# DYNAMIC RESPONSE OF VVER 1000 TYPE REACTOR EXCITED BY PRESSURE PULSATIONS

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*The paper deals with the modelling of forced vibrations of reactor components excited by pressure pulsations generated by main circulation pumps. For the vibration analysis a new generalised model of the reactor with spatial localization of the nuclear fuel assemblies and protection tubes, continuously mass distribution of beam type components and more accurate model of the linear stepper drives for actuation of control cassettes was applied. Slightly different pump revolutions are sources of the beating which causes an amplification of vibration and possibility of the contact loss in internal linkages of the core barrel.*

Key words : *reactor vibration, pressure pulsations, displacements, deformations, beating*

## 1. Introduction

One of the basic operation conditions of the reactor VVER is a guarantee of the contact in the suspension of the core barrel to the pressure vessel flange along the whole contact surface. This is achieved by sufficient pre-stressing toroidal tubes (TT) inserted between the upper flange of the core barrel and the pressure vessel cover and also by pre-stressing springs (S) in the top nozzle of fuel assemblies, which roll back the core barrel bottom against the pressure vessel [3]. The dynamic effects, as e.g. pressure pulsation in the space between the pressure vessel and the core barrel walls, could cause, under inadequate pre-stressing above mentioned components, loss of the contact [2].

It was proved experimentally, that the main circulation pumps in cooling loops operate at slightly different revolutions. Consequently, the pressure pulsations of poly-harmonic character with slightly different basic rotational frequencies in particular pipe loops in the section of pump cooling medium outlet till the reactor pressure vessel inlet are generated.

The goal of the paper is to use conservative mathematical model of the VVER 1000 reactor derived by the method presented in [4], to complete it with damping and excitation by the pressure pulsations generated by main circulation pumps and to analyse a steady dynamic response of the reactor. The dynamic response computation is aimed to the investigation of beat vibrations identified by extreme dynamic displacements and deformations. For the assessment of the stability of the reactor inner couplings their extreme contact deformations will be analysed in dependence on the contact surface position and on time for different configuration of operating pumps.

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## 2. Computational and mathematical model

Mathematical model of the VVER 1000/320 type reactor is based on computational (physical) model, whose structure is shown at Fig. 1.

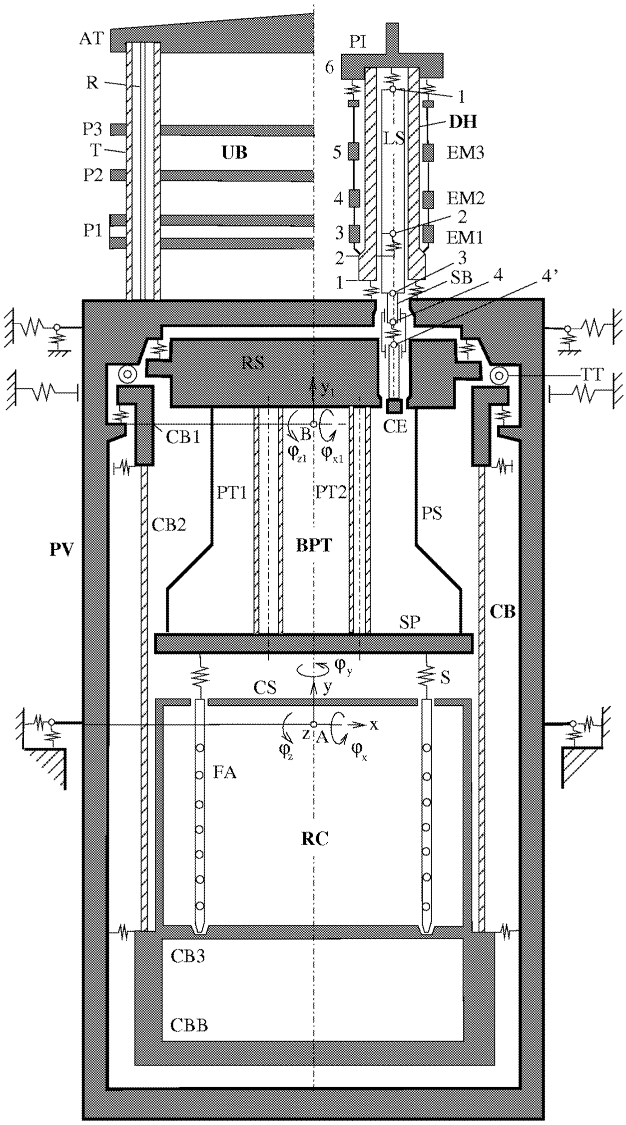


*Fig.1: Scheme of the reactor*

For its derivation in the research report [5] reactor was decomposed to further listed subsystems.

