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Research Article

Comparison of two key analysis methods for the seismic stability of equipment on the example of a ventilation unit*

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Abstract

Results of calculation seismic resistance analysis of light equipment of nuclear power plants performed on the example of a ventilation unit using two most common analytical techniques - linear spectral analysis and direct dynamic methods - are discussed.

The basic concepts, assumptions and limitations of the linear spectral method are described. Examples are given of specific calculation cases when the method in question is not applicable in the generally accepted formulation. In particular, the phase difference and, possibly, accelerations (displacements) must be taken into consideration in the calculations of extended spatial structures for mutually remote boundary conditions. Another example are the reservoirs not completely filled with liquids. In such case waves may be formed in the liquid and taking them into account is not possible in the linear spectral method.

Specific features are examined of application of the dynamic analysis method including the input data, approaches and methodologies required for synthesizing the calculated accelerograms. A sequence of operations performed during synthesizing calculated accelerograms is provided, materials are provided containing the description of the mathematical apparatus applied for deriving the final mathematical relations for calculating response spectra and the calculation relations as such are given. The concept of the damping coefficient is explained, its influence on the calculated results and the approaches to its determination are demonstrated. Options with complete absence of damping and with absolute damping are discussed.

A real ventilation set applied in active ventilation systems of nuclear power plants was accepted as the test model. Results calculated for the detailed finite-element model of the ventilation unit using the Zenith-95 software package are presented. These results include the distribution of the calculated reduced stresses. Analysis of the results obtained using the two methods demonstrated overestimation of calculated results by the linear spectral method as compared to those obtained by the dynamic analysis method, which means that the former method underestimates the equipment's resistance to seismic effects. In addition, the dynamic method shows additional areas in the ventilation unit where significant reduced stresses are found while the linear spectral method ignores these areas.

Keywords

Seismic stability; linear spectral method; dynamic analysis method; reduced stresses; accelerogram; finite element model

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Introduction

Modern requirements to the design of equipment and pipelines of NPPs and other objects where nuclear energy is used include the requirements on seismic resistance (NP 031-01 2001). Three categories of seismic stability are singled out, with the first one being the highest. Thus, for instance, for the first category of seismic stability equipment (reactor vessel, spent fuel storage pool racks, cooling loop circulation pumps, elements of the ventilation system, etc.) must remain functional after the earthquake, aircraft crash or the impact of air shock wave. Situations when each of the impacts under discussion superpose on the normal operational conditions together with superposition of design-basis accidents (for instance, fracturing of a cooling loop) must be examined in this case. All the above allows ensuring the required safety performance of the specific reactor facility. However, as pertains to the seismic resistance analysis, there exist a number of uncertainties and assumptions significantly affecting the obtained results.

Comparison of results of seismic resistance analysis performed using two most widely applied methods is of immediate interest. Speaking about heavy equipment, it was demonstrated in (Petrenko et al. 2012, Kangarlu 2012, Shipitsyn 2012) that calculated results obtained using the linear spectral method overestimate actual loads and, consequently, underestimate the seismic resistance by 20 – 40%. Will the above picture be the same for light equipment loaded only with its own weight, which is not significant? This is the main question which is addressed in the present paper. Besides this, associated questions including synthesis of accelerograms of seismic impact are briefly addressed as well.

Methods for calculating seismic resistance

At present the following two calculation methods are the most widely spread: method of direct dynamic analysis and linear spectral method. There exist other, less widely spread, methods, for instance, the method described in (Bulushev et al. 2016).

The first among the above indicated methods presupposes solution of the differential equation describing displacements of the point by the numerical integration methods (PNAEG-7-002-86 1989).

$$\mathbf{M}\cdot\frac{\partial^2}{\partial t^2}\mathbf{U}+\mathbf{C}\frac{\partial}{\partial t}\mathbf{U}+\mathbf{U}+\mathbf{R}=-\mathbf{M}\frac{\partial^2}{\partial t^2}\mathbf{X}, \quad (1)$$

where **M** and **C** are the matrices of masses and damping; **U** and **X** are the displacement vectors for nodes of the system (degrees of freedom) and of supports; **R** is the vector of reactions; t is the time.

In current practice the above set of equations is solved using the finite-element method searching spatial distribution of displacements and other desirable functionals. Information on the displacements in the course of seismic impact (X(t) is the time dependence of displacements of supports) is used as the input data in the solution of Eq. (1). However, accelerograms of accelerations, i.e. the dependence of acceleration on the supports on time, are the most often used. Here, several important assumptions are made: each support behaves as the single rigid body (Mkrtychev and Dzhinchvelashvili 2014) when acceleration accelerograms are used and accelerations are immediately translated from the supports on the whole structure under analysis.

