THE SEISMIC RESPONSE AFFECTION OF THE NUCLEAR REACTOR WWER 1000 BY NUCLEAR FUEL ASSEMBLIES

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The paper deals with mathematical modelling and computer simulation of the seismic response of chosen components of the nuclear WWER 1000 reactor. The seismic response is investigated by numerical integration method in time domain. The seismic excitation is given by two horizontal and one vertical synthetic accelerograms at the level of the pressure vessel seating adjusted for a certain damping value 5 %. The main aim of the paper is seismic response assessment for two variants of nuclear fuel assemblies – VVANTAGE 6 and TVSA-T. The maximal values of displacements and linkages or component deformations are compared for both fuel assembly variants.

Keywords: *reactor vibration, identification, seismic response, accelerogram*

1. Introduction

One of the basic operation conditions of the nuclear reactor is the guarantee of the feasible seismic response. Two basic approaches can be applied to seismic response determination. The stochastic approach [1] is based on statistics of loading process and on the parameters of vibrating system. For the sake of simplicity, it is mostly supposed to stochasticity is solely due to the loading process, while the vibrating system is considered as a deterministic one. The deterministic approach is based on description of the seismic excitation in either analytical or digital form.

The seismic action is most often represented by the response spectrum in displacement, pseudo-velocity or pseudo-acceleration [2] in the analytical form as a function of the eigenfrequency and relative damping of a simple oscillator. The seismic response is calculated by the response spectrum method based on different combination of vibration mode contributions [3]. The specific method of response spectrum method, so called missing mass correction method, includes the high frequency rigid modes into the system response pseudostatically [4]. The seismic action in the digital form is represented by synthetic accelerograms corresponding to given response spectra generally for damping value 5 % for ground spectra and 2 % for floor spectra [2]. Both deterministic approaches require command the mathematical model of the reactor for frequency area up to about 50 Hz.

Authors of this article have concerned with modelling of the nuclear WWER 1000 type reactor in co-operation with Nuclear Research Institute, Řež, p.l.c. and ŠKODA Nuclear Machinery, Co. Ltd. more than one decade. The linearized spatial model of the WWER 1000/320 type reactor of the NPP Temelín, intended for dynamic response calculation excited by pressure pulsations generated by main circulation pumps, was derived as late as the year 2006 [5], [6]. This model was corrected by considering primary circuit

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influence [7] and more accurately modelling of the total vertical contact stiffness in the suspension of the core barrel to the pressure vessel flange and guide wedge stiffnesses [8].

The goal of the paper is to modify the mathematical model of the WWER 1000 type reactor presented in [9] and to use it for analysis of seismic response affected by nuclear fuel assembly (FA). Motivation to this research work was exchange the American nuclear VVANTAGE 6 FA for Russian TVSA-T FA in NPP Temelín.

2. Identification of fuel assembly model

Nuclear fuel assemblies are in term of mechanics very complicated systems of beamed type composed of absorption control and fuel elements shaped in to spacer grids. It is possible to replace them approximately by one dimensional continuum of beamed type with mass concentrated into chosen nodes. Experimentally gained eigenfrequencies and eigenvectors, investigated by measurement in the air, serve as initial data for parametric identification of the TVSA-T fuel assembly, analogous to identification of the VVANTAGE 6 fuel assembly [10].

Mass matrix $\mathbf{M} = \mathrm{diag}[m_i]$ of the identified FA is diagonal, where m_i, $i = 1, 2, \ldots, n$ are masses concentrated in chosen nodes at FA axis. Let $\mathbf{v}_j$, $j = 1, 2, \ldots, n$ are experimentally gained eigenvectors of plane lateral FA vibrations in terms of definite boundary conditions. The coordinates of eigenvectors are FA lateral displacements in nodes. The orthogonal properties of the eigenvectors $\widetilde{\mathbf{v}}_i$ and $\widetilde{\mathbf{v}}_j$, corresponding to different eigenfrequencies $\Omega_i \neq \Omega_j$, $j \in \{1, 2, \ldots, n\}$ and normalized by M- (mass) norm, are defined by relations

$$\widetilde{\mathbf{v}}_i^{\mathrm{T}}\, \mathbf{M}\, \widetilde{\mathbf{v}}_j = \delta_{ij} \ ; \qquad \widetilde{\mathbf{v}}_i^{\mathrm{T}}\, \mathbf{K}\, \widetilde{\mathbf{v}}_j = \Omega_j^2\, \delta_{ij} \ , \tag{1}$$

where $\mathbf{K}$ is stiffness matrix and δ_{ij} is Kronecker's symbol. For every eigenvector $\widetilde{\mathbf{v}}_j$ exists square matrix $\mathbf{X}_j$ of order n, satisfying the condition

$$\mathbf{M}\, \widetilde{\mathbf{v}}_j = \mathbf{X}_j\, \mathbf{m} \ ; \qquad \mathbf{m} = [m_i] \ . \tag{2}$$