- *Pressure vessel* (**PV**) with top head mounted on a building well on the point A level.
- *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).
- *Reactor core* (**RC**) formed from 163 nuclear fuel assemblies (FA).

- *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 protections tubes (PT2) and perforated shell (PS).
- *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.
- 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.
- 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.
- System of 61 *drive assemblies* (**DA**) for an actual drive operation placed inside the drive housings. 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 an upper and a lower part with a bayonet joint for connecting with the control element. There is an elastic mounting between the upper and the lower suspension bars. All components are axe-symmetric cylindrical bodies which can be modelled as one-dimensional continuum.

The influence of the main circulating loops on the reactor internal component vibration excited by the main circulation pumps pressure pulsation in space between the reactor pressure vessel and the core barrel is small. That is why the mass and static stiffness of the primary coolant loops between a reactor pressure vessel nozzles and steam generators are approximately replaced by mass points and springs placed in gravity centres of the nozzles. The components marked grey in Fig. 1 are conceived as rigid bodies. Other components are modelled as one-dimensional continuums of beam types. Each fuel assembly is replaced with a beam which is simply supported at both ends in top and bottom nozzle position. The mass of the beam is concentrated in the seven mass points placed at mid grids. The diagonal mass matrix and symmetric stiffness matrix of the fuel assembly were identified on the basis of the seven eigenfrequencies and mode shapes measured in SKODA Nuclear Machinery, Co. Ltd. in cooperation with SKODA Research, Co. Ltd. from the lateral vibration test [6]. The identification method of the fuel assembly mathematical model based on spectral and modal adherence to measured real fuel assembly was published in [7].

The subsystems (components) are linked by discrete couplings and one-dimensional continuums by ideal boundary conditions in longitudinal, torsional and transverse direction (fixed-free, pinned-pinned, fixed-fixed, fixed-pinned). The discrete couplings are characterized by translation and rotational stiffness with regard to axes parallel to axes of the global coordinate system $x$, $y$, $z$ (Fig. 1). The contact stiffnesses in vertical direction and corresponding bending stiffnesses about the lateral axes are replaced by continuously distributed stiffnesses along the central circle of the contact annulus (see for example a core barrel over-hanging on the pressure vessel flange).

The positions of the rigid bodies is described by six or three generalized coordinates expressing relative motion with respect to the configuration space (see Table 1) connected with the supporting body. The vibrations of the nuclear fuel assemblies (FA), protection tubes (PT1 and PT2) and components of linear stepping drives (DH, EM, DA) are supposed

| Subsystem | Sub-system mark | Degrees of freedom | Sequence of coor-dinates | Generalized coordinates | Confi-guration space |
|---|---|---|---|---|---|
| Pressure vessel | PV | 6 | 1 to 6 | $x, y, z, \varphi_x, \varphi_y, \varphi_z$ | Building well |
| Core barrel (CB1+CB2+CB3) | CB | 15 | 7 to 21 | $y_1, \varphi_{x1}, \varphi_{z1}$, $x_2, y_2, z_2, \varphi_{x2}, \varphi_{y2}, \varphi_{z2}$, $x_3, y_3, z_3, \varphi_{x3}, \varphi_{y3}, \varphi_{z3}$ | Pressure vessel |
| Reactor core (163∗FA) | RC | 21 | 22 to 42 | $x_i, y_i, z_i$, $i = 1, \ldots, 7$ | Core barrel bottom |
| Block of protection tubes (RS+61∗PT1+ +60∗PT2+PS+SP) | BPT | 9 | 43 to 51 | $y_1, \varphi_{x1}, \varphi_{z1}$, $x_2, y_2, z_2, \varphi_{x2}, \varphi_{y2}, \varphi_{z2}$ | Pressure vessel |
| Supporting structure of upper block (P1+P2+P3+AT+ +6∗T+6∗R) | UB | 24 | 52 to 75 | $x_i, y_i, z_i, \varphi_{xi}, \varphi_{yi}, \varphi_{zi}$, $i = 1, 2, 3, 4$ | Pressure vessel |
| Drive housing (61∗DH + 61∗PI) | DH | 36 | 76 to 111 | $x_i, y_i, z_i, \varphi_{xi}, \varphi_{yi}, \varphi_{zi}$, $i = 1, \ldots, 6$ | Pressure vessel |
| Electromagnet blocks (61∗EM1+61∗EM2+ +61∗EM3) | EM | 8 | 112 to 119 | $y_1, y_2, y_3, y_4$, $\varphi_{y1}, \varphi_{y2}, \varphi_{y3}, \varphi_{y4}$ | Drive housing |
| Drive assemblies (61∗LS+61∗SB+61∗CE) | DA | 18 | 120 to 137 | $y_1, \varphi_{y1}, y_2, \varphi_{y2}, x_3, y_3$, $z_3, \varphi_{x3}, \varphi_{y3}, \varphi_{z3}, x_4, y_4$, $z_4, \varphi_{x4}, \varphi_{y4}, \varphi_{z4}, y_4', y_5$ | Pressure vessel |