Damping (dissipation of energy) is preset in the damping matrix and determines to a significant extent the results of calculation analysis. Acting regulations recommend setting the value of the damping coefficient to be equal to 2% for all elements and structural nodes. It is important that the results of calculation analysis are determined to a significant extent by the damping coefficient. If the coefficient is preset to be equal to zero, then all energy deposited by the seismic impact is conserved in the analyzed structure (i.e. it is spent on the displacements of its elements). Along with dissipation of energy damping determines the shift of eigenfrequences, which is of significance.

Calculation of the damping coefficient is a separate complex task, solution of which is, in particular, discussed in (Vorobyova et al. 2016, Kutko and Sorokin 2013, Edwards and Penney 2008). It has to be noted that it is customary to represent damping as the sum of elastic and inelastic components (ANP-0264NP 2010, Petrov et al. 2002).

Direct dynamic analysis method is realized in the majority of software complexes. This instrument of analysis of seismic resistance allows taking into account all types of nonlinearities of the structure under analysis. All kinds of contacts (Miryakha 2015, NUREG-1061 1985), plastic deformations, permissible displacements of elements (for example, rotation of a wheel, accounting for the effects of waves in the liquids (Sakharov and Evdokimenko 2015)) can be used as the examples of non-linearity. The obtained results are relatively easy for interpretation and are in conformity with understanding about the physics of the processes. However, one of the main drawbacks of this method is the necessity of expenditure of significantly larger computational resources.

Linear spectral method is currently the most widely used. It is widely applied both in Russia and abroad and represents, in general terms, the symbiosis of dynamic and quasi-dynamic analyses. Affinity to the quasi-dynamic method resides in the fact of calculation of seismic inertial loads s_i which are applied to the centers of mass m_i of the system under examination. Following this the structure is calculated to determine the effects of inertial forces s_i statically applied to the examined system. Dynamics of the structure is taken into account in the determination of loads s_i finding which constitutes the main element of analysis of seismic stability.

Seismic impact is determined for each form of seismic vibrations from the following relation:

$$s_{ij} = m_{ij} \cdot \eta_{ij} \cdot w_j, \tag{2}$$

where s_{ij} is the seismic load for the j-th form of seismic vibrations acting on the mass m_{ij}; n_{ij} is the eigenform factor taking into account the projection of the eigenform on the current coordinate plane; w_i is the acceleration for the j-th form for the response spectra of fastenings of the structure. Product of free-fall acceleration by the dynamic response factor depending on the period for j-th form of vibrations T_i, inelastic resistance coefficient γ_i and the type of the impact (calculated accelerogram of the base).

Formula (2) is derived from the equation for vibrations of arbitrary multi-mass system. The main assumption in its derivation is the small effect of damping on the relation between the forms of vibrations. This condition is satisfied in the examination of structures when for all elements the inelastic resistance coefficient is below 0.3.

Spectral method is accepted at present as the main method in regulatory documents acting in construction engineering (SP 14.13330.2014 2014) including construction of NPPs (NP 031-01 2001).

Despite the abundant assumptions inherent to the linear spectral method, this methodology demonstrates satisfactory agreement with observed results. However, within the framework of this method there exist different approaches to the determination of the final seismic load knowing the loads for different forms of vibrations (Ushakov 2015). This is the reason why recommendations in (Vorobyova et al. 2016, BNL-NUREG-66410 1999) prescribe determination of the final seismic load as the root-mean-square value of the sum of loads for each node of the analyzed system for separate forms of vibrations in order to ensure the required level of conservatism.

Significantly lower expenditures of computational resources for performing calculations are the main advantage of the linear spectral method. This method was often applied for performing manual calculations without the use of computers (Birbraer 1998). Drawbacks of the method are reflected in its name since non-linearity is not accounted for and, in particular, displacements for stretching and compression are assumed to be the same, which is not always true.

Accelerograms

One of the problems emerging in the use of the dynamic method for seismic resistance analysis of equipment and pipelines is the lack of accelerograms and information about displacements in the process of seismic impact. As a rule, calculations with determination of seismic response spectra for different elevations of installation of equipment are performed within the framework of development of project of seismically resistant building.

