Account of Modal Damping Instead Rayleigh One in Floor Response Spectra Analysis in Civil Structures of Nuclear Power Plants (NPP) Under Aircraft Crash

Ph.D. V.Korotkov, A.Ivanov, A.Naumkin,

JSC Atomenergoproekt, Moscow

Abstract. *Presently the problem of safety providing of NPP under aircraft crash (AC) has special importance, because rather often floor response spectra (FRS) obtained in the AC analysis are dominant with respect to spectra, obtained in other special dynamic loadings, such as seismic load and explosive wave. It leads to necessity of obtaining more realistic solution of the problem under consideration with taking into account the following factors. Firstly it is necessary to consider inelastic behavior of concrete in the area of aircraft crash using model of concrete from Abaqus software. Secondly it is also necessary to use more accurate damping in materials. The case is that in direct integration method Rayleigh formula is used to describe material damping, which gives too conservative results. In this paper we suggest approach, which gives an opportunity to change global Rayleigh damping matrix on global modal damping matrix, that previously was determined by special way. Also in this paper we represent results of the analysis of test model and of the real example, where authors represent significant diminishing of spectral accelerations in case of changing Rayleigh global damping matrix on modal global damping matrix.*

Keywords: *civil structures of NPP, Floor response spectra, Direct integration method, modal method, Rayleigh damping, modal damping.*

1.Introduction

To obtain realistic solution of the problem of obtaining floor response spectra of NPP structures under aircraft crash we have to take into account the following factors: contact interaction of striker and barrier, inelastic behavior of concrete in impact area, influence of inelastic soil. Consideration of these factors is possible only in the direct integration method in Abaqus. However with an advantage (possibility of solving nonlinear problems, including contact interaction) this method has a significant disadvantage – accounting material damping in soil-structure system. The case is that Rayleigh damping, used in direct integration method, gives too conservative results, comparing to normative values of material damping, used in modal methods of analysis.

Rayleigh formula to obtain the global damping matrix is:

$$C_1 = \alpha M + \beta K \qquad (1)$$

Matrices M and K are global matrices of mass and stiffness respectively, parameters α and β obtained as follows:

$$\alpha = 2\xi\omega_1\omega_2/(\omega_1 + \omega_2) \qquad (2)$$

$$\beta = 2\xi/(\omega_1 + \omega_2)$$

In formulas 2 ω_1 and ω_2 are values of natural frequencies, where material damping is equal to ξ – normative value. On other frequencies damping values can be obtained as follows:

$$\xi = 0.5(\alpha / \omega + \beta\omega) \qquad (3)$$

From equation 3 it can be seen, that for loads, exciting oscillations on frequencies between ω_1 and ω_2, we will get significantly higher values of floor response spectra (FRS), because corresponding calculated values of damping are lower than their normative values. On the contrary for loads, exciting oscillations higher than ω_2 or lower than ω_1, spectra will be nonconservatively lower, because damping values are rather higher than normative.

Here is the demonstration of the technology of application the Rayleigh damping in case of aircraft type Phantom RF-4E crash with load amplitude, represented in figure 1, on concrete box-type building, with material damping 7% and frequency of the first mode 3,46Hz. Notice, that detailed description of the building is represented further in section 3.