*Tab.1: Subsystem mark and meaning of generalized coordinates*

identical for each continuum of a kind. This simplifying assumption results from slightly different boundary conditions. The one-dimensional continuum generalized coordinates express relative displacements (deformations) with respect to supporting body configuration space.

The method of the modelling is based on the expression of kinetic energy of the reactor in the positive definite quadratic form of generalized velocities $E_k(\dot{\mathbf{q}}) = \frac{1}{2}\,\dot{\mathbf{q}}^T\,\mathbf{M}\,\dot{\mathbf{q}}$, where mass matrix $\mathbf{M}$ is symmetric and positive definite. Potential energy of the reactor is compound on potential energy of all one-dimensional continuums of beam type and potential (deformation) energy of couplings between subsystems in the positive definite quadratic form of generalized coordinates $E_p(\mathbf{q}) = \frac{1}{2}\,\mathbf{q}^T\,\mathbf{K}\,\mathbf{q}$. Stiffness matrix $\mathbf{K}$ is symmetric and positive definite. Detailed expression of the kinetic and potential energy of the VVER 1000/320 type reactor decomponated into subsystems (see Table 1) is presented in the report [5]. Substituting the kinetic and potential energy to Lagrange equations we obtain conservative model

$$\mathbf{M}\,\ddot{\mathbf{q}}(t) + \mathbf{K}\,\mathbf{q} = \mathbf{0} \tag{1}$$

described by matrices $\mathbf{M}$ and $\mathbf{K}$ of order 137.

The structure of the reactor mass and stiffness matrices is shown in Fig. 2. Each subsystem is modelled in suitable chosen configuration space of the supporting subsystem by Lagrange equations. For the core barrel, block of protection tubes, supporting structure of upper block and drive housing the supporting subsystem is the pressure vessel. Each subsystem Y ≡ CB, BPT, UB contributes to the global mass matrix by sub-matrices at the positions XX, XY, YX and YY because the subsystem X = PV is for them the supporting subsystem. The subsystems Z = RC, EM and DA contribute to the global mass matrix by sub-matrices XX, XY, XZ, YX, YY, YZ, ZX, ZY, ZZ because the subsystem X = PV is supporting subsystem for Y and Y = CB is supporting subsystem for Z = RC and Y = DH for Z = EM and DA.