The matrix $\mathbf{X}_j$, in consequence of diagonal mass matrix $\mathbf{M}$, is diagonal too. From equations (1) and (2) results $\widetilde{\mathbf{v}}_i^T \mathbf{X}_j \mathbf{m} = \delta_{ij}$; $i, j = 1, \ldots, n$ and for all $i, j \geq i$ we obtain the system of algebraic equations in the form

$$\begin{bmatrix} \widetilde{\mathbf{v}}_1^{\mathrm{T}}\, \mathbf{X}_1 \\ \vdots \\ \widetilde{\mathbf{v}}_1^{\mathrm{T}}\, \mathbf{X}_n \\ \widetilde{\mathbf{v}}_2^{\mathrm{T}}\, \mathbf{X}_2 \\ \vdots \\ \widetilde{\mathbf{v}}_2^{\mathrm{T}}\, \mathbf{X}_n \\ \vdots \\ \widetilde{\mathbf{v}}_n^{\mathrm{T}}\, \mathbf{X}_n \end{bmatrix} \mathbf{m} = \begin{bmatrix} 1 \\ \vdots \\ 0 \\ 1 \\ \vdots \\ 0 \\ \vdots \\ 1 \end{bmatrix} \tag{3}$$

or shortly

$$\mathbf{A}\, \mathbf{m} = \boldsymbol{\delta} \ . \tag{4}$$

The matrix $\mathbf{A}$ is regular and rectangular of type $(n(n+1)/2, n)$. The vector of identified masses can be written in the form

$$\mathbf{m} = \mathbf{m}_0 + \Delta\mathbf{m} \ , \tag{5}$$

where $\mathbf{m}_0$ is estimated starting mass vector and $\Delta\mathbf{m}$ is mass correction vector. Since matrix $\mathbf{A}$ is rectangular, the mass correction vector can be expressed using pseudoinverse matrix

$$\Delta\mathbf{m} = \mathbf{A}^{+}\,\boldsymbol{\delta} - \mathbf{m}_0\ . \tag{6}$$

Eigenvectors must satisfy the M-norm condition namely before and after correction. That is why experimentally gained eigenvectors are in (3) replaced by vectors

$$\widetilde{\mathbf{v}}_j = \frac{\mathbf{v}_j}{\sqrt{\displaystyle\sum_{i=1}^{n} m_i\, v_{ij}^2}}\ ; \qquad \mathbf{v}_j = [v_{1j}, \ldots, v_{nj}]^{\mathrm{T}}\ . \tag{7}$$

Relations (5), (6) and (7) take up iterative. For $r = 0, 1, \ldots$ step by step we calculate

$$\Delta\mathbf{m}^{(r)} = (\mathbf{A}^{(r)})^{+}\,\boldsymbol{\delta} - \mathbf{m}^{(r)}\ , \tag{8}$$

$$\mathbf{m}^{(r+1)} = \mathbf{m}^{(r)} + \Delta\mathbf{m}^{(r)} \Rightarrow m_i^{(r+1)} = m_i^{(r)} + \Delta m_i^{(r)}\ , \tag{9}$$

$$\widetilde{\mathbf{v}}_j^{(r+1)} = \frac{\widetilde{\mathbf{v}}_j^{(r)}}{\sqrt{\displaystyle\sum_{i=1}^{n} m_i^{(r+1)}\,(\widetilde{v}_{ij}^{(r)})^2}}\ . \tag{10}$$

The starting mass vector $\mathbf{m}_0$ and experimentally gained eigenvectors normed by M-norm describe the zero iteration

$$\mathbf{m}^{(0)} = \mathbf{m}_0\ ; \qquad \widetilde{\mathbf{v}}_j^{(0)} = \frac{\mathbf{v}_j}{\sqrt{\displaystyle\sum_{i=1}^{n} m_i^{(0)}\, v_{ij}^2}}\ .$$

The end of the iteration process is determined by achievement of a relative small change of the mass parameters

$$\sum_{i=1}^{n} \frac{|\Delta m_i^{(r)}|}{m_i^{(r)}} < \varepsilon\ ,$$

where ε is a small global relative mass correction. The stiffness matrix $\mathbf{K}^{(r)}$ is determined after iteration process termination from the inverse relation of the second orthonormal condition in (1)

$$\mathbf{K}^{(r)} = (\mathbf{V}^{(r)})^{-\mathrm{T}}\ \mathrm{diag}[\Omega_i^2]\,(\mathbf{V}^{(r)})^{-1}\ . \tag{11}$$

Along iteration process, the condition of the total FA mass $M_0 = \sum_{i=1}^{n} m_i^{(0)}$ is disturbed. Final replacement of the fuel assembly by the beam is characterized by diagonal mass matrix and full symmetric stiffness matrix

$$m_i = \frac{m_i^{(r)}}{\displaystyle\sum_{i=1}^{n} m_i^{(r)}}\, M_0\ ; \qquad \mathbf{K}_{\mathrm{FA}} = \frac{M_0}{\displaystyle\sum_{i=1}^{n} m_i^{(r)}}\, \mathbf{K}^{(r)} \tag{12}$$

of order n. The influence of the coolant surrounding FA was approximately respected by additional masses Δm_i resulting from FA eigenfrequencies decreasing and conservation of FA eigenmodes. Every fuel assembly is constrained in vertical direction with bottom supporting plane (SP) by spring k_{FA} (see Fig. 1) in the top nozzle of FA.

3. Shortly to computational and mathematical model of the reactor

Mathematical model of the WWER 1000/320 type reactor is based on computational (physical) model, whose structure is shown in Fig. 1. It was derived in [9] by the decomposition method presented in [5] and modified by considering the main circulating loop influence [3].

