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Seismic Response of Primary Circuit with Viscous Dampers

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ABSTRACT

The seismic upgrading of safety significant piping of NPPs with VVER reactors operating in Czech Republic, Slovak Republic and Hungary has been performed using viscous dampers GERB. The primary circuit is a very large dynamical system including a reactor and main circulating loops with other components. The damping matrix in the mathematical model is not proportional and the damping $\mathbf{B}(\omega)$ and stiffness $\mathbf{K}(\omega)$ matrices of the dampers GERB are frequency dependent. The primary circuit is decomponated into subsystems (reactor R, main circulating loops $j = 1, 2, \ldots$) and its mathematical model is created by means of the modal synthesis method. The model in condensed form may be written as

$$\ddot{\mathbf{x}}(t) + \left(\mathbf{B}_0 + \mathbf{B}(\omega) + \mathbf{V}^{\,T}\mathbf{B}_C\,\mathbf{V}\right)\dot{\mathbf{x}}(t) + \left(\Lambda + \mathbf{K}(\omega) + \mathbf{V}^{\,T}\mathbf{K}_C\,\mathbf{V}\right)\mathbf{x}(t) = -\sum_{l=1}^{3}\mathbf{m}_l\,\ddot{u}_l(t)$$

The seismic excitation is caused by the translation of the base with $\ddot{u}_l(t)$ acceleration in the direction of the coordinate axes in sequence $x(l=1)$, $y(l=2)$, $z(l=3)$. The influence of the discrete couplings between subsystems is expressed by stiffness $\mathbf{K}_C$ and damping $\mathbf{B}_C$ matrices calculated by means of FEM analysis. Matrix $\mathbf{B}_0$ expresses the proportional damping of the uncoupled subsystems without GERB dampers.

The seismic response of subsystem j (considered as a part of the whole system) caused by the seismic excitation in the direction l can be expressed by eigenvalues λ_ν and eigenvectors $\mathbf{x}_\nu^{(j)}$ of the condensed model in form

$$\mathbf{q}_j^{(l)}(t) = -\sum_{\nu=1}^{2m}\mathbf{q}_\nu^{(j)}\sum_s\left(\mathbf{q}_\nu^{(s)}\right)^T\mathbf{M}_s\,\mathbf{e}_s^{(l)}\int_0^t\ddot{u}_l(\tau)e^{\lambda_\nu(t-\tau)}d\tau, \quad j,s = R, 1, 2, \ldots, \quad l = 1, 2, 3$$

where

$$\mathbf{q}_\nu^{(j)} = \mathbf{V}_j\,\mathbf{x}_\nu^{(j)} \qquad \mathbf{q}_\nu^{(s)} = \mathbf{V}_s\,\mathbf{x}_\nu^{(s)},$$

$\mathbf{V}_j$, $\mathbf{V}_s$ are modal matrices of the uncoupled conservative subsystems j, s; $\mathbf{M}_j$ is mass matrix of the subsystem s and $\mathbf{e}_s^{(l)}$ is vector of the static displacement of the subsystem s generated by the unit translation of the base in the direction l. The seismic response of the subsystems is calculated by the modified response spectrum method.

KEY WORDS: seismic response, viscous dampers, mathematical model, decomposition, submodels, damping and stiffness matrices, eigenvalues.

INTRODUCTION

Nuclear power plants (NPPs) with Russian type of PWR-VVER 440/213 (Water-Water Power Reactor) net electrical power 440 MW represents the second generation of Russian PWRs. They are designed with six primary loops in mirror symmetry and six horizontal steam generators (SG). The SG´s are hinged on the ceiling of hermetic zone as a pendulum. Due to this fact the first mode shape is so called "pendulum" mode with the frequency approximately 1 Hz. In case of strong motion earthquake the pendulum motion induces very high bending stresses on the reactor pressure vessel nozzles.