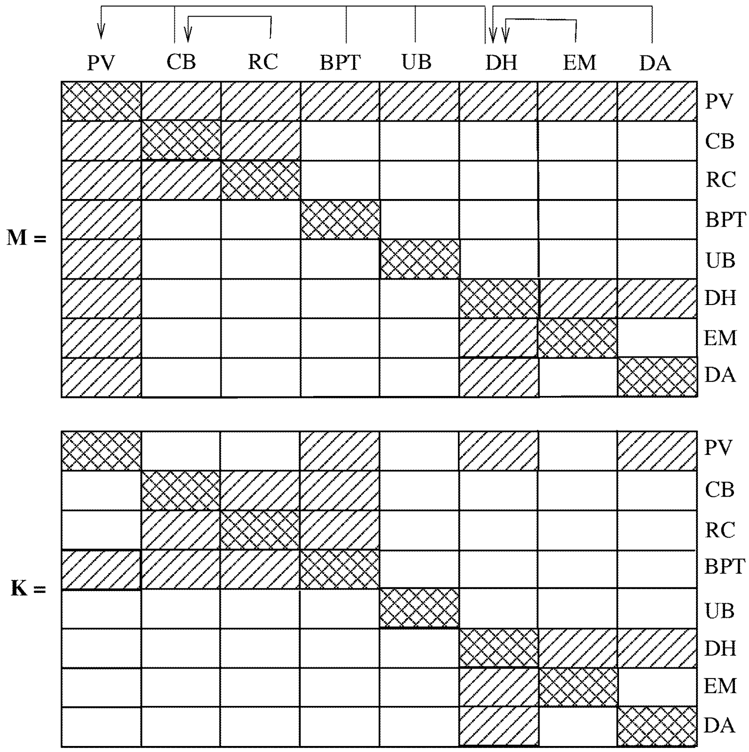


*Fig.2: The structure of the reactor mass and stiffness matrices*

The lower eigenfrequencies $f_v$ of the reactor conservative model (1) in frequency range 0–20 Hz, with corresponding eigenmodes characterized by dominantly vibrating components, are presented in Table 2 (more in research report [9]).

The reactor is a large multi-body system which includes no special dampers. The first approximation of the damping consists in assuming that the system is lightly damped and that the damping matrix **B** satisfies the general condition of proportional damping in the form

$$\mathbf{V}^{\mathrm{T}}\,\mathbf{B}\,\mathbf{V} = \mathrm{diag}(2\,D_v\,\Omega_v)\ . \tag{2}$$

In equation (2) $\mathbf{V} = [\mathbf{v}_v]$ is modal matrix of the reactor conservative model described by equation (1). Its eigenfrequencies are noted $\Omega_v$ and eigenvectors $\mathbf{v}_v$ satisfy the norm $\mathbf{v}_v^{\mathrm{T}}\,\mathbf{M}\,\mathbf{v}_v = 1$, $v = 1, 2, \dots, 137$. The dimensionless damping factors $D_v$ were considered, on the basis of experience in modelling of nuclear reactor vibrations, equal 0.05 with the exception of the damping factors corresponding to eigenmodes, where dominantly vibrates reactor core (here $v = 1, 2, 6, 7, 13, 14, 15, 16$ – see Table 2). In consequence of an influence of coolant these factors were considered larger, concrete $D_v = 0.08$. After an estimation of all damping factors the damping matrix in the mathematical model (4) is calculated in accordance with (2) as

$$\mathbf{B} = (\mathbf{V}^{-1})^{\mathrm{T}}\ \mathrm{diag}(2\,D_v\,\Omega_v)\,\mathbf{V}^{-1}\ . \tag{3}$$

| Order of eigen-frequencies | $f_v$ [Hz] | Vibrations – eigenmode characterization |
|---|---|---|
| 1, 2 | 3.00 | lateral of rector core (1. mode) |
| 3 | 4.16 | vertical of drive assemblies (all components in phase) |
| 4, 5 | 5.06 | lateral of supporting structure of upper block (1. mode) |
| 6, 7 | 6.35 | lateral of reactor core (2. mode) |
| 8 | 6.69 | torsion of supporting structure of upper block (1. mode) |
| 9, 10 | 8.88 | lateral of drive housing with electromagnet blocks in phase with drive assemblies |
| 11, 12 | 9.33 | lateral of drive housing with electromagnet blocks in opposite phase with drive assemblies |
| 13, 14 | 10.8 | lateral of reactor core (3. mode) |
| 15, 16 | 16.2 | lateral of reactor core (4. mode) |
| 17 | 17.0 | torsion of pressure vessel, core barrel with reactor core and supporting structure of upper block (2. mode) |
| 18, 19 | 17.6 | lateral of supporting structure of upper block (2. mode) |
| 20 | 18.86 | vertical of lifting system mechanisms with upper part of suspension bars in opposite phase with lower part of suspension bars with control elements |
| 21, 22 | 18.89 | rocking of pressure vessel in phase with core barrel and lateral of the others components |
| 23 | 19.7 | vertical of lower part of suspension bars with control elements in opposite phase with lifting system mechanisms and upper part of suspension bars |

*Tab.2: Eigenfrequencies of the reactor VVER 1000/320 type*

The damping factors $D_v$ in expression (3) can be specified more precisely on the basis of future knowledge.

The mathematical model of the reactor after discretization of the one-dimensional continuums and after completion of the damping approximated by a damping matrix according to (3) and an excitation has the form

$$\mathbf{M}\,\ddot{\mathbf{q}}(t) + \mathbf{B}\,\dot{\mathbf{q}}(t) + \mathbf{K}\,\mathbf{q}(t) = \mathbf{f}(t)\ , \tag{4}$$

where the vector of generalized coordinates $\mathbf{q}(t)$ of dimension 137 is specified in Table 1.