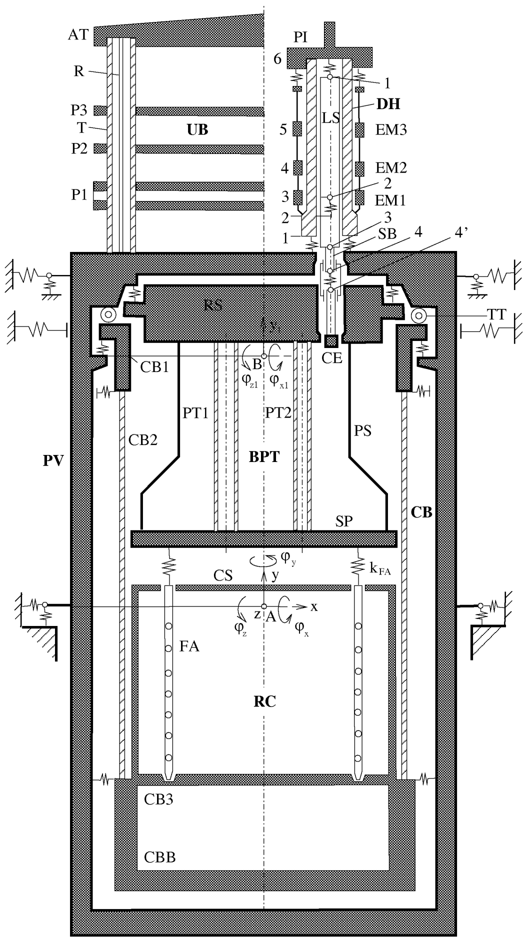

Fig.1: Scheme of the reactor

The reactor was decomposed to eight subsystems:

1. Pressure vessel (PV) with top head mounted on a building well at the point A level.
2. Core barrel (CB) composed from two rigid bodies (CB1 and CB3) which are connected by one-dimensional beam-type continuum (CB2). The lower part of core barrel (CB3) includes core barrel bottom (CBB) and core shroud (CS).

3. Reactor core (RC) formed from 163 nuclear fuel assemblies (FA).
4. Block of protection tubes (BPT) composed from relative rigid shell (RS) and supporting plate (SP). These components are connected by system of 61 protection tubes (PT1), 60 different type protection tubes (PT2) and perforated shell (PS).
5. Supporting structure of upper block (UB) composed from the three plates (P1, P2, P3) and assembly traver (AT) which are mutually connected by 6 tubes (T) and 6 circular rods (R) placed inside the tubes.
6. System of 61 control rod drive housing (DH) with position indicators (PI) which make up a pressure barrier between the reactor coolant system and the room above the reactor head.
7. System of 61 electromagnet blocks (EM) consisted of pulling (EM1), retaining (EM2) and holding (EM3) electromagnets which ensure the function of the lifting system mechanisms and hence a motion of the suspension bar. The electromagnets in one block are linked to the control drive housing by tubes placed outside the housing.
8. System of 61 drive assemblies (DA) for an actual drive operation placed inside the drive housing. The drive assembly is composed from a lifting system mechanism (LS) which ensures a suspension bar (SB) motion with the control element (CE). The suspension bar is divided into upper and lower part with a bayonet joint for connecting with the control element. There is an elastic mounting between the upper and lower suspension bars. All components are axe-symmetric cylindrical bodies which can be modelled as one-dimensional continuum.

The mass and static stiffness of the primary coolant loops between a reactor pressure vesel nozzles and steam generators were approximately replaced by mass points and springs placed in gravity centers of the nozzles. The components marked grey in Fig.1 were reflected as rigid bodies with six or three degrees of freedom. Other components are modelled as one-dimensional continuums of beam types. Each fuel assembly VVANTAGE 6 or TVSA-T was replaced with a beam whose mass was concentrated in seven mass points. The diagonal mass matrix and symmetric stiffness matrix of the fuel assembly were identified on the basis of seven eigenfrequencies and mode shapes measured for VVANTAGE 6 in ŠKODA Nuclear Machinery [10] and for TVSA-T published in [11] using the identification method described in section 2. Each fuel assembly was simply supported at both ends in top and bottom nozzle position.

The eigenfrequencies of the both type fuel assemblies, presented in Table 1, were measured in the air. The relative errors of the replaced beam eigenfrequencies $\Omega_\nu^{(r)}$, $\nu = 1, 2, \ldots, 7$ with respect to measured eigenfrequencies $\widetilde{\Omega}_\nu$ defined by $|\Omega_\nu^{(r)} - \widetilde{\Omega}_\nu|/\widetilde{\Omega}_\nu$ and identified masses in successive iterations are presented in Table 2 and 3.

Generalized coordinates of subsystems in global vector $\mathbf{q}$ are chosen as relative with respect to the supporting subsystem. For the core barrel (CB), block of protection tubes (BPT), supporting structure of upper block (UB), drive housing (DH) and drive assemblies

FA type	Measured eigenfrequencies $\widetilde{\Omega}_\nu$ [rad/s]						
	1	2	3	4	5	6	7
VVANTAGE 6	21.4	45.3	77.0	115.6	145.5	186.3	215.8
TVSA-T	25.7	55.9	85.5	114.9	144.5	176.0	207.4

Tab.1: Measured eigenfrequencies of fuel assembly

(DA) the supporting subsystem is the pressure vessel (PV). For reactor core (RC) the supported subsystem is core barrel bottom (CBB) and for electromagnet blocks (EM) it is drive housing (DH) (see Fig. 1).