Dynamics of seismic impact on the ground surface of the base can be selected on the basis of comparison of geological conditions and estimation of the distance to the nearest epicenter of the earthquake according to the data of seismic observations. However, such approach is absolutely not applicable to the presetting seismic impact on the equipment installed inside the building. Dynamics of construction structures must be taken into account here. Unfortunately, Russian national regulations in nuclear power engineering do not contain easily understandable recommendations on the synthesis of accelerograms for analysis of seismic resistance of equipment. The only guidance is provided in (RB 006-98 2000) and even these instructions are limited enough.

Two different approaches are used in construction for obtaining seismic impact accelerograms: synthesis on the basis of a package of close accelerograms registered during observations (Mkrtychev and Reshetov 2015); synthesis of accelerogram as a random process with the preset level of maximum acceleration of the base (depends on the magnitude of the earthquake and on the geological conditions).

The following conditions must be satisfied in case when the package of accelerograms is applied: 1) representability of the accelerograms in the package, which amounts to the overlapping by the prevailing period of the whole range of variation of possible periods of seismic impact; 2) absence of serious distortions in the calculated accelerograms; 3) taking into account correlation between the calculated degree of intensity, magnitude and prevailing frequency of the impact. Synthesized accelerogram must produce after integration seismic response spectrum close to that preset in the design project.

Synthesis of accelerograms using generation of random process during the short interval of time found its application along with the synthesis of the calculated accelerogram using the data from the package of real accelerograms. Already at the dawn of elaboration of seismic resistance theory its founders in the name of Professors Mononobe and Suehiro performed modeling of seismic impact using section of the function $x''(t) = A \cdot sin\ (\omega \cdot t)$ (Haskin and Ivanov 2005). Another widely spread model of seismic impact was suggested by I.L. Korchinsky (Korchinsky et al. 1961): $x''(t) = A \cdot exp(-\xi \cdot t) \cdot sin\ (\omega \cdot t)$ (Haskin and Ivanov 2005), where ξ is the damping coefficient. The latter relation takes into account only the prevailing frequency of the impact on which all seismic energy is concentrated. Other more complex approximations are applied in order to account for the real spectrum of the seismic impact.

Modern methodologies (Drunovtseva 2013, Kumar Ashok 2004) presuppose the synthesis of accelerograms according to the designed seismic response spectrum according to the following sequence: 1) generation of the random process with random magnitudes and phase shifts; 2) normalization of random magnitudes by the maximum acceleration (zero-period acceleration) either preset in the design spectrum, or determined according to the preset

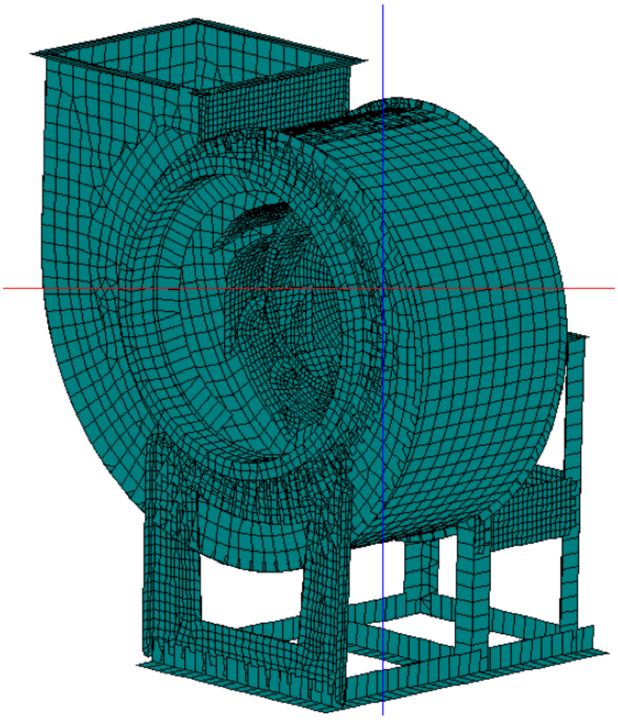

Figure 1. Model of the ventilator

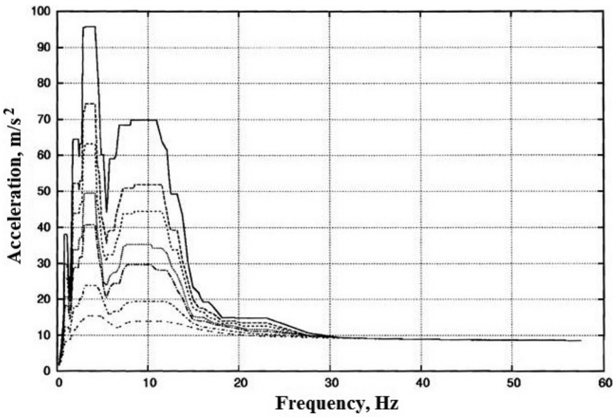

Figure 2. Designed spectrum of seismic impact. Vertical component.