## 3. Steady dynamic response of the reactor on the pressure pulsations generated by the main circulating pumps

The hydrodynamic forces generated by the main circulation pumps (MCP) were calculated on the basis of a solution a one-dimensional wave equation with related boundary conditions. The solution of wave equation describes the pressure disturbance along the primary circuit in coolant loop sections between outflow from MCP and pressure vessel nozzles. The configuration of coolant loops in the segment between the main circulating pump outlet and the reactor VVER 1000/320 inflow is shown in Fig. 3a.

The force effect of pressure pulsations in the gap between core barrel and pressure vessel walls caused by $j$-th MCP can be replaced by horizontal components $F_{j\mathrm{x}}^{\mathrm{PV}}(t)$, $F_{j\mathrm{z}}^{\mathrm{PV}}(t)$ acting on PV and by components $F_{j\mathrm{x}}^{\mathrm{CB}}(t)$, $F_{j\mathrm{z}}^{\mathrm{CB}}(t)$ acting on CB (Fig. 3b). Their computation is based on the theory presented in the report [1], where values of force total components are tabulated for the hot mode and different configuration of operating MCP. The forces act in the CB plane of symmetry between its bottom and sealing at distance $h = 0.73\,\mathrm{m}$ under the plane of the pressure vessel seating.

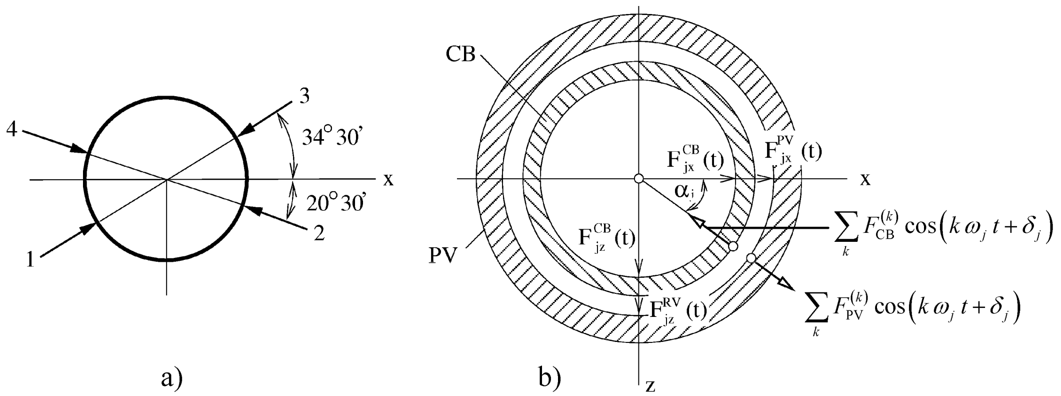


*Fig.3: Configuration of the main circulation loops (a) and hydrodynamic forces generated by one MCP (b)*

The force components have a periodical character in time with the basic angular speed MCP $\omega_j$ in $j$-th loop. Respecting the first three harmonic components we have

$$F^{\mathrm{PV}}_{j\mathrm{x}}(t) = \sum_{k=1}^{3} F^{(k)}_{\mathrm{PV}} \cos\alpha_j \, \cos(k\,\omega_j\,t + \delta_j) \ , \quad F^{\mathrm{PV}}_{j\mathrm{z}}(t) = \sum_{k=1}^{3} F^{(k)}_{\mathrm{PV}} \sin\alpha_j \, \cos(k\,\omega_j\,t + \delta_j) \ , \quad (5)$$

where $F^{(k)}_{\mathrm{PV}}$ is an amplitude of $k$-th harmonic component of the force acting on PV and $\alpha_j$ is an angle between the axis of the pipeline at the outlet of $j$-th MCP in the location of the socket at the pressure vessel and the $x$-axis (Fig. 3b). Similarly the force components acting on the core barrel can be expressed in the form

$$\begin{aligned} F^{\mathrm{CB}}_{j\mathrm{x}}(t) &= -\sum_{k=1}^{3} F^{(k)}_{\mathrm{CB}} \cos\alpha_j \, \cos(k\,\omega_j\,t + \delta_j) \ , \\ F^{\mathrm{CB}}_{j\mathrm{z}}(t) &= -\sum_{k=1}^{3} F^{(k)}_{\mathrm{CB}} \sin\alpha_j \, \cos(k\,\omega_j\,t + \delta_j) \ . \end{aligned} \qquad (6)$$