FA type	r	Relative errors of the eigenfrequencies [%]						
		1	2	3	4	5	6	7
VVANTAGE 6	1	0.0312	3.964	5.294	8.447	8.641	0.6576	3.459
	2	0.0054	0.036	0.0066	0.0453	0.0691	0.6462	1.157
	3	0.0057	0.0675	0.0205	0.0055	0.0243	0.6072	1.067
TVSA-T	1	0.0043	0.0197	0.0191	0.0827	0.0772	0.0024	0.3245
	2	0.0029	0.0143	0.0113	0.0605	0.1330	0.0003	0.398
	3	0.0029	0.0143	0.0124	0.0605	0.1330	0.0003	0.3979

Tab.2: Relative errors of the fuel assembly eigenfrequencies

FA type	r	Identified masses $m_i^{(r)}$ [kg] in nodes							
		1	2	3	4	5	6	7	m_0
VANTAGE 6	0	110.75	95.5	95.5	95.5	95.5	95.5	152.9	741
	1	148.03	89.37	79.66	102.61	110.15	123.41	87.98	
	2	147.7	89.37	79.69	102.75	110.29	123.4	87.92	
	3	147.69	89.36	79.69	102.75	110.29	123.41	87.93	
TVSA-T	0	97.0	110.35	110.35	110.35	110.35	110.35	101.26	750
	1	98.38	106.67	109.53	110.68	110.81	109.6	104.33	
	2	97.32	108.92	111.79	112.37	111.68	108.9	99.02	
	3	99.76	109.09	112.1	112.67	111.96	108.99	98.42	

Tab.3: Identified masses of the fuel assembly

The conservative mathematical model of the reactor with corresponding fuel assemblies, characterized by mass **M** and stiffness **K** matrices, was created using decomposition method described in [5] and in detail in research report [12]. The vibrations of the all fuel assemblies (FA), protection tubes (PT1 and PT2), and components of linear stepping drives (DH, EM, DA) were supposed identical for each continuum of the same kind. The influence of the primary circuit was approximately respected by additional masses and stiffnesses inserted into centres of reactor pressure vessel nozzles on the basis of equivalent kinetic and potential energy [7]. The generalized coordinates of all subsystems are presented in Table 4.

All parameters of the reactor components are specified in the research reports [3], [13].

Subsystem	Generalized coordinates	Sequence in $\mathbf{q}$
PV	$x, y, z, \varphi_x, \varphi_y, \varphi_z$	1–6
CB	$y_1, \varphi_{x1}, \varphi_{z1}, x_2, \dots, \varphi_{z2}, x_3, \dots, \varphi_{z3}$	7–21
RC	$x_1, \dots, x_7, y_1, \dots, y_7, z_1, \dots, z_7$	22–42
BPT	$y_1, \varphi_{x1}, \varphi_{z1}, x_2, \dots, \varphi_{z2}$	43–51
UB	$x_1, \dots, \varphi_{z1}, \dots, x_4, \dots, \varphi_{z4}$	52–75
DH	$x_1, \dots, \varphi_{z1}, \dots, x_6, \dots, \varphi_{z6}$	76–111
EM	$y_1, \dots, y_4, \varphi_{y1}, \dots, \varphi_{y4}$	112–119
DA	$y_1, \varphi_{y1}, y_2, \varphi_{y2}, x_3, \dots, \varphi_{z3}, x_4, \dots, \varphi_{z4}, y_4', y_5$	120–137

Tab.4: The generalized coordinates of the reactor subsystems

The lower eigenfrequencies f_ν [Hz] of the reactor conservative model with both alternatives of the fuel assemblies in frequency range 0–20 Hz, with corresponding eigenmodes characterized by dominantly vibrating components, are presented in Table 5 (more in research report [13]).

Eigenfrequencies [Hz]				Eigenmode characterization
VVANTAGE 6		TVSA-T		
1, 2	3.00	1, 2	3.65	lateral of fuel assemblies (1.mode)
3	4.16	3	4.16	vertical of drive assemblies
4, 5	5.06	4, 5	5.06	lateral of supporting structure of upper block (1st mode)
6, 7	6.35	7, 8	7.98	lateral of fuel assemblies (2nd mode)
8	6.7	6	6.7	torsion of supporting structure of upper block (1st mode)
9, 10	8.88	9, 10	8.88	lateral of drive housing with electromagnet blocks in phase with drive assemblies
11, 12	9.33	11, 12	9.33	lateral of drive housing with electromagnet blocks in opposite phase with drive assemblies
13, 14	10.8	13, 14	12.1	lateral of fuel assemblies (3rd mode)
15, 16	16.2	15, 16	16.4	lateral of fuel assemblies (4th mode)
17, 18	17.6	17, 18	17.6	lateral of supporting structure of upper block (2nd mode)
19	18.8	19	19.0	vertical of lifting system mechanisms
20, 21	19.0/19.4	21, 22	19.7	rocking of pressure vessel in phase with core barrel
22	19.7	20	19.3	torsion of pressure vessel, core barrel with reactor core and supporting structure of upper block (2nd mode)

Tab.5: Eigenfrequencies of the reactor WWER 1000/320 type

4. Seismic response of the reactor

The mathematical model of the reactor after discretization by the one-dimensional continua and in consequence of the hypothesis of identical vibrations of same type continua and after completion of the damping approximated by proportional damping matrix $\mathbf{B}$ has the form

$$\mathbf{M}\,\ddot{\mathbf{q}} + \mathbf{B}\,\dot{\mathbf{q}} + \mathbf{K}\,\mathbf{q} = \mathbf{f}(t)\ , \tag{13}$$

where $\mathbf{f}(t)$ is vector of seismic excitation. The first three generalized coordinates of the pressure vessel are relative translation displacements with relation to a rigid support (reactor building well at level of point A) in directions of axes x, y, z (see Fig. 1). That is why the vector $\mathbf{f}(t)$ has the form

$$\mathbf{f}(t) = -\mathbf{m}_1\,\ddot{u}_x(t) - \mathbf{m}_2\,\ddot{u}_y(t) - \mathbf{m}_3\,\ddot{u}_z(t)\ , \tag{14}$$

where $\ddot{u}_l(t)$, $l = x, y, z$ are accelerograms of the support given in three directions in space– two horizontal $\ddot{u}_x(t)$, $\ddot{u}_z(t)$ and one vertical $\ddot{u}_y(t)$. The vectors $\mathbf{m}_i$, $i = 1, 2, 3$ are the first three columns of the mass matrix $\mathbf{M}$.