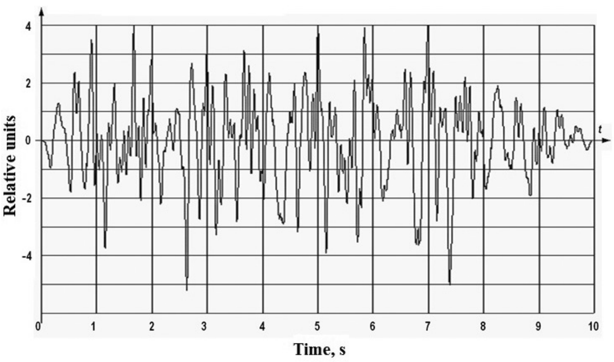

Figure 3. Synthesized accelerogram of the seismic impact. Vertical component.

earthquake magnitude; 3) fine tuning of phase shifts and magnitudes of the generated random process in such a way as to achieve coincidence of the response spectrum with the design one. Here, a number of requirements on the discretization of the frequency band and time interval during synthesis of accelerograms are satisfied (Durnovtseva 2013a). Thus, time step must not be less than 0.01 s. Methodologies for constructing the response spectrum are not provided in the Russian national documents and are accessible only in documentation such as (Gupta Ajaya 1990, Xing et al. 2004). It has to be noted that the approaches per se to the synthesis of accelerograms and their implementation contain a number of unresolved issues. As it is demonstrated by the experience of synthesis of accelerograms, when reliable methodologies are applied main part of computer time is expended for the construction of calculated response using accelerograms, and not on the generation of the accelerograms as such.

Comparative analysis of the two methods using the example of design of the ventilator unit of the positive pressure ventilation system of the NPP

Design of real radial ventilation unit applied in the special ventilation systems of NPPs was used for comparison of calculations performed by the spectral and dynamic methods. Calculations were performed by the finite-element method for the detailed model of the ventilation unit developed in the Zenith-95 software complex (Zenith-95 2015) (see Fig. 1). Zenith-95 software complex used in the calculations allows solving wide spectrum of static and dynamic problems by the finite-element method and has a wide spectrum of types of finite elements.

The material of the ventilator model is stainless steel. Internal diameter of the round flange if equal to 500 mm. Upper flange is square-shaped with internal dimension equal to 350 mm. The motor in the model is represented as the absolutely rigid body with mass equal to 18 kg. The motor is connected to the fan propeller via the shaft with diameter equal to 24 mm. Internal pressure was not preset. The ventilator is rigidly fixed to the lower nodes of the rack frame. Coupling of the elements was achieved by the following two methods. In the first case the parts were coupled by way of "joining" the nodes, and in the second case it was achieved by the parts interacting via the "rigid" contact (analogue of welding) preset over the surfaces of the joint.

Spectra of interactions of the real building of the NPP in two mutually perpendicular directions and in one vertical direction were used for the calculation. Spectrum of seismic impact in the vertical direction is represented in Fig. 2. Spectrum for seismic impact in horizontal directions differs from that presented in Fig. 2, but, however, it is not provided here because of its cumbersomeness.

