation

ξ_{conc}(%), ξ_{soil}(%)	ξ_ε (%) as per formula (3)	Udin(mm)	ξ_{theor}(%) as per formula (4)	Error (%)
4,0	1.79	14.09	3.96	
4,4	4.0	9.79	5.70	30
4,7	5.66	7.94	7.00	19.10

4,10	7.31	6.77	8.24	11.28
4,20	12.80	4.58	12.10	5.80
4,30	18.36	3.54	15.70	16.90
4,40	23.88	2.96	18.80	27.00
4,50	29.41	2.60	21.45	37.00
4,60	34.93	2.37	23.58	48.00
4,70	40.45	2.21	25.20	60.00

Results presented in Table 2, are also depicted as a graph in figure 3. As seen from the graph, as far as "soil" dashpot attenuation increases the modal damping also increases, but with various gradients for the theoretical solution and with calculation per the formula (3).

Let us remind that in this test the soil damping comprises 70%, and relevant modal composite damping obtained by the formula (3) exceeds a theoretical value non-conservatively. Therefore, it is unacceptable for practical use and, in accordance with figure 3, this damping, comprising 40%, should be limited to the value of its theoretical meaning - 25%.

In this regard it is necessary to note that various world standards also introduce various limitations for modal composite damping of the "soil-structure" systems. As an example, in ASCE4-98 there is a limitation for damping when using formulae (1) and (2), and this limitation comprises 20% in case of it's exceeding.

Of course, to solve the problem of maximum permissible value of the modal composite damping applicable for any "soil-structure" system using the stated in the paper approach it is necessary to carry out full study taking into account other components of movement, besides the vertical component, as well as to consider various soil properties and influence of various buildings. The buildings themselves need to be modeled more detail, in this case, but this work is not a goal of this paper.

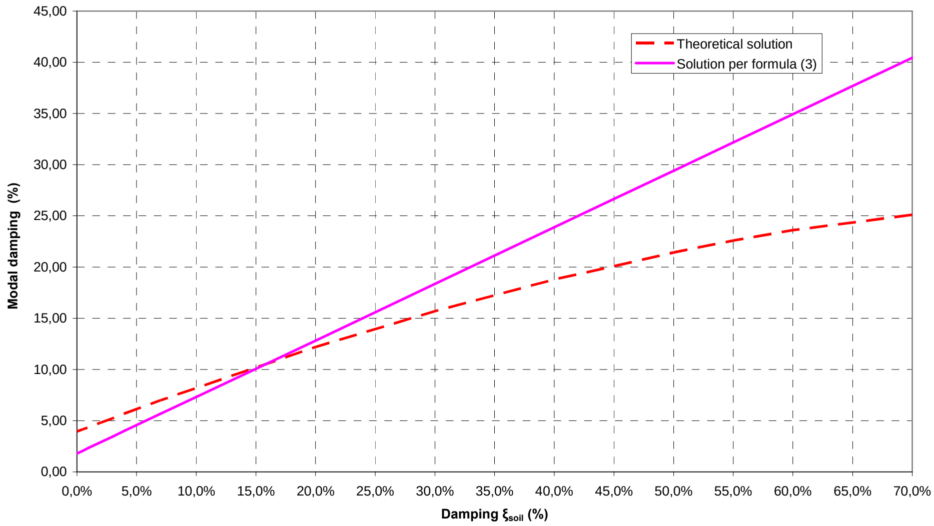

Figure 3

Test-3. Let us consider, as a real problem, analysis of response spectra in a typical box-type building in the point A on the roof level under SSE-level seismic impact. The model is B25 concrete-made structure with damping 7%. Its foundation plate is considered as an absolutely rigid body. A general view of the model is shown on figure 4. This model contains:

total number of nodes - 23094;
total number of equations - 137700;
total number of elements - 42883.