The synthetic accelerograms, given by ŠKODA Nuclear Machinery as compatible with a given spectra for damping value 5%, were defined by time interval $t \in \langle 0; 10\rangle$ [s] with sampling period $\Delta t = 0.001$ [s]. Time behaviour of the horizontal (identical in both directions) and vertical accelerograms are presented in Fig. 2 and Fig. 3, along with their power spectral densities.

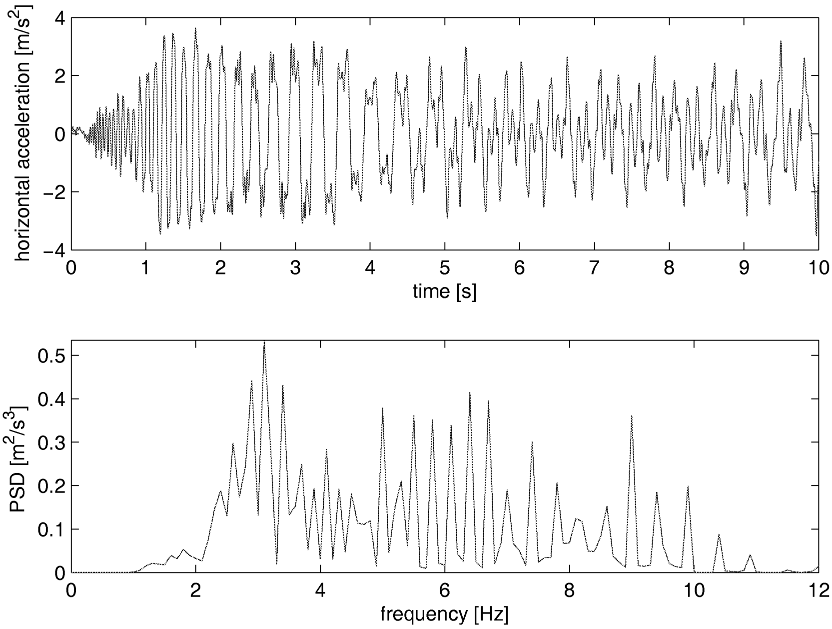

Fig.2: Accelerogram and its power spectral density in the horizontal direction

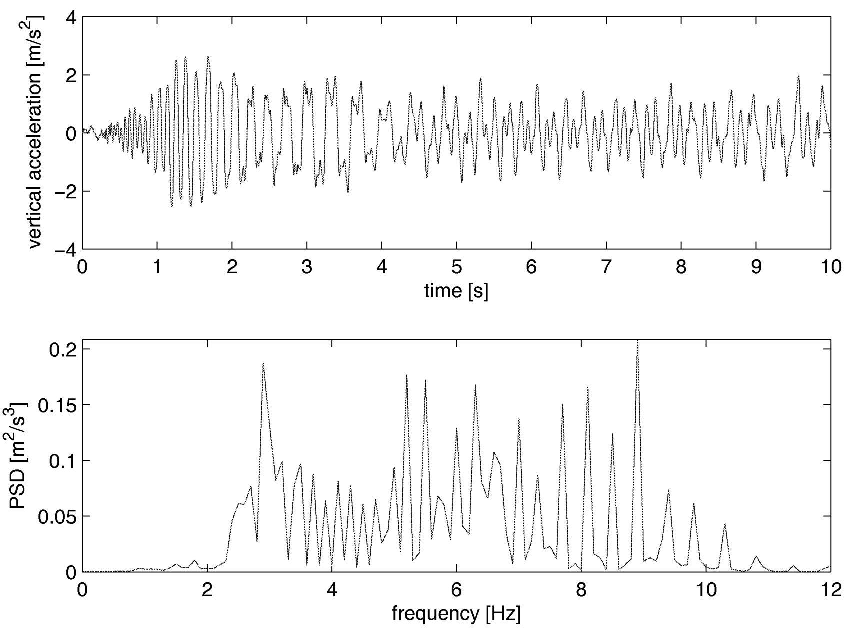

Fig.3: Accelerogram and its power spectral density in the vertical direction

The number of degrees of freedom reduction of the mathematical model (13) is suitable for numerical integration of the equations of motion. In order to reduce we use the modal transformation of generalized coordinates

$$\mathbf{q}(t) = {}^m\mathbf{V}\,\mathbf{x}(t) \;, \tag{15}$$

where ${}^m\mathbf{V}$ is modal submatrix of the conservative system

$$\mathbf{M}\,\ddot{\mathbf{q}} + \mathbf{K}\,\mathbf{q} = \mathbf{0}$$

assembled from the first m ($m < n$) so called master (corresponding to m lowest eigenfrequencies Ω_i) eigenvectors. The modal submatrix with normed eigenvectors meets the orthonormality conditions

$$ {}^m\mathbf{V}^{\mathrm{T}}\,\mathbf{M}\,{}^m\mathbf{V} = \mathbf{E}\;, \qquad {}^m\mathbf{V}^{\mathrm{T}}\,\mathbf{K}\,{}^m\mathbf{V} = \mathrm{diag}[\Omega_i^2]\;. \tag{16}$$