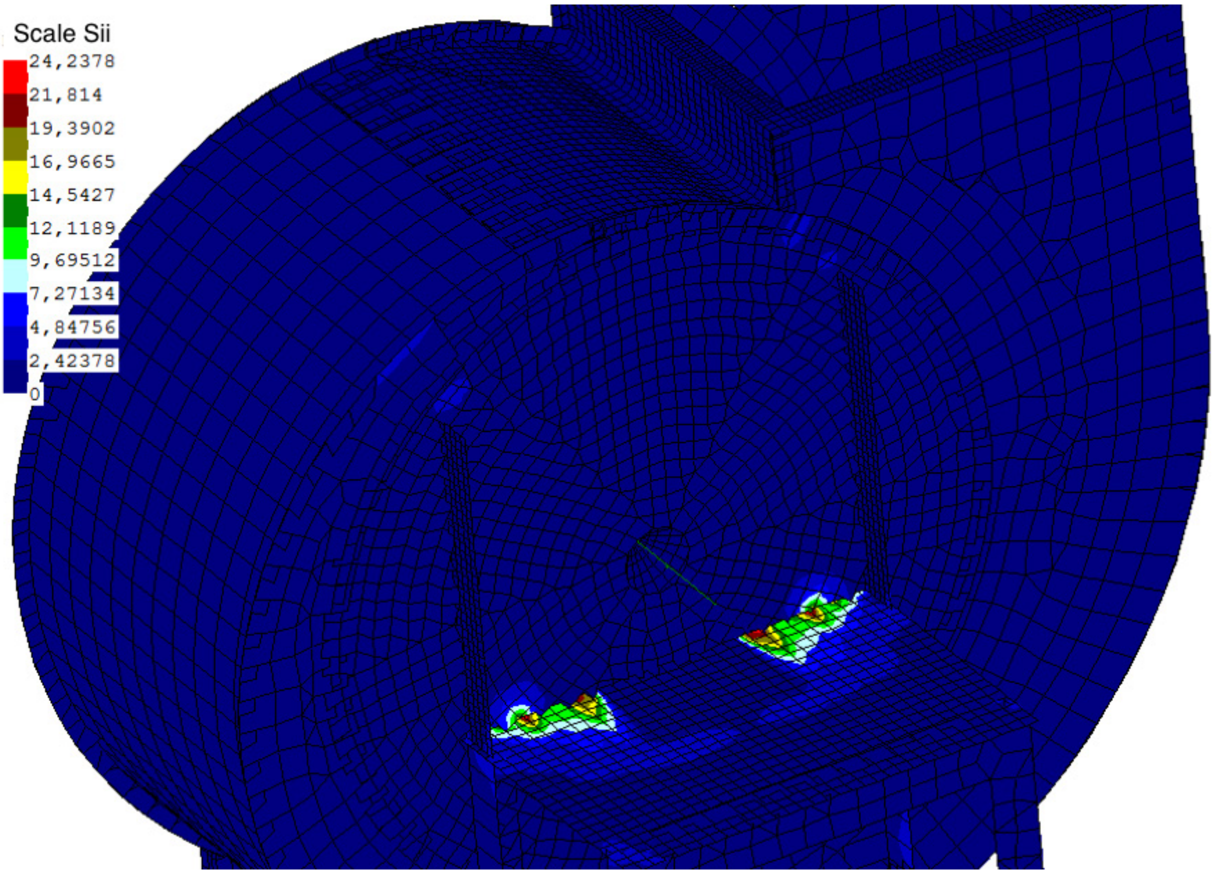

Figure 4. Amplitude values of reduced stresses calculated for the ventilator by the dynamic analysis method, MPa.

Modern methodologies described in (Gaberson 1981) were applied for synthesizing calculated accelerograms. Synthesized accelerogram of seismic impact in vertical direction is shown in Fig, 3. Accelerograms for two vertical directions are different from that presented in Fig. 3, however, they are not addressed here as well.

Maximum reduced stress in the ventilator in the analysis of seismic resistance by the method of direct dynamic analysis amounts to 24.2 MPa (Fig. 4). The software provides the possibility of animation scanning variation of stresses for the model during the whole time interval of the seismic impact. It is also possible to obtain the time dependence of variation of stress in the node (Fig. 5) allowing estimating the time moment when maximum stress occurs. In the case in question maximum stresses appear within the interval between 6.8 and 6.9 seconds. Calculation by spectral method shows that maximum reduced stress amounts for the model to 34.6 MPa (Fig. 6). As it is evident from Figs 4, 6, nodes where maximum stresses occur coincide in both cases, but, however, the values of highest stresses obtained by two different methods differ from each other by 30%.

It follows from the obtained results that spectral method using integral characteristics of the seismic impact produces overestimated calculated values of stresses, thus underestimating the real characteristics of seismic resistance of the equipment. In other words, when strength criteria are to be substantiated for the equipment for the

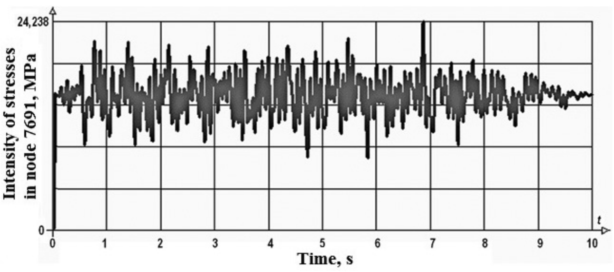

Figure 5. Time variation of calculated stresses in the critical node.

seismic impact using the results of linear spectral calculation it will be guaranteed that these criteria will be satisfied (by wide margins) when dynamic analysis is applied. Despite the fairly similar picture of stresses, additional stressed areas are present in the ventilator model calculated using the dynamic method. Presence of these stressed areas indicates the advantage of the method in question consisting of the more detailed description of operation of the structure during seismic process.