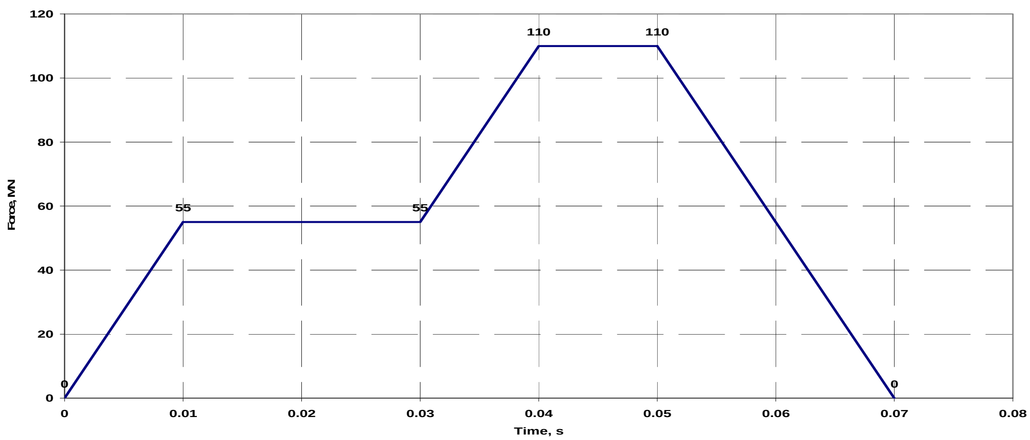

Figure 1. Amplitude of plane impact
(in time domain)

To obtain boundary frequency $\omega_2=2\pi f_2$, we recalculate load from time domain to frequency domain by means of floor response spectra method. Resultant load in frequency domain is represented in figure 2.

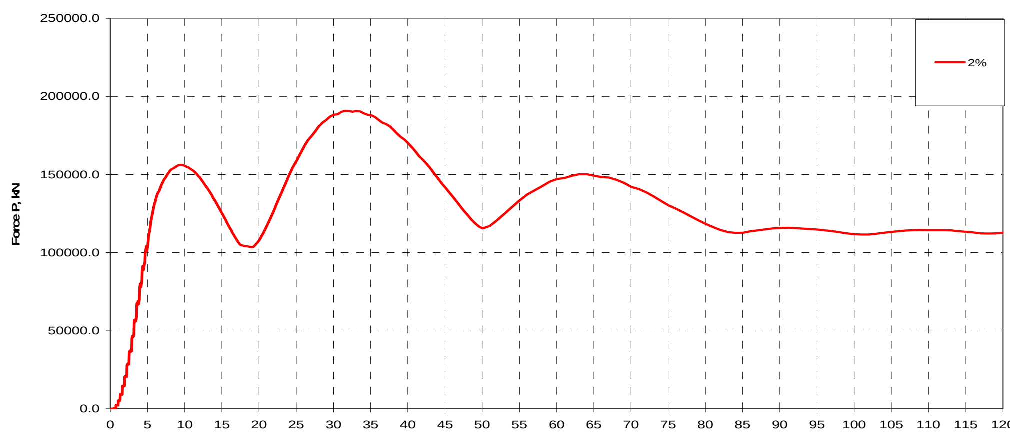

Figure 2. Load of plane impact
(in frequency domain)

From figure 2 it can be seen, that on frequency about 85 Hz spectrum becomes asymptotically equal to the maximum value of load amplitude (110MN), and higher frequencies don't represent any value in obtaining Rayleigh damping. Considering foresaid, we will get α=2.547 and β=0.000253.Plot I - damping, relative to frequency (equation 3) is represented in figure 3. Modal damping coefficients (III) are also represented on this plot.