The axes of coolant loop pipelines of the ETE primary circuit form with the $x$ axis of the basic coordinate system, in which the reactor was modelled, angles $\alpha_1 = 145.5°$, $\alpha_2 = 20.5°$, $\alpha_3 = 325.5°$ and $\alpha_4 = 200.5°$. In expression (5), (6) also the possibility of mutual phase differences in particular MCP represented by angles $\delta_j$ is supposed. The revolution fluctuation is based on the measurement at the first and second ETE blocks, presented in the research report [8]. The revolutions per minute (rpm) of particular MCP measured at the same time are slightly different (fluctuation range is 997.2–999.6 rpm). That is why the corresponding rotational frequencies $f_j = n_j/60\,\mathrm{Hz}$ were considered in two variants: a) the same $f_j = 16.64\,\mathrm{Hz}$ for $j = 1,2,3,4$; b) slightly different – see Table 4.

Applying virtual work principle generalized forces associated to generalized coordinates of the pressure vessel (PV) and core barrel (CB) are determined. The excitation vector $\mathbf{f}(t)$

in reactor mathematical model (4) can be written in a complex form

$$\mathbf{f}(t) = \mathrm{Re}\left\{\sum_j \sum_{k=1}^{3} \mathbf{f}_j^{(k)} \,\mathrm{e}^{\mathrm{i}\,k\,\omega_j\,t}\right\}, \qquad j \in \{1,2,3,4\}\,, \tag{7}$$

where vectors of complex amplitudes of excitation harmonic components are

$$\mathbf{f}_j^{(k)} = \begin{bmatrix} \left(F_{\mathrm{PV}}^{(k)} - F_{\mathrm{CB}}^{(k)}\right)\,\cos\alpha_j \\ 0 \\ \left(F_{\mathrm{PV}}^{(k)} - F_{\mathrm{CB}}^{(k)}\right)\,\sin\alpha_j \\ -h\left(F_{\mathrm{PV}}^{(k)} - F_{\mathrm{CB}}^{(k)}\right)\,\sin\alpha_j \\ 0 \\ h\left(F_{\mathrm{PV}}^{(k)} - F_{\mathrm{CB}}^{(k)}\right)\,\cos\alpha_j \\ 0 \\ (\overline{AB}+h)\,F_{\mathrm{CB}}^{(k)}\,\sin\alpha_j \\ -(\overline{AB}+h)\,F_{\mathrm{CB}}^{(k)}\,\cos\alpha_j \\ -F_{\mathrm{CB}}^{(k)}\,\cos\alpha_j \\ 0 \\ -F_{\mathrm{CB}}^{(k)}\,\sin\alpha_j \\ ----------- \\ \mathbf{0} \end{bmatrix} \mathrm{e}^{\mathrm{i}\,\delta_j} \in C^{137,1}\,. \tag{8}$$

The steady dynamic response of the reactor in generalized coordinates (Table 1) is given by the particular solution of the model (4)

$$\mathbf{q}(t) = \mathrm{Re}\left\{\sum_j \sum_{k=1}^{3} \left[-\mathbf{M}(k\,\omega_j)^2 + \mathrm{i}\,k\,\omega_j\,\mathbf{B} + \mathbf{K}\right]^{-1}\,\mathbf{f}_j^{(k)}\,\mathrm{e}^{\mathrm{i}\,k\,\omega_j\,t}\right\}. \tag{9}$$

Then the generalized coordinates can be written in the form

$$q_i(t) = \sum_j \sum_{k=1}^{3} \left(\overline{q}_{i,j}^{(k)}\,\cos k\,\omega_j\,t - \overline{\overline{q}}_{i,j}^{(k)}\,\sin k\,\omega_j\,t\right)\,, \tag{10}$$

where real (with one strip) and imaginary (with two strips) components of complex vector coordinates are introduced

$$\mathbf{q}_j^{(k)} = \left[\overline{q}_{i,j}^{(k)} + \mathrm{i}\,\overline{\overline{q}}_{i,j}^{(k)}\right]\,. \tag{11}$$

Subscript $i \in \{1,\ldots,137\}$ is assigned to the generalized coordinate, subscript $j \in \{1,2,3,4\}$ to the operating MCP and subscript $k$ to the harmonic component of pressure pulsations.

The main results of the computations are extremes of selected generalized coordinates in sufficiently long time interval $t \in \langle 0, 50\rangle$ s and their time functions, which, as a consequence of slightly different MCP revolutions, show beats. To compare the steady response excited by the pressure pulsations generated by MCP solved using the reactor model with experimentally determined displacements at the reactor pressure vessel bottom or cover a special code for drawing orbits of points at the pressure vessel axis was developed. The code enables to draw the orbit of an arbitrary point L of the pressure vessel axis in selected time interval.