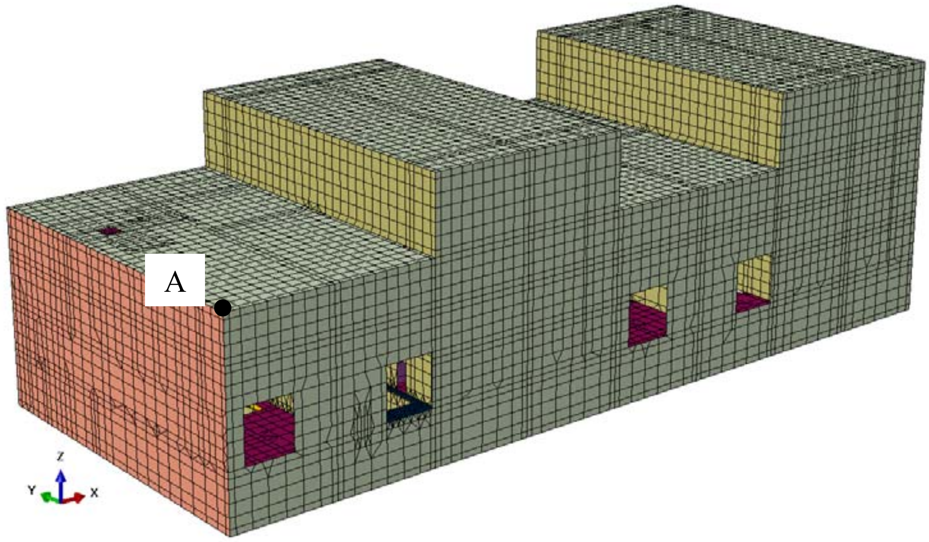

Figure 4. General view of the building model.

Soil was accounted at the expense of six elements of "soil" springs and dashpots applied in the center of the foundation plate. Properties of the springs and dashpots are given in Table 3.

Table 3. Equivalent stiffness and attenuations

	ASCE equivalent stiffness
k_x, kN/m	3.1×10^8
k_y, kN /m	3.7×10^8
k_z, kN /m	4.3×10^8
k_{φ_x}, kN $\times$m	1.2×10^{11}
k_{φ_y}, kN $\times$m	4.2×10^{11}
k_{φ_z}, kN $\times$m	3.3×10^{11}

	ASCE equivalent attenuations
b_x, kN $\times$s/m	5.0×10^6(80%)
b_y, kN $\times$s/m	6.0×10^6(88%)
b_z, kN $\times$s/m	10.3×10^6(139%)
b_{φ_x}, kN $\times$s$\times$m	7.4×10^8(40%)
b_{φ_y}, kN $\times$s$\times$m	4.2×10^9(75%)
b_{φ_z}, kN $\times$s$\times$m	15.0×10^8(30%)

As seen from Table 3, this model possesses very high radiation damping, which all components exceeds 20%, therefore, in accordance with ASCE4-98 let's make a 20% limitation on these components.

Table 4 contains modal damping coefficients for some dominate tones of oscillations of the system obtained per formulae (1) and (3).

Table 4. Modal damping coefficients.

Tone №	Frequency, Hz	Effective mass, $10\times$t			Modal composite damping	
		X	Y	Z	$\xi_{Abaqus}(\%)$	$\xi_{\varepsilon}(\%)$
7	9.6918	**2487.3**	1.4935	0.93638	6.96	20.0
8	10.119	1.3729	**2383.1**	0.1034	6.97	20.0
9	13.034	1.6628	53.532	1.17E-02	6.97	14.40
10	14.137	4.8502	8.31E-04	**790.96**	5.26	20.0
11	14.338	0.70964	0.37921	5.7381	6.54	7.59
12	14.578	1.2211	4.34E-03	**89.013**	4.62	9.48
13	15.058	**27.073**	9.30E-02	0.20515	6.97	7.58
14	15.569	0.29642	0.28629	**85.111**	6.87	9.50
15	15.753	1.2247	5.88E-02	**1050**	6.58	20.0
16	16.303	13.825	0.14665	6.4298	6.94	7.64
17	16.508	2.7201	1.50E-07	50.936	6.98	9.56
18	16.936	0.20266	3.83E-04	**212.97**	6.97	14.40
19	17.195	2.05	7.80E-05	13.444	6.99	7.96
20	17.569	9.36E-02	1.57E-04	**414.37**	6.88	20.0

Presented in the Table tones 7 & 8 of oscillations are associated with rocking in directions X and Y. Coefficients of participation per effective mass are high for these tones, they comprise about 80% and are conditioned, mostly, by soil movement. The tenth tone of oscillations is associated with vertical displacements, but already in lesser extent, because coefficient of participation comprises 25%. However, due to very high values of soil attenuations, the relevant modal attenuations are also high, therefore, they got 20% limitation.

Resultant response spectra in the point A of the building roof are given in figure 4.