In order to eliminate this effect the primary loop is restrained by GERB viscous damper [Ref. 1, 2] linked in the case of NPP Mochovce (Slovak Republic) to the SGs, to the body of main circulation pumps (MCPs) and to the nozzles of motor operated isolation valves (MOIV), see Fig. 1. Since the stiffness and damping of viscous dampers are frequency-dependent, new approach for calculation of eigenfrequencies and seismic response was developed. Details are described in next two sections.

MATHEMATICAL MODEL OF THE PRIMARY CIRCUIT

Mathematical model of the standard primary circuit (PC) of VVER 440/213, see Fig. 2 is developed by using of the modal synthesis method, see [Ref. 3]. All couplings between reactor pressure vessel (RPV) and each of six main circulation loops (MCLs) are respected. The methodology [Ref.4] is based on the decomposition of PC using hypothetical cross sections in the weldments of RPV nozzles with the hot legs (points A_j) and cold legs (points B_j) of MCLs. As the result we obtain following independent subsystems: RPV with internals (subscript j = R) and isolated MCLs (subscripts j = 1, 2, …, 6). Each of this ones is characterized by the spectral submatrix ${}^{m}\Lambda_j$ = diag $\left(\Omega_{\nu}^{(j)^2}\right)$ and modal submatrix ${}^{m}\mathbf{V}_j$ of type (n_j, m_j) which consist number m_j of lowest eigenfrequencies $\Omega_{\nu}^{(j)}$ and m_j normalised eigenvectors fulfilling the relation ${}^{m}\boldsymbol{V}_j^T \boldsymbol{M}_j {}^{m}\boldsymbol{V}_j = \boldsymbol{E}_j$. Damping of the decoupled subsystems without dampers is supposed to be proportional with modal damping ratio $D_{\nu}^{(j)}$, $\nu = 1, 2, \dots m_j$, j = R, 1, 2, …, 6.

The static compliance matrix is developed using static deformations of RPV nozzles which have been loaded by the unit forces and moments. The FEM methodology and the ANSYS computer code have been used. The coupling stiffness matrix $\mathbf{K}_j$ of order 12 of all loops „j" with RPV is developed as the inverse of compliance matrix. Subscript „j" denote the coordinate system of each loop. The stiffness matrix $\mathbf{K}_C$ of all couplings in configuration space of generalized coordinates is given as

$$\frac{\delta E_p}{\delta \mathbf{q}} = \mathbf{K}_C \, \mathbf{q} \tag{1}$$

where E_p denote the potential energy of all RPV nozzles and $\mathbf{q} = [\mathbf{q}_j]$ is the vector of whole generalized coordinates of the all system of dimension n = Σ n_j. The $\mathbf{q}_j$ denote the vector of generalized coordinates of subsystem j, j = R 1, 2, …, 6.

The dynamic model of VVER 440/213 reactor is illustrated in Fig. 3. This one consist of rigid bodies, i.e. RPV, core barrel CB, lower part of core barrel LPCB, core shroud CS, top head TH, core hold-down/upper internal unit CHD, upper part of top head UPTHi (i = 1, 2, 3, 4) and the elastic bodies of beam type CHD, hexagonal can HC, fuel rods FR, control rod driving mechanism housings CRDM, control rods CR, rods of upper part of top head R with the masses located in the specified mass points. The above mentioned bodies are coupled by either contact compliances in x, y, z or in y directions or springs.

The dimension of the generalized coordinates vector of the reactor is n_R = 77 and takes form [Ref. 5]

$$\mathbf{q}_R = \left[\mathbf{q}_{RPV}^T, \mathbf{q}_{CB}^T, \mathbf{q}_{LPCB}^T, \mathbf{q}_{CHD}^T, \mathbf{q}_{HC}^T, \mathbf{q}_{FR}^T, \mathbf{q}_{UPTH}^T, \mathbf{q}_{CRDM}^T\right]^T \tag{2}$$

in accordance with Fig. 3.