The time parameter should be changed with a relatively short step $\Delta t \leq 10^{-3}$ s. In direct relationship to the research report [5] also dynamic deformations of reactor inner couplings were analysed.

## 4. Selected results of simulations

For the assessment of the influence of slightly different main circulation pump revolutions always two variants – with the same and slightly different rotational frequencies in so called hot mode – are presented. Amplitudes of particular harmonic components of hydrodynamic force excited by one pump, taken from the report [2], are tabulated in Tab. 3.

| Force acting on | Amplitude | Unit | Harmonic components | | |
|---|---|---|---|---|---|
| | | | $k = 1$ | $k = 2$ | $k = 3$ |
| Pressure vessel | $F_{\mathrm{PV}}^{(k)}$ | $10^6$ N | 0.301 | 0.326 | 0.375 |
| Core barrel | $F_{\mathrm{CB}}^{(k)}$ | $10^6$ N | 0.268 | 0.290 | 0.334 |

*Tab.3: Force amplitudes generated by one MCP*

As an illustration of results obtained by simulations using newly developed codes in MATLAB [8] extreme values of lateral displacements of the reactor pressure vessel bottom in the transition from the cylindrical part to the elliptical bottom ($d_{\mathrm{PVB}}$), the drive housing at node 5 level ($d_{5\mathrm{DH}}$), suspension bars of regulating unit drives at node 4 level ($d_{4\mathrm{SB}}$) and dynamic components of deformations at point of suspension of the core barrel at the pressure vessel flange ($d_{\mathrm{CB}}$), toroidal tubes ($d_{\mathrm{TT}}$) and the springs in the top nozzle of fuel assembly ($d_{\mathrm{S}}$) are presented in Tab. 4 for the different configuration the operating pumps in the main circulation loops according Fig. 3a.

| MCP configu-ration | Rotational frequency of MCPs [Hz] | | | | Displacements | | | Deformations | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $f_1$ | $f_2$ | $f_3$ | $f_4$ | $d_{\mathrm{PVB}}$ | $d_{\mathrm{DH}}$ | $d_{\mathrm{SB}}$ | $d_{\mathrm{CB}}$ | $d_{\mathrm{TT}}$ | $d_{\mathrm{S}}$ |
| 1+2 | 16.64 | 16.64 | | | 22.8 | 83.2 | 25.0 | 29.4 | 29.1 | 32.4 |
| | 16.62 | 16.66 | | | 38.5 | 184.1 | 67.5 | 36.7 | 36.2 | 106.4 |
| 1+2+3 | 16.64 | 16.64 | 16.64 | | 24.1 | 102.5 | 38.1 | 26.2 | 25.9 | 57.8 |
| | 16.62 | 16.64 | 16.66 | | 46.8 | 215.2 | 80.1 | 48.9 | 48.4 | 120.2 |
| 2+3 | | 16.64 | 16.64 | | 42.8 | 186.2 | 70.5 | 45.2 | 44.7 | 106.6 |
| | | 16.62 | 16.66 | | 42.7 | 186.2 | 70.1 | 45.0 | 44.5 | 106.6 |
| 2+3+4 | | 16.64 | 16.64 | 16.64 | 24.2 | 98.7 | 34.8 | 27.5 | 27.2 | 53.4 |
| | | 16.62 | 16.64 | 16.66 | 46.9 | 221.6 | 85.2 | 46.4 | 45.9 | 125.0 |
| 1+2+3+4 | 16.64 | 16.64 | 16.64 | 16.64 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 16.62 | 16.64 | 16.66 | 16.64 | 43.7 | 196.2 | 68.1 | 41.9 | 41.4 | 106.7 |

*Tab.4: Maximum lateral displacements and deformations [μm]*

Orbits of points of the pressure vessel axis in the transition of the cylindrical part to the elliptical bottom for identical and slightly different pump revolutions with the pump configuration 1+2+3 (Tab. 4) in the time interval close to the extreme lateral displacement $d_{\mathrm{PVB}}$ are shown in Fig. 4.