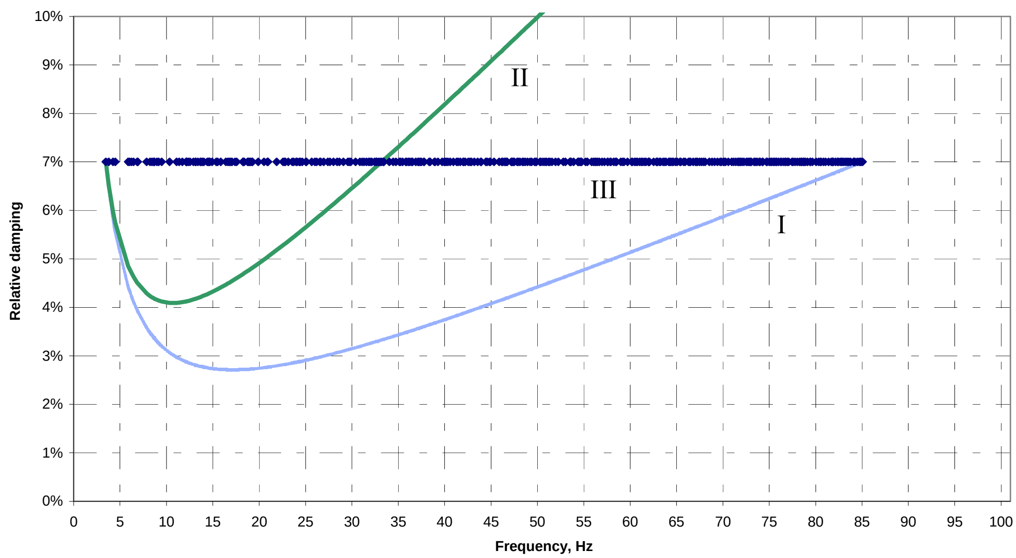

Figure 3 Comparison between Rayleigh damping and modal composite damping.

As can be seen from figure 3, damping on operating frequencies decreases to 2.7%, which is significantly lower, than corresponding modal damping coefficients. Therefore, to decrease conservatism, an attempt to replace Rayleigh damping with modal damping is made in this paper.

Considering Rayleigh damping, we should notice, that if we take, for example, the upper frequency limit 33Hz (boundary frequency for seismic analysis), instead of 85Hz, we can get some decrease of conservatism (plot II on figure 3). But this solution isn't acceptable for aircraft crash analysis, because there is a significant high-frequency loading, that has influence on the whole system response in frequency range higher than 33Hz. And in case of using damping from plot II this influence is nonconservatively lowered because of too high damping on this frequency range.

2. Theoretical overview

To solve the problem of replacing Rayleigh damping matrix on modal damping matrix in direct integration method let us firstly consider some aspects of modal method. This method is based on orthogonal property of global matrices in system of equations of motion. It means that projecting these matrices on eigenmodes basis make them diagonal. Considering matrices of mass and stiffness, there is strong mathematic proof of orthogonal property, but considering damping matrix – it is just a hypothesis, which can be wrong, for example, considering “soil” dashpot, which takes into account radiation damping. But, when considering only material damping, this hypothesis is acceptable. Orthogonal property for material damping matrix C_I looks as follows:

$$\Phi^T C_I \Phi = 2\Omega Z, \text{ where} \tag{4}$$

Φ (NxN) – fundamental matrix, composed of eigenmodes,

$\Omega = daig[\omega_i]$ – diagonal matrix, elements are eigenfrequencies,

$Z = diag[\xi_i]$ – diagonal matrix, elements are modal damping values.

Upper script T means that matrix is transposed.

To obtain detailed matrix C_I from equation 4 we can use following normalization condition of eigenmodes:

$$\Phi^T M \Phi = E \tag{5}$$

Multiplying both parts of this equation on $(\Phi^T)^{-1}$, we obtain:

$$(\Phi^T)^{-1}\, \Phi^T M \Phi = (\Phi^T)^{-1} \text{ or } (\Phi^T)^{-1} = M\Phi \tag{6}$$

Transposing matrix 6, we obtain:

$$\Phi^{-1} = (M\Phi)^T \tag{7}$$

Then multiplying both parts of equation 4 on $(\Phi^T)^{-1}$ on the left and on Φ^{-1} - on the right and considering matrices 6 and 7 we obtain equation for global modal damping matrix:

$$C_I = 2M\Phi\Omega Z(M\Phi)^T \tag{8}$$

Notice, that equation 8 was mentioned earlier, for example in [1, page 112]. But authors demonstrated independent way of obtaining it to show that there is a strong theoretical justification and no restrictions in further usage.

Using the following matrix property:

$(AB)^T=B^TA^T$, we can get:

$$C_1^T=2(M\Phi\Omega Z(M\Phi)^T)^T=2M\Phi(M\Phi\Omega Z)^T=2M\Phi(\Omega Z)^T(M\Phi)^T=2M\Phi\Omega Z(M\Phi)^T=C_1$$

So matrix C_1, defined by equation 8 is symmetric. It is important in further calculations.