The selected j-th MCL which is cuted off from RPV in the points A_j, B_j is illustrated in Fig. 4. The vector of the generalized coordinates of the MCL is of dimension n_j = 435 and takes the form

$$\mathbf{q}_R = \left[\left(\mathbf{q}_j^{HL}\right)^T, \left(\mathbf{q}_j^{SG}\right)^T, \left(\mathbf{q}_j^{COL}\right)^T, \left(\mathbf{q}_j^{MCP}\right)^T, \left(\mathbf{q}_j^{CL}\right)^T\right]^T \qquad j = 1, 2, ..., 6 \tag{3}$$

where superscripts HL, CL, etc are to seen on Fig. 4. Details are given in [Ref. 6].

Using standard transformation of the generalized coordinates of each subsystem we can write

$$\mathbf{q}_j\,(t) = {}^m\mathbf{V}_j\ \mathbf{x}_j\,(t) \qquad j = R, 1, 2, ...,6 \tag{4}$$

where ${}^m\mathbf{V}_j$ is the corresponding modal submatrix. After evaluation of the coupling forces between subsystems on the basis of stiffness $\mathbf{K}_C$ and damping $\mathbf{B}_C$ matrices of all couplings it is possible to derive the condensed model of the primary circuit without dampers. In the configuration space $\mathbf{x}\,(t) = [\mathbf{x}_j\,(t)]$ of dimension $m = m_R + \sum_{j=1}^{6} m_j$ the equation of motion takes the form [Ref. 4]

$$\ddot{\mathbf{x}}\,(t) + \left(\mathbf{B}_0 + \mathbf{V}^T\ \mathbf{B}_C\ \mathbf{V}\right)\dot{\mathbf{x}}\,(t) + \left(\ddot{\mathbf{E}} + \mathbf{V}^T\ \mathbf{K}_C\ \mathbf{V}\right)\mathbf{x}\,(t) = \mathbf{V}^T\ \mathbf{f}\,(t) \tag{5}$$

where

$$\mathbf{B}_0 = 2\ diag\left(..., D_\nu^{(R)}\ \Omega_\nu^{(R)}\ ..., ...\ D_\nu^{(1)}\ \Omega_\nu^{(1)} ...\ , ...\ D_\nu^{(6)}\ \Omega_\nu^{(6)}\right)$$

is the diagonal matrix of damping of the subsystems and

$$\mathbf{V} = diag\left({}^m\mathbf{V}_j\right),\ \ddot{\mathbf{E}} = diag\left({}^m\ddot{\mathbf{E}}_j\right)$$

are block diagonal matrices generated from the spectral and modal submatrices of uncoupled subsystems. The damping of the couplings is supposed to be proportional and takes the form $\mathbf{B}_C = \beta_C\ \mathbf{K}_C$.

After transformation the vector of exciting forces may be written as

$$\mathbf{V}^T\ \mathbf{f}\,(t) = \left[{}^m\mathbf{V}_j\ \mathbf{f}_j\,(t)\right], \qquad j = R, 1, 2, ..., 6 \tag{6}$$

where $\mathbf{f}_j\,(t)$ are the exciting vectors of all subsystems described in corresponding generalized coordinates spaces.

MODAL PROPERTIES OF THE PRIMARY CIRCUIT

Modal properties of the primary circuit without dampers may be analysed using conservative condensed model

$$\ddot{\mathbf{x}}\,(t) + \left(\ddot{\mathbf{E}} + \mathbf{K}(\omega) + \mathbf{V}^T\ \mathbf{K}_C\ \mathbf{V}\right)\mathbf{x}\,(t) = \mathbf{0} \tag{7}$$

The related eigenvectors $\mathbf{x}_\nu$ fulfil the condition

$$\left(\ddot{\mathbf{E}} + \mathbf{K}(\omega) + \mathbf{V}^T\ \mathbf{K}_C\ \mathbf{V} - \Omega^2\ \mathbf{E}\right)\mathbf{x}_\nu = \mathbf{0}, \qquad \nu = 1, 2, \ \ ...\ m \tag{8}$$

and of course the requirement of Eucleidien norm ${}^T\mathbf{x}_\nu\ \mathbf{x}_\nu = 1$ and must be transformed into subsystems eigenvectors in original configuration spaces of the generalized coordinates

$$\mathbf{q}_\nu^{(j)} = {}^m\mathbf{V}_j\ \mathbf{x}_\nu^{(j)}, \qquad j \ = R, 1, 2, ...\ 6$$

(9)

where $\mathbf{x}_\nu^{(j)}$ is the subvector or the eigenvector $\mathbf{x}_\nu = \left[\mathbf{x}_\nu^{(j)}\right]$ corresponding to the subsystem „j”.