If computer time resources required for performing calculations by the two methods are compared, then the CPU time needed for performing the dynamic calculation is by one – two orders of magnitude higher than that for the spectral calculation.

Thus, when detailed estimation of the behavior of the structure or its separate elements during seismic impact or in the course of analysis of especially important equip-

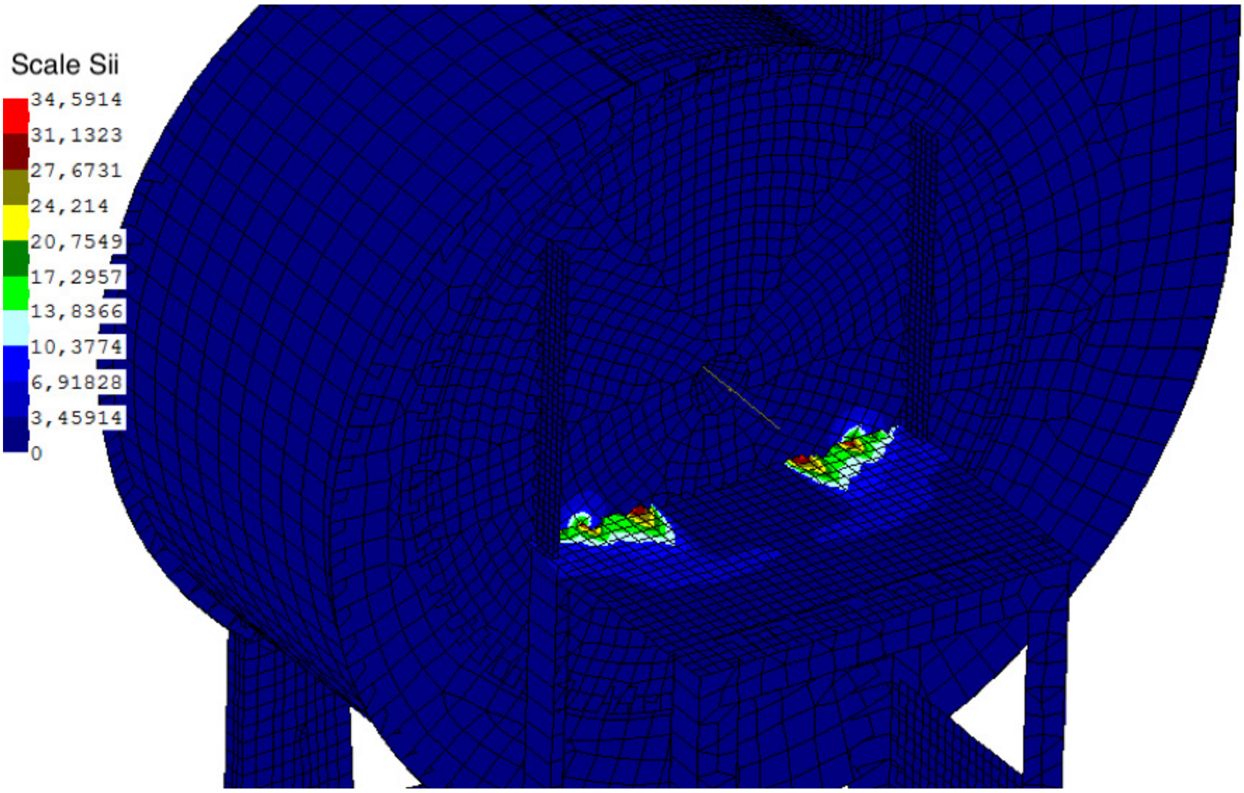

Figure 6. Amplitude values of reduced stresses of the ventilator calculated by linear spectral method, MPa.

ment (reactor vessel, steam generator, etc.) is needed, then the method of direct dynamic analysis should be applied. Application of linear spectral method underestimating seismic resistance due to the shifting of calculated functionals characterizing seismic resistance at its worst will be sufficient in case when seismic stability must be estimated as a whole without taking a close look at the specific features of dynamics of the impact from seismic process on the structure under analysis with economy of expenditures of computational and time resources.

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