To get matrix C_1, all components of the right part of equation 8 were obtained in Abaqus. Then using the additional software, wish damping matrix C_1 was generated. *Matrix input option is not supported in Abaqus with *Dynamic step, but there is a possibility to generate a substructure and to embed it in the model as superelement, suchwise we can get elements with recalculated damping matrix C_1, adopted to Abaqus software.

As noticed above, replacing matrix 1 on matrix 8 in direct integration method leads to significant decrease of conservatism, and this is an obvious advantage. But matrix 8 is fully populated so more computational recourses are needed to realize this method.

3. FE model descriptions and results.

Two following tests were made to verify the method and to analyse advantages of the development.

Test 1.

Forced oscillations of 3 masses on 3 springs, connected consequentially are considered. Loading is a harmonic function $A=A_0 sin2\pi f_2(t)$, where A_0=1.

Test model is represented in figure 4.

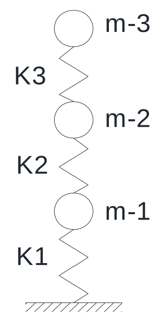

Figure 4. Test 1 model.

Masses are the same and equal to 1kg

Spring stiffnesses: K_1=1300N/m

K_2=3250N/m

K_3=6750N/m

Damping in system is considered 5% and accounted as Rayleigh damping in masses, where α=1.641, β=0, и $\xi=0.5\alpha/2\pi f_1$=1.2%

Eigenfrequencies are: f_1=3 Hz (18.856 rad/s)

f_2=11.3 Hz (70.978 rad/s)

f_3=20 Hz (126.12 rad/s)

As a result of different methods (direct integration method with Rayleigh damping matrix and direct integration method with recalculated damping matrix) of application of harmonic load A=A0sin2πf2(t) to the base of the model, response spectra were obtained. They are represented in figure 5.

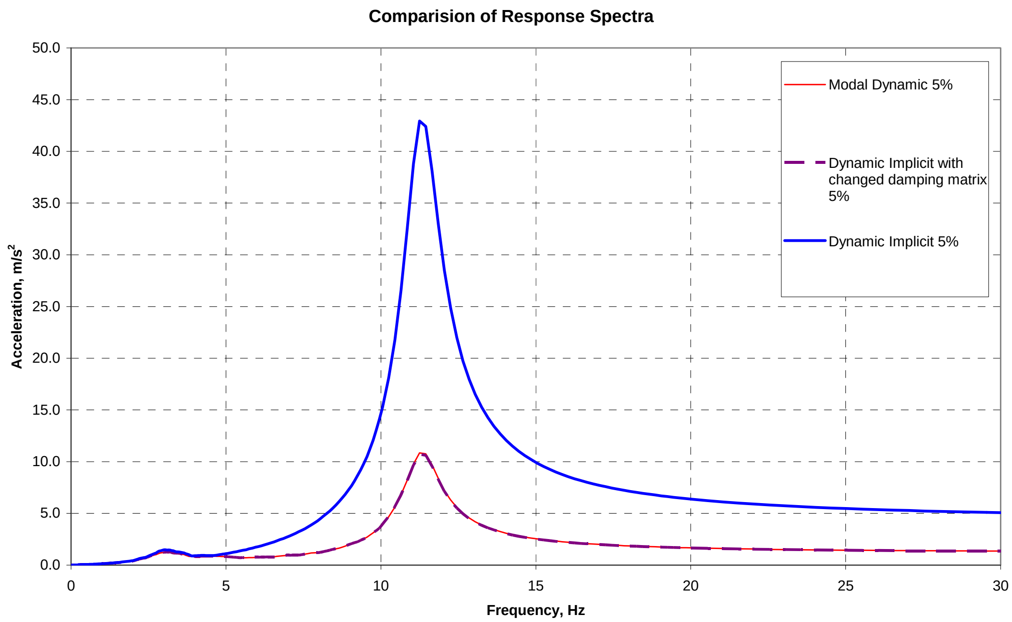

Figure 5. Response spectra in test1.