We suppose that the damping matrix satisfies the general condition of proportional damping in the form

$$ {}^m\mathbf{V}^{\mathrm{T}}\,\mathbf{B}\,{}^m\mathbf{V} = \mathrm{diag}[2\,D_i\,\Omega_i]\;, \tag{17}$$

where D_i are damping factors corresponding to eigenmodes. Using transformation (15) appled to equations of motion (13) we receive the reduced mathematical model

$$\ddot{\mathbf{x}}(t) + 2\;\mathrm{diag}[D_i\,\Omega_i]\,\dot{\mathbf{x}}(t) + \mathrm{diag}[\Omega_i^2]\,\mathbf{x}(t) = -{}^m\mathbf{V}^{\mathrm{T}}\,[\mathbf{m}_1\,\ddot{u}_{\mathrm{x}}(t) + \mathbf{m}_2\,\ddot{u}_{\mathrm{y}}(t) + \mathbf{m}_3\,\ddot{u}_{\mathrm{z}}(t)]\;. \tag{18}$$

This system of m differential equations of the second order can be transformed into $2m$ differential equations of the first order

$$\frac{\mathrm{d}\mathbf{z}}{\mathrm{d}t} = -\begin{bmatrix} \mathbf{0} & -\mathbf{E}_m \\ \mathrm{diag}[\Omega_i^2] & 2\;\mathrm{diag}[D_i\,\Omega_i] \end{bmatrix}\mathbf{z} - \begin{bmatrix} \mathbf{0} \\ {}^m\mathbf{V}^{\mathrm{T}}\,[\mathbf{m}_1\,\ddot{u}_{\mathrm{x}}(t) + \mathbf{m}_2\,\ddot{u}_{\mathrm{y}}(t) + \mathbf{m}_3\,\ddot{u}_{\mathrm{z}}(t)] \end{bmatrix}\;, \tag{19}$$

where $\mathbf{z}^{\mathrm{T}}(t) = [\mathbf{x}^{\mathrm{T}}(t), \dot{\mathbf{x}}^{\mathrm{T}}(t)]$. Using standard software (for example ODE45 in Matlab code) the system of differential equations (19) is integrated on suitable interpolation of the accelerograms $\ddot{u}_l(t)$. We obtain the numerical values of vector $\mathbf{z}(t_k)$ components in time steps $t_1 = 0 < t_2 < \cdots < t_K = 10$[s]. According to (15) we get

$$\dot{\mathbf{q}}(t_k) = {}^m\mathbf{V}\,\dot{\mathbf{x}}(t_k)\;, \qquad \mathbf{q}(t_k) = {}^m\mathbf{V}\,\mathbf{x}(t_k) \tag{20}$$

and in accordance with (18) then

$$\begin{aligned}\ddot{\mathbf{q}}(t_k) = -{}^m\mathbf{V}\{&\mathrm{diag}[2\,D_i\,\Omega_i]\,\dot{\mathbf{x}}(t_k) + \mathrm{diag}[\Omega_i^2]\,\mathbf{x}(t_k) + \\ &+ {}^m\mathbf{V}^{\mathrm{T}}\,[\mathbf{m}_1\,\ddot{u}_{\mathrm{x}}(t) + \mathbf{m}_2\,\ddot{u}_{\mathrm{y}}(t) + \mathbf{m}_3\,\ddot{u}_{\mathrm{z}}(t)]\}\;.\end{aligned} \tag{21}$$

The testing of the sufficient number m of eigenvectors in modal submatrix ${}^m\mathbf{V}$ is based on relative error of the maximum dynamic state values calculated using full (for $m = n$) and reduced (for $m < n$) mathematical model (19). The reactor dynamic response excited by testing polyharmonic accelerograms $\ddot{\mathbf{u}}(t) = [\ddot{u}_{\mathrm{x}}(t), \ddot{u}_{\mathrm{y}}(t), \ddot{u}_{\mathrm{z}}(t)]^{\mathrm{T}}$ in form

$$\ddot{\mathbf{u}}(t) = \sum_{k=1}^{3} \ddot{\mathbf{u}}_k\,\sin 2\pi\,f_k\,t$$

for three frequency variants (low $f_k = 2;\ 1.5;\ 2$ [Hz], middle $f_k = 10;\ 7.5;\ 10$ [Hz] and high $f_k = 30;\ 22.5;\ 30$ [Hz]) and the same vector of acceleration amplitude $\ddot{\mathbf{u}}_k = [1;\ 0.8;\ 1]^{\mathrm{T}}\,[\mathrm{ms}^{-2}]$, $k = 1, 2, 3$ expressed by relative errors of maximal displacement and acceleration of the chosen point L[1.298; 7.55; 0.2044] [m] at the top head of the pressure

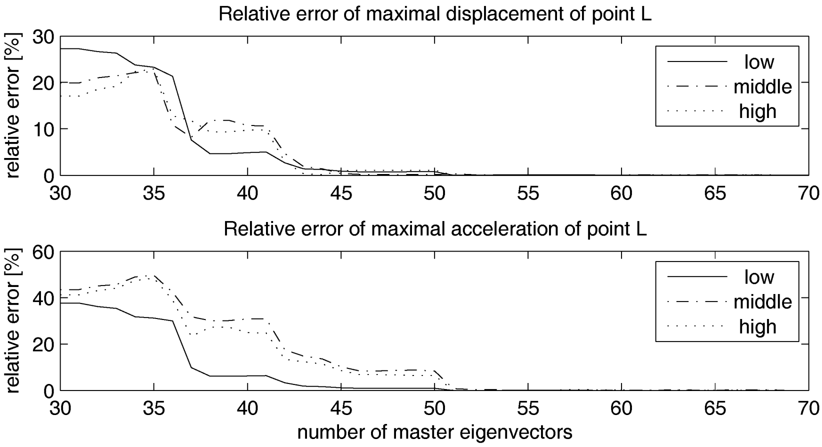

Fig.4: Relative error dependence of point L maximal displacement and acceleration on degree of mathematical model reduction

vessel (coordinates are in system x, y, z) is presented in Fig. 4. It stands to reason that the number $m = 52$ of the master eigenvectors suffices for testing type excitation. With respect to given synthetic accelerograms (see Fig. 2 and Fig. 3) the mathematical model of the reactor was finally reduced to $m = 65$ number of degrees of freedom, because the real accelerograms include even higher frequencies.