Numerical experiments proved that the primary circuit of the unit with VVER 440/213 reactor may be condensed to the m = 677 degrees of freedom (m_R = 77, m_j = 100 for j = 1, 2, … 6) in the frequency range $\langle 0;30\rangle$ Hz if the seismic and fluido-elastic analyses are needed. In Table 1 are presented lowest eigenfrequencies f_ν of system without dampers $\left(\mathbf{K}(\omega)=0,\ \boldsymbol{B}(\omega)=0\right)$ and f_ν^G with dampers (for $\left(\mathbf{K}(\omega)\neq 0,\ \boldsymbol{B}(\omega)=0\right)$.

Without dampers		**With dampers**			
			without damping	**with damping**	
ν	f_ν[Hz]	ν	f_ν^G [Hz]	α_ν^G [Hz]	β_ν^G [Hz]
1,2	0,775	1,2	0,775	0,0388	0,774
3-8	~ 1,15	3,4	1,43	0,0717	1,43
9, 10	1,43	5,6	1,46	0,0730	1,46
11, 12	1,46	7,8	1,59	0,0796	1,59
13, 14	1,59	9	1,659	0,0830	1,657
15	1,659	10 – 15	~2,42	0,767	~2,30
16-21	~ 2,09	16 – 21	~3,74	1,06	~3,61
22 – 27	~ 3,6	22 – 27	~4,7	0,79	~4,6
28, 29	5,66	28, 29	5,66	0,283	5,66
30 – 35	~ 5,9	30, 31	6,43	0,322	6,42
36, 37	6,43	32 – 37	~6,99	0,859	~6,97
38, 39	≈ 7,5	38, 39	≈7,6	≈0,5	≈7,6
40 – 50	~ 8,5	40 – 45	~8,87	0,454	~8,86
46	8,894	46	8,952	0,496	8,93
47, 48	9,87	47, 48	9,87	0,493	9,86
49, 50	10,5	49, 50	10,48	0,525	10,5
51 – 56	10,95	51	11,554	0,621	11,54
27	11,515	52, 53	≈12,1	≈0,62	≈12,1
58, 59	≈ 12,0	54 – 59	~12,37	0,47	~12,5
60 – 65	~ 12,2	60 – 65	~12,66	0,54	~12,7
66 – 71	~ 12,26	66 – 71	~13,6	0,53	~13,39
72 – 77	~ 13,25	72 – 77	~14,36	1,06	~14,35
78, 79	≈14,4	78, 79	≈14,4	≈0,72	≈14,4
80 - 85	~ 15,0	80, 81	15,83	0,792	15,81

Table 1: lowest eigenfrequencies and eigenvalues

SEISMIC RESPONSE OF CONDENSED MODEL

In the case of seismic excitation the equation of motion of primary circuit with viscous dampers has form

$$\ddot{\mathbf{x}}(t)+\left[\mathbf{B}_0+\mathbf{B}\ (\omega)+\mathbf{V}^T\ \mathbf{B}_C\mathbf{V}\right]\dot{\mathbf{x}}(t)+\left[\ddot{\mathbf{E}}+\mathbf{K}\ (\omega)+\mathbf{V}^T\ \mathbf{K}_C\ \mathbf{V}\right]\mathbf{x}(t)=-\sum_{l=1}^{3}\boldsymbol{m}_l\ddot{\boldsymbol{u}}_l(t) \qquad (11)$$

where matrices $\mathbf{B}(\omega)$, $\mathbf{K}\ (\omega)$ of the dampers are frequency dependent and $\boldsymbol{m}_l=\left[{}^{m}\boldsymbol{V}_j^T\boldsymbol{M}_j\boldsymbol{c}_j^{(l)}\right]$ for $j=R,1,2,\ldots 6$.