As an illustration of the beat character of the reactor component vibrations the time course of lateral displacements of the pressure vessel bottom $x_{\mathrm{PVB}}$, drive housings $x_{5\mathrm{DH}}$,

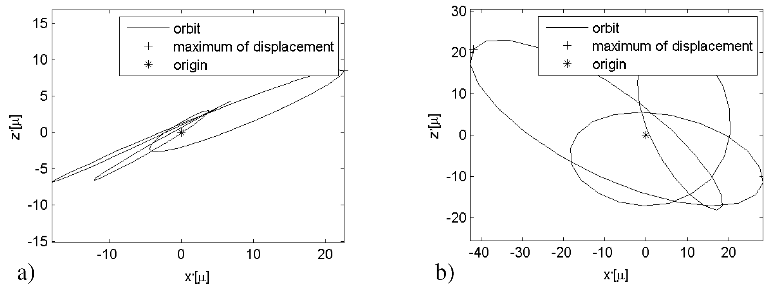


*Fig.4: Orbit of point at a pressure vessel axis about its bottom for MCP configuration 1+2+3 on identical (a) and slightly different (b) pump revolutions (see Table 4)*

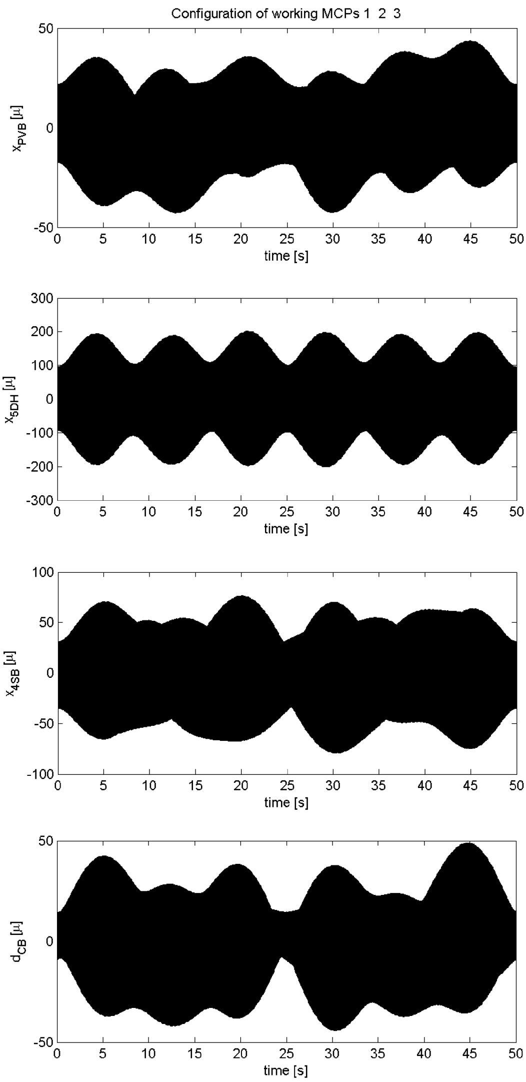


*Fig.5: Time response of lateral displacements ($x_{\mathrm{PVB}}$, $x_{\mathrm{5DH}}$, $x_{\mathrm{4SB}}$) and linkage deformation in the contact between core barrel and pressure vessel ($d_{\mathrm{CB}}$)*

drive suspension bars $x_{4\mathrm{SB}}$ and dynamic components of deformation in point of core barrel suspension $d_{\mathrm{CB}}$ in the location of the extreme deformation for the pump configuration 1+2+3 under slightly different revolutions given in Table 4 in time interval $t \in \langle 0, 50\rangle$ s are shown in Fig. 5.

## 5. Conclusion

VVER 1000/320 ETE reactor spatial model tuned on some experimentally determined eigenfrequencies [5] can be used for determination of dynamic response in displacements, deformations or accelerations of components excited by pressure pulsations generated by main circulation pumps. The software developed in MATLAB is conceived so, that, using input parameters, enables to chose an arbitrary configuration of operating pumps, their rotational frequencies, phases and amplitudes of harmonic components of hydrodynamic forces acting between walls of the pressure vessel and the core barrel.

The change in rotational frequencies of pumps in experimentally determined frequency interval $f \in \langle 16.62, 16.66\rangle$ Hz significantly influences the beat period, but relatively little the extreme magnitude of state values. Knowledge of the maximum dynamic component of deformation in the suspension of the core barrel to the pressure vessel flange and pre-stressing of springs in the top nozzle of nuclear full assemblies enables to determine minimal pre-stressing of toroidal tubes to guarantee the contact in the whole contact surface. As a consequence of beat effects the increase of vibration of reactor inner parts takes place and consequently it requires the increase of needed pushing forces of the toroidal tubes and the springs in the top nozzle of fuel assemblies to guarantee stable contact in couplings of reactor inner parts.


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