5. Seismic response dependence on fuel assembly parameters

In term of cooperation with ŠKODA Nuclear Machinery, CO.Ltd., the time behaviour of the important reactor node displacements and accelerations (for example the access point of drive assembly) and coupling deformations were investigated. As an illustration, the relative displacement extreme values of the former point L at the top head pressure vessel in direction of axes x, y, z, maximal dynamic spring compression d_{S} in the top nozzle of fuel assembly and maximal lateral deformation d_{FA} of the fuel assembly given in millimetres are presented in Table 6.

Fuel assembly	u_{xL}	u_{yL}	u_{zL}	d_{S}	d_{FA}
VVANTAGE 6	0.155	0.279	0.153	0.186	87.1
TVSA-T	0.201	0.270	0.190	0.113	59.1

Tab.6: Extreme values of seismic response with relation to the reactor building well

The time behaviour of relative displacements of the point L for both FA variants are shown in Fig. 5 and 6.

An influence of the fuel assembly design parameters (mass, flexural and longitudinal stiffness, stiffness of the springs in the top nozzle of fuel assembly) on seismic response was studied. As an illustration, the dependences of the maximal and integral dynamic compression d_{S} of the springs in the top nozzle FA on the multiple of flexural stiffness matrix $\mathbf{K}_{\mathrm{FA}}$ corresponding to VVANTAGE 6 FA defined in (12) are shown in Fig. 7. The dependences of the maximal and integral lateral deformation of the fuel assembly on the multiple of flexural stiffness matrix corresponding to TVSA-T FA are shown in Fig. 8.

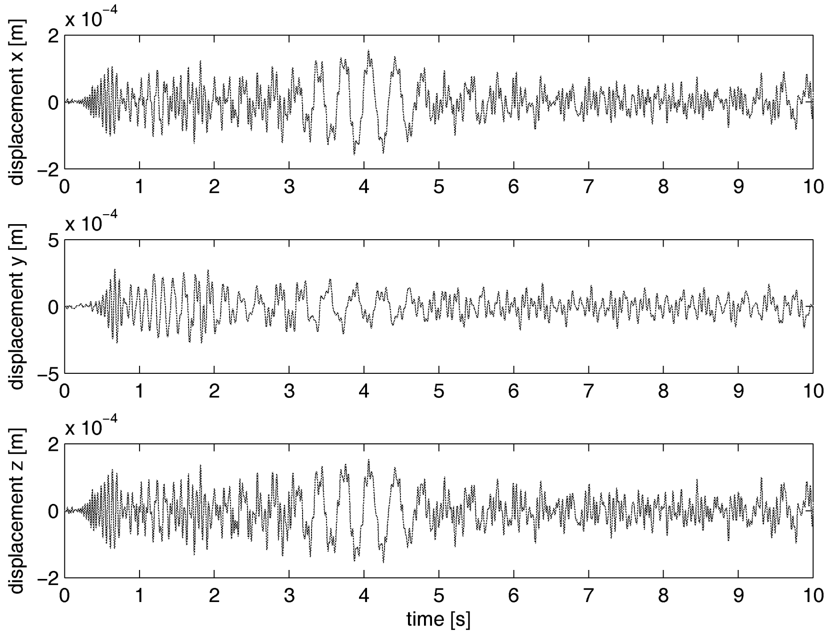

Fig.5: Displacement of the point L at the top head of pressure vessel for the reactor with VVANTAGE 6 fuel assembly

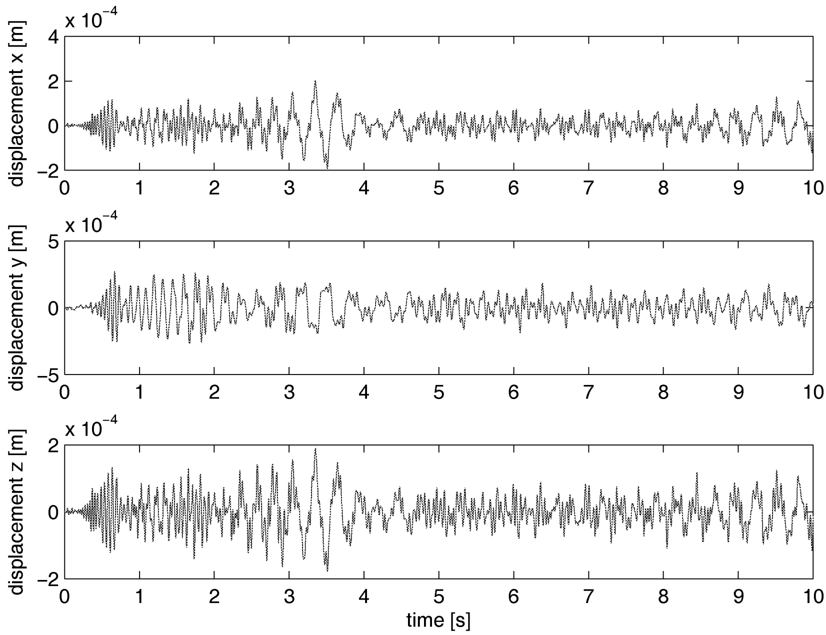

Fig.6: Displacement of the point L at the top head of pressure vessel for the reactor with TVSA-T fuel assembly