The complete homogenous part of the condensed model is used for calculation of the complex eigenvalues $\lambda_\nu=-\alpha_\nu+i\beta_\nu$, $\lambda_{\nu+m}=-\alpha_\nu-i\beta_\nu$ and corresponding eigenvectors $\boldsymbol{x}_\nu=\left[\boldsymbol{x}_\nu^{(j)}\right]$, $\boldsymbol{x}_{\nu+m}=\boldsymbol{x}_\nu$, $\acute{\imath}=1,2\ldots,m$ satisfying the orthonormality conditions.

The seismic response of subsystem j (considered as a part of the whole system) can be expressed by eigenvalues and eigenvectors of the condensed model in form [Ref.4]

$$\mathbf{q}_j^{(l)}(t) = -\sum_{\nu=1}^{2m} \mathbf{q}_\nu^{(j)} \sum_s \left(\mathbf{q}_\nu^{(s)}\right)^T \mathbf{M}_s\, \mathbf{e}_s^{(l)} \int_0^t \ddot{u}_l(\tau) e^{\lambda_\nu (t-\tau)} d\tau, \quad j,s = R, 1, 2, ...6, \quad l = 1, 2, 3 \tag{12}$$

where $\mathbf{q}_\nu^{(j)} = {}^m\mathbf{V}_j\, \mathbf{x}_\nu^{(j)} = \left[q_{i,\nu}^{(j)}\right]$ is complex eigenvector corresponding to eigenvalue λ_ν, $\mathbf{M}_s$ is mass matrix of the subsystem s and $\mathbf{e}_s^{(l)}$ is vector of static displacement of the subsystem s generated by the unit translation of the base in the direction l.
If we rewritte coordinates before integral Eq. 12 as

$$q_{i,\nu}^{(j)} \sum_s \left(\mathbf{q}_\nu^{s}\right)^T \mathbf{M}_s\, \mathbf{e}_s^{(l)} = \left| q_{i,\nu}^{(j)} \sum_s \left(\mathbf{q}_\nu^{(s)}\right)^T \mathbf{M}_s\, \mathbf{e}_s^{l} \right| e^{i\varphi_{i,\nu}} \tag{13}$$

and adding complexe conjugate terms related to the eigenvalues λ_ν and $\lambda_{\nu+m}$, Eq. 12 for coordinates $q_{i,j}^{(l)}(t)$ of the node i of subsystem j change to

$$q_{i,j}^{l}(t) = -2\sum_{\nu=1}^{m} \left| q_{i,\nu}^{(j)} \sum_s \left(\boldsymbol{q}_\nu^{(s)}\right)^T \boldsymbol{M}_s \boldsymbol{e}_s^{(l)} \right| \int_0^t \ddot{u}_l(\tau) e_j^{-\alpha_\nu (t-\tau)} \cos\left[\beta_\nu (t-\tau) + \varphi_{i,\nu}\right] d\tau \tag{14}$$

Maximum of absolute values of integrals in Eq. 14 it is possible to express as $\beta_\nu S_d^{(l)}(\Omega_\nu, D_\nu)$ where $S_d^{(l)}(\Omega_\nu, D_\nu)$ is the displacement response spectrum in direction l. The arguments are as follows

$$\Omega_\nu = \left|\lambda_\nu\right|, D_\nu = \frac{\alpha_\nu}{\left|\lambda_\nu\right|} \tag{15}$$

After application of standard SRSS methodology as a result we obtain

$$\hat{q}_{i,j}^{\,l} = 2\sqrt{\sum_{\nu=1}^{m} \left\{ \left| q_{i,\nu}^{(j)} \sum_s \left(\boldsymbol{q}_\nu^{(s)}\right)^T \boldsymbol{M}_s \boldsymbol{e}_s^{(l)} \right| \beta_\nu S_d^{(l)}\left(\left|\lambda_\nu\right|, \frac{\alpha_\nu}{\left|\lambda_\nu\right|} \right) \right\}^2} \tag{16}$$

NUMERICAL EXAMPLE

Effect of installed viscous dampers according Fig. 1 is illustrated in Tables 2 and 3 for reactor pressure vessel and rigid bodies of primary loops j=1,2,…,6. The radical decreasing of displacements in directions *x, z* of seismic excitation is evident.