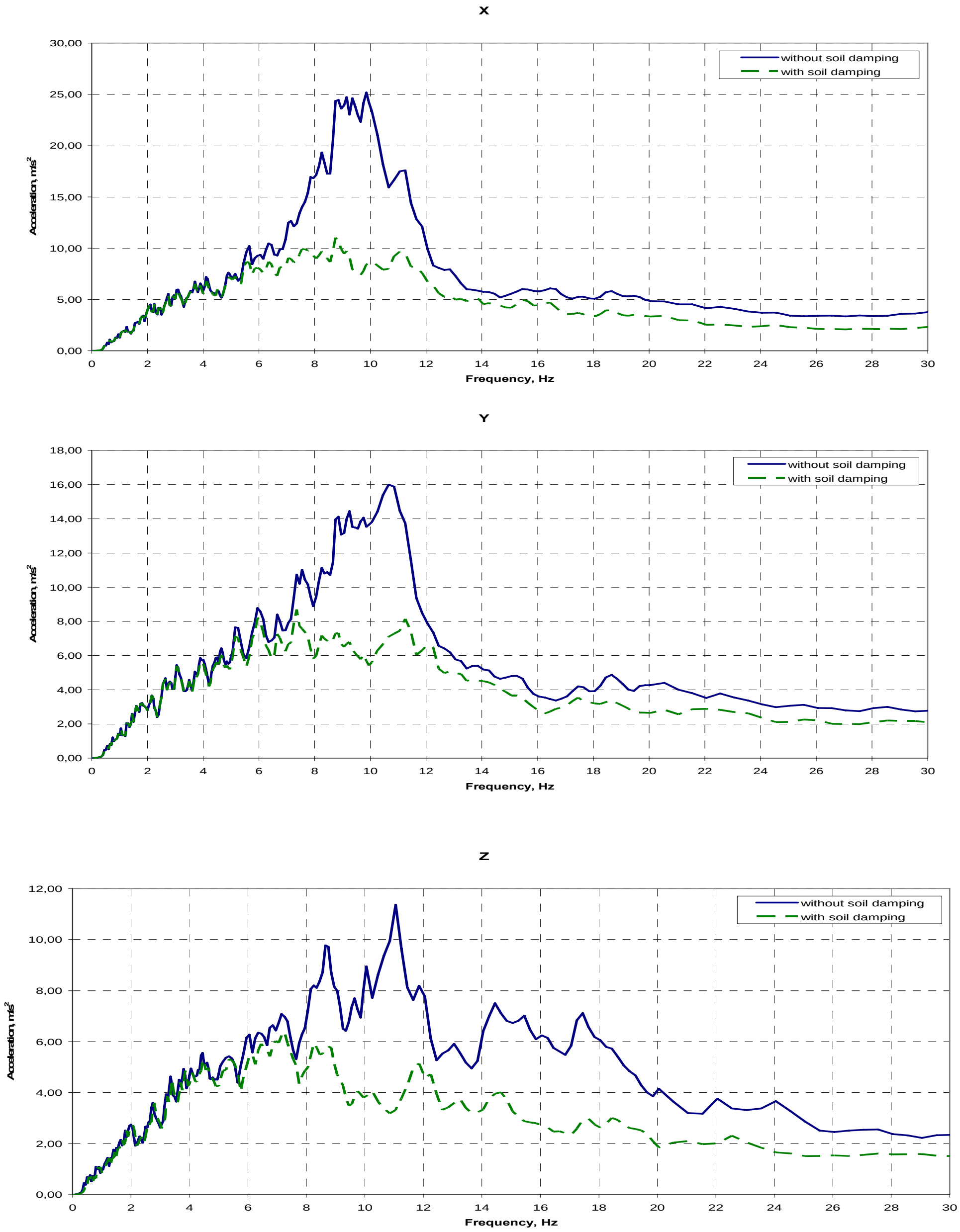

Figure 5.Response spectra (ξ=2%) on the building roof (point A) calculated with and without regard to the soil damping

As seen from figure 4 calculations per the formula (1) give rather overestimated results as compared with calculations per the formula (3). It is associated with the fact that the proposed in Abaqus formula (1) does not allow to consider attenuation in "soil" springs.

4. Conclusions

- Methods and independent program of modal composited damping definition for dynamic analysis of NPP civil structures were developed using the modal method of analysis and Abaqus program.

- The program has passed approbation on test problems dealing with comparison with the author's theoretical solution, as well as with a solution per the program Solvia (Sweden).

- With account of the presented in this paper approach the modal method realized in Abaqus is recommended by the authors for use in dynamic analysis of NPP civil structures.

5. Reference

1. ASCE 4-98. ASCE STANDARD. Seismic ANALYSIS OF safety Related Nuclear Structures and Commentary. Approval 1998.

2. V.A. Korotkov, K.A. Ilyin Application of "Soil" Dashpots in Modal Method Analysis of Civil Structures of Nuclear Power Plants. 2011 SIMULIA Customer Conference.

3. V.L. Biderman. Applied theory of mechanical oscillations. "Vysshaya shcola" publisher, Moscow,1972.

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