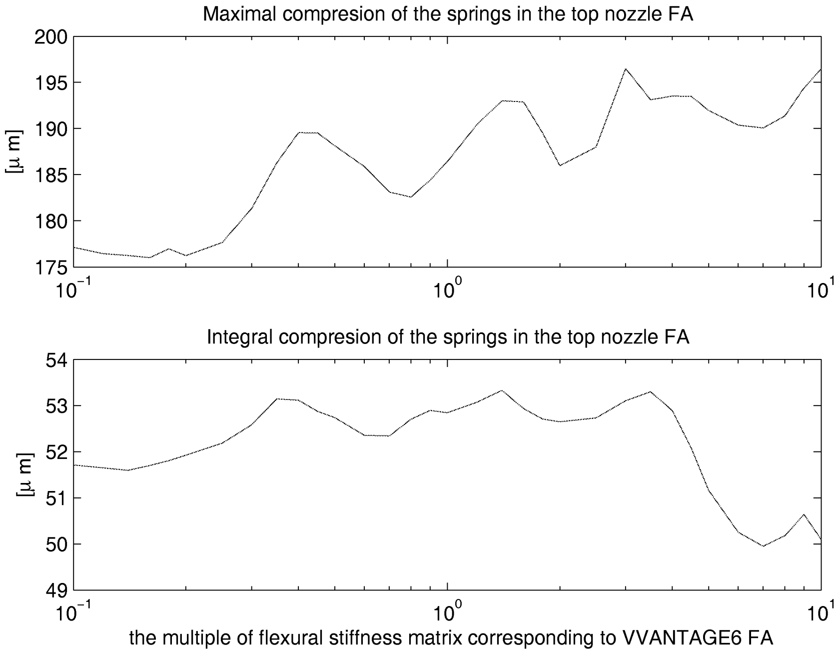

Fig.7: Maximal and integral dynamic compression of the springs in the top nozzle FA

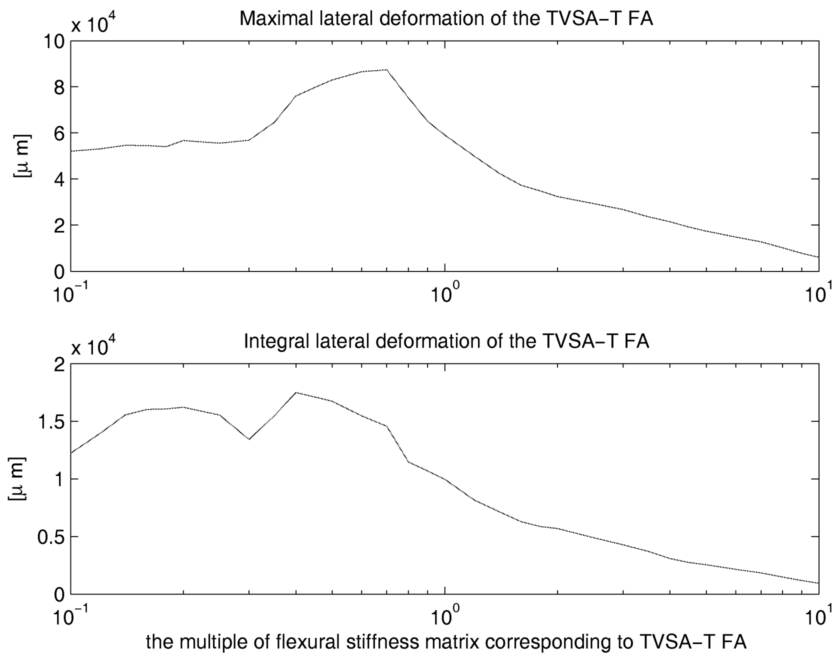

Fig.8: Maximal and integral lateral deformation of the TVSA-T FA

6. Conclusion

The original linear mathematical model of the WWER 1000/320 type reactor with American fuel assemblies VVANTAGE 6 presented in paper [9] was modified for the Russian fuel assemblies TVSA-T and by including primary circuit influence. The new identification method of fuel assembly model, based on modal properties, was used for an integration of the Russian fuel assemblies into mathematical model of the reactor. The numerical integration method applied to reduced mathematical model of the large mechanical system with sufficient number of degrees of freedom was used for seismic analysis of the WWER type reactor. The software developed in MATLAB code makes possible to study an influence of the fuel assembly design parameters and another reactor components parameters on seismic response excited by translation motion of the building well in three directions at point of pressure vessel seating. Seismic excitation is described by synthetic accelerograms in these directions with sufficiently short sampling period $\Delta t < 10^{-3}$ [s].

The most investigated dynamic state values depends on longitudinal stiffness and stiffness of the springs in the top nozzle of fuel assemblies very little whereas the total mass and flexural stiffness of fuel assemblies influence seismic response significantly. The fuel assembly TVSA-T in comparison with VVANTAGE 6 has benign influence to the deformation of springs in the top nozzle of fuel assemblies, vertical displacements of reactor components, deformation of linkage at point of suspension of the core barrel at the pressure vessel flange and especially to lateral deformations of the fuel assemblies. Other investigated displacements in horizontal directions are affected by changing FA very little (in detail in [13]).

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