Coordinate	Without dampers			With dampers		
	$\hat{q}_i^{(x)}$	$\hat{q}_i^{(y)}$	$\hat{q}_i^{(z)}$	$\hat{q}_i^{(x)}$	$\hat{q}_i^{(y)}$	$\hat{q}_i^{(z)}$
x_{RPV} [μ]	120,1	0,74	8,83	40,0	0,44	1,26
y_{RPV} [mm]	0,023	2,55	0,960	0,028	2,38	0,126
z_{RPV} [μ]	3,28	4,35	38,02	1,04	5,51	22,0

Table 2: displacements of the reactor pressure vessel

Coord. of loop	Without dampers						With dampers					
	1	2	3	4	5	6	1	2	3	4	5	6
ξ_{MOIVH}	8,51	9,42	8,90	8,90	9,43	8,51	1,73	2,13	1,88	1,88	2,13	1,73
η_{MOIVH}	16,0	16,6	16,9	16,9	16,6	16,0	3,13	3,58	3,45	3,46	3,53	3,14
ζ_{MOIVH}	23,0	21,5	23,1	24,5	23,1	24,1	2,93	2,91	2,98	3,27	3,27	3,14
ξ_{SG}	15,7	16,8	16,3	16,3	16,8	15,7	2,99	3,60	3,27	3,32	3,67	3,02
η_{SG}	1,14	1,35	1,54	1,56	1,25	1,13	0,76	0,91	1,10	1,10	0,84	0,75
ζ_{SG}	47,3	44,8	49,2	52,4	48,6	50,1	5,38	5,03	5,59	6,05	5,58	5,77
φ_{SG}	6,06	5,50	5,64	5,61	5,50	5,98	0,87	0,96	0,83	0,93	1,08	0,91
ξ_{MCP}	8,98	8,46	9,13	8,95	8,41	8,66	1,21	1,14	1,12	1,12	1,20	1,28
η_{MCP}	~0,02						~ 0,01					
ζ_{MCP}	16,0	14,9	16,2	17,4	16,2	16,7	2,27	2,09	2,05	2,19	2,34	2,56
φ_{MCP}	4,11	3,88	4,25	4,53	4,22	4,35	0,45	0,43	0,47	0,51	0,48	0,49
ξ_{MOIVC}	4,48	4,17	4,37	4,65	4,44	4,55	0,80	0,75	0,67	0,70	0,82	0,91
η_{MOIVC}	0,99	1,04	0,91	0,92	1,04	1,00	0,65	0,64	0,62	0,61	0,64	0,66
ζ_{MOIVC}	8,41	7,67	8,12	8,57	8,09	8,34	1,63	1,46	1,32	1,36	1,60	1,86

Table 3: displacements / rotations of selected rigid bodies of primary loops j=1,2,..,6 (for symbols see Fig.4) in [mm] / [10^{-3} rad]

CONCLUSIONS

New methodology for calculation of seismic response of primary circuit upgraded with viscous dampers GERB has been presented. The results of numerical calculations can be summarized as follows

- the coupling of main coolant loops with reactor pressure vessel result in slightly different seismic response each other
- the seismic responses of main coolant loops No. 1, 2, 3 are slightly different from loops No. 4, 5, 6. This phenomenon is influenced by the asymmetry of MCP legs
- the viscous dampers installed on the MCL decrease also the seismic response of reactor pressure vessel. Reactor internals are not influenced.
- the pendulum motion of SG is documented (see local coordinate ξ_{SG}). The installed dampers strongly decrease this phenomenon.
- the seismic response of cuted off main coolant loops with boundary condition clamping to infinite rigid body (simulation of reactor) is higher than the same ones if they are coupled with reactor.