From figure 5 a significant decrease of spectral acceleration with replaced damping matrix can be noticed on resonance frequency 11.3Hz. This is because of the modal damping value, which is frequency independent and is equal to 5% on all frequency range, and Rayleigh damping on 11.3Hz is about 1.2%. Besides, response spectrum, obtained by modal method, when damping on all 3 modes was 5%, was almost identical to spectrum, obtained by direct integration method with replaced damping matrix. Time increment was constant 0.003s.

Test 2. In this test considered a crash of aircraft type Phantom RF-4E on industrial box-type building with two bridge cranes. Model of the building and its section are represented in figure 6.

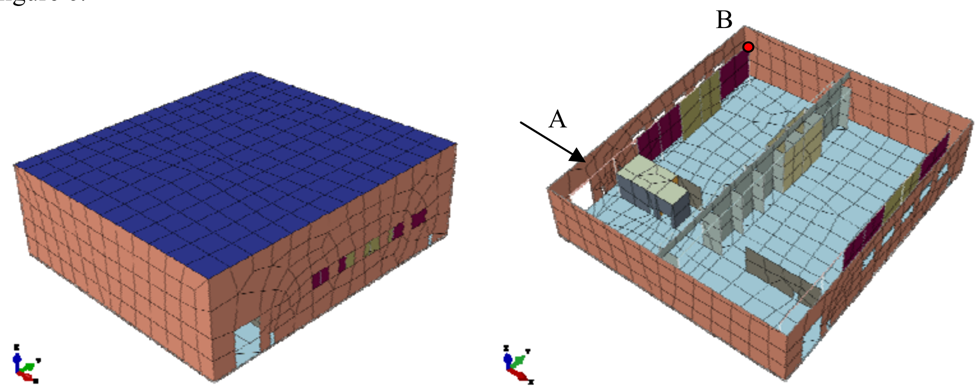

Figure 6. Model of the building from test 2

Building is modelled with shell and beam elements, dimensions of the foundation are 48,3m x 54,9m

Material used: concrete — Young's modulus $3.31 \cdot 10^{10}$ N/m^2

Poisson's ratio 0,2

Damping ratio 7%

Equivalent stiffness and damping of the soil were calculated, considering ASCE 4-98 [3, sect 3.3.4.2.2]. Homogeneous elastic half-space soil was taken with the following properties: Velocity of shear wave – V_s=600m/s, density of the soil – ρ=2.2t/m^3, Poisson's ratio – υ=0.4. Destribution of equivalent stiffness on foundation slab was made with a "saddle" form, equivalent damping was distributed evenly. The solution was made with variable time increment, but not more than 0.0002s. Loading of aircraft crash, represented in figure 1, was applied in point A, and comparative analysis of obtained response spectra (figure 7) in point B (figure 6). From figure 7 a significant difference between spectra can be seen, especially in horizontal directions. Maximal difference is about 30%. But it should be noticed, that on high frequencies (more than 35Hz) sometimes replacing damping matrix leads to enlargement of spectral accelerations, but these frequencies are not interesting in facilities analyses.