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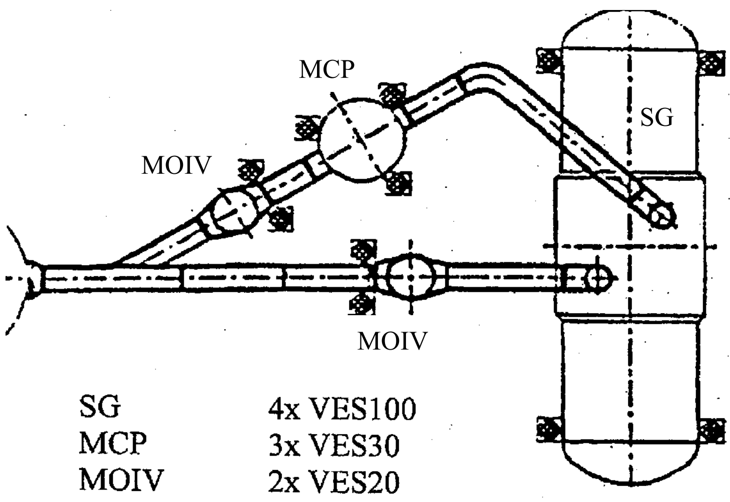

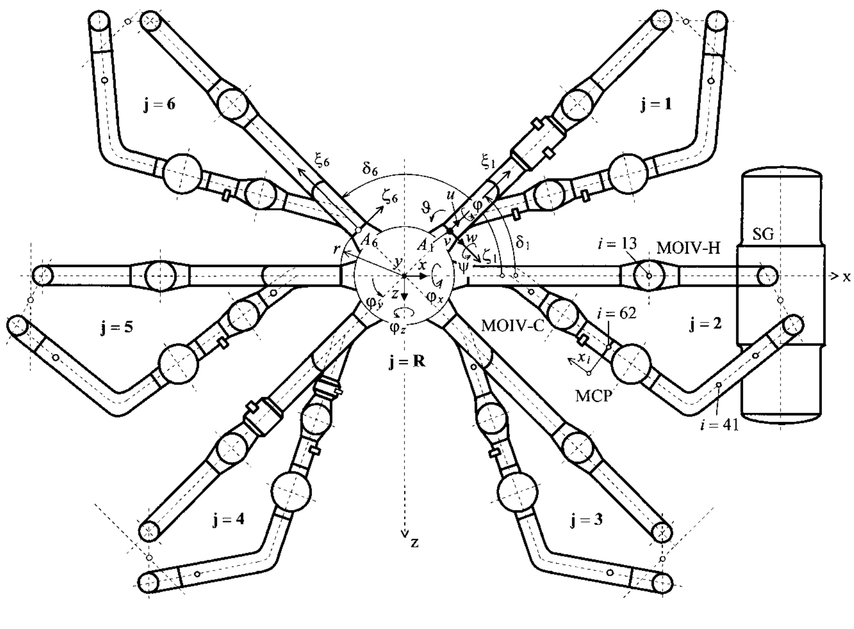

Fig. 2 The dynamic model of primary circuit