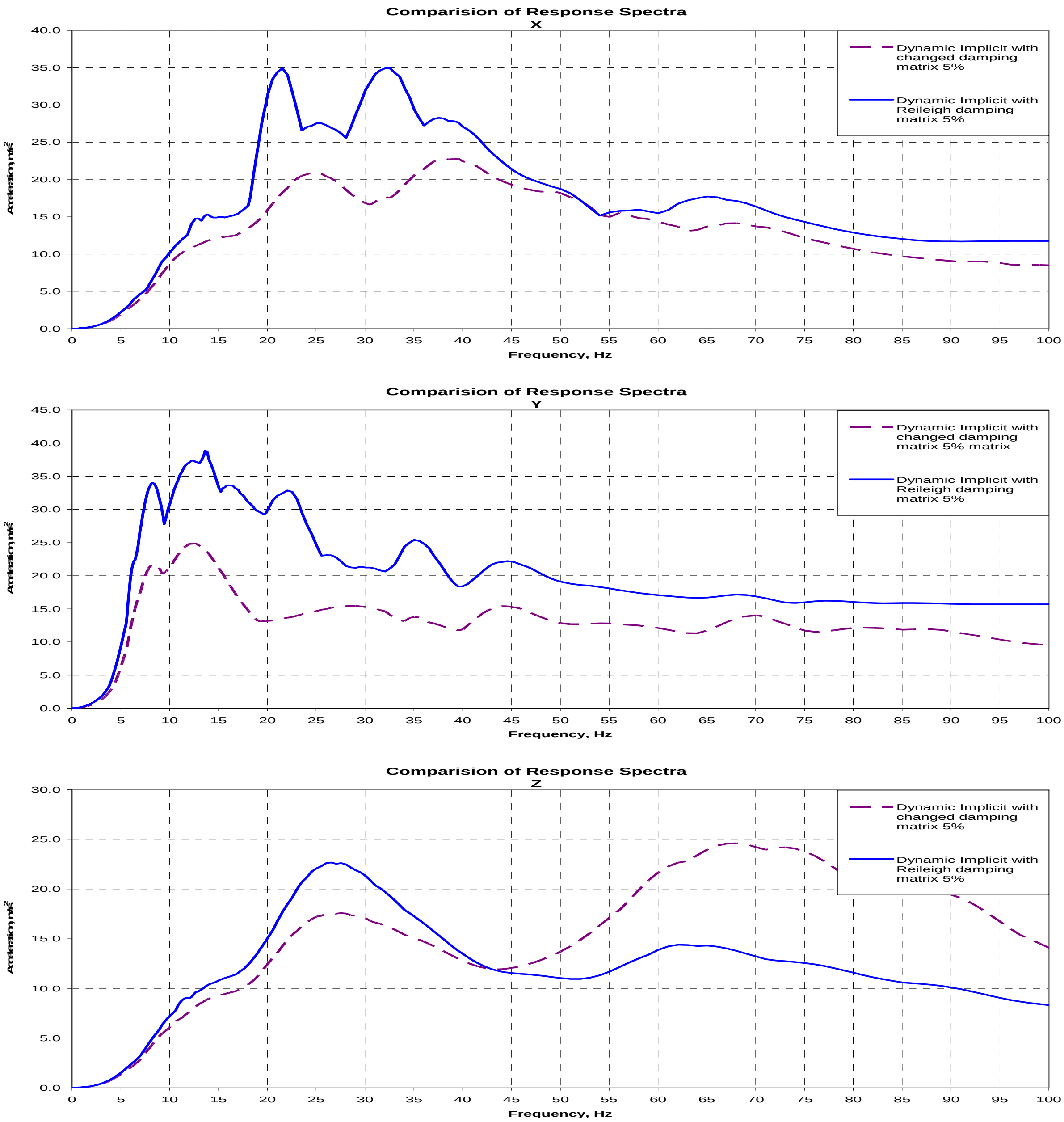

Figure 7. Comparison of response spectra in point B of box-type building.

4. Conclusion.

1. Developed a new method, allowing to use global modal damping matrix instead of Rayleigh damping matrix in direct integration method, while solving dynamic problems

2. Method realisation showed significant decrease of spectral accelerations (up to 30%), which gives positive effect.

3. Method can be used not only for aircraft crash analysis, but also in explosive wave and seismic analyses.

4. Considering high positive effect, authors suggest to include this method in Abaqus software with some improvements.

5. References

1. A.N. Birbraer. Seismic Analysis of Structures. St.-Petersburg, «Nauka», 1998.
2. SIMULIA: Abaqus Analysis User's Manual. Version 6.13
3. ASCE 4-98. ASCE STANDARD. Seismic ANALYSIS of safety Related Nuclear Structures and Commentary. Approval 1992

6. Acknowledgement

The Authors would like to thank Ph.D Bouzinov Pavel, Dassault Systèmes Simulia Corp. (Providence) for the help with adopting global damping matrix in Abaqus environment.