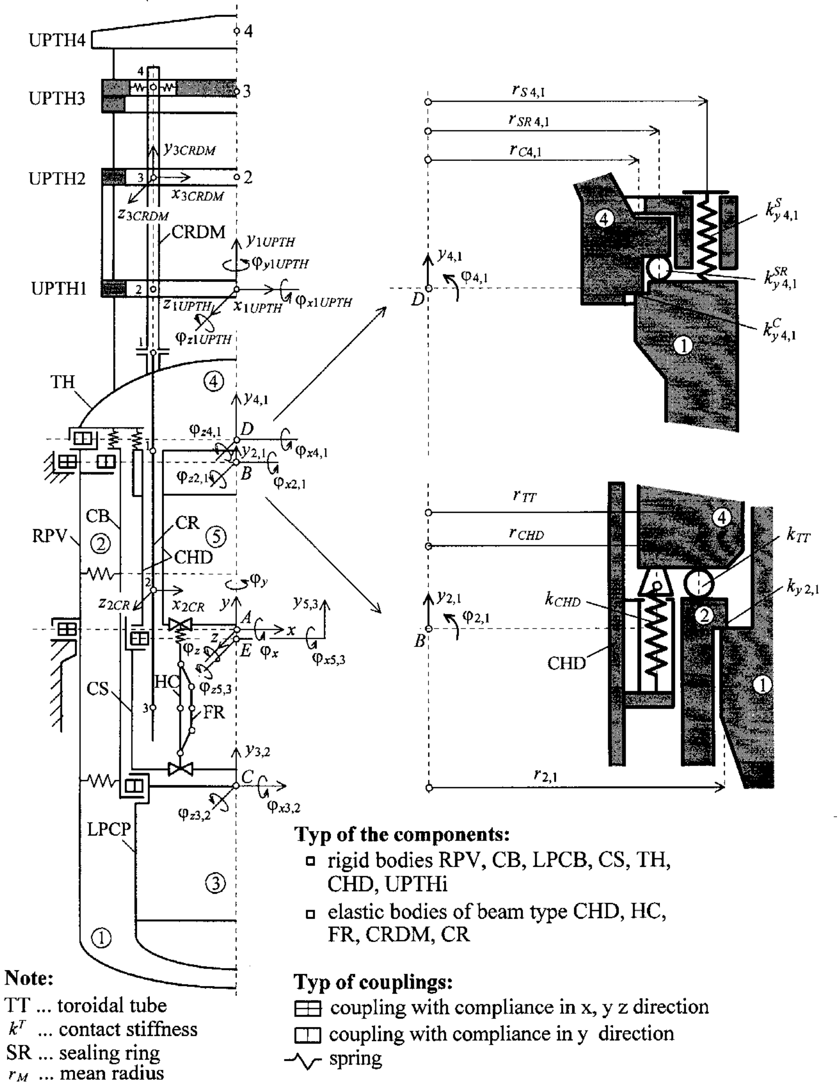

Fig. 3 The dynamical model of WWER 440 reactor

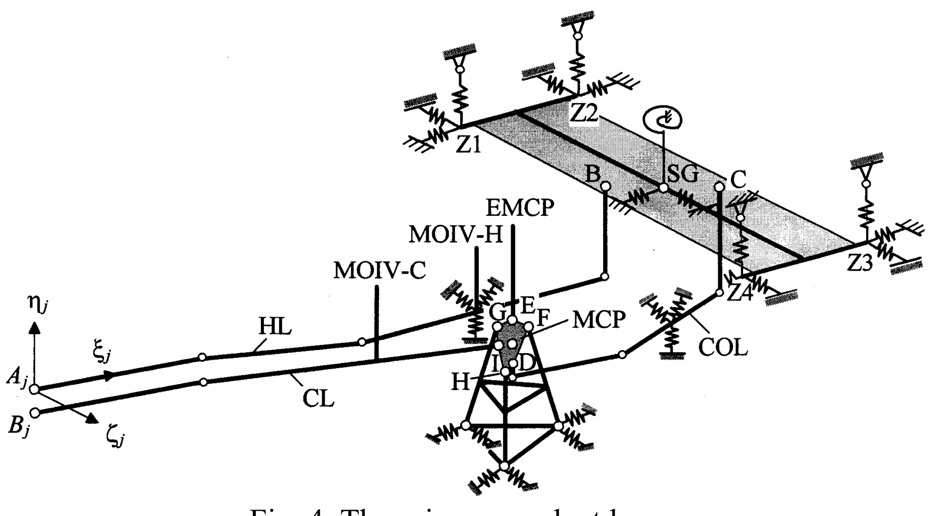

Fig. 4 The primary coolant loop