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SEISMIC RESPONSE OF NUCLEAR FUEL ASSEMBLY COMPONENTS

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Abstract: *The paper deals with mathematical modelling and computer simulation of the seismic deformation and dynamic load of nuclear fuel assembly components. The seismic excitation is given by two horizontal and one vertical synthetic accelerogram at the level of the reactor pressure vessel suspension in the reactor hall. The seismic vibration is investigated by numerical integration method in time domain in two phases – at the global reactor level and at the fuel assembly level. Seismic vibration of the nuclear fuel assembly is caused by spatial motion of the fuel assembly lower and head pieces fixed in the support plates of the reactor core. The modal synthesis method with DOF reduction is used for calculation of the fuel assembly component deformations and dynamic load on the level of the spacer grid cells. The presented method is applied for the Russian TVSA-T fuel assembly in the WWER 1000/320 type reactor core in NPP Temelín.*

Keywords: Seismic response, Reactor, Fuel assembly, Condensation.

1. Introduction

One of the basic operation conditions of the nuclear reactor and its components is the guarantee of the feasible seismic response. The seismic action is most represented by the acceleration response spectra or by the synthetic accelerograms corresponding to given response spectra generally for damping value 2% - 10% (Betbeder-Matibet, 2008). An assessment of nuclear fuel assemblies (FA) behaviour at standard and extreme operating conditions belongs to important safety and reliability audit. A significant part of FA assessment plays dynamic deformation and load of FA components especial of fuel rods (FR). The beam type FA model used in seismic analyses of WWER type reactors (Hlaváč and Zeman, 2010) do not enable investigation of seismic deformations and load of FA components. The goal of this contribution, in direct sequence at an interpretation of FA modelling, modal analysis and calculation of dynamic response caused by pressure pulsation (Hlaváč and Zeman, 2013), is a presentation of the newly developed method for seismic analysis of FA components.

2. Condensed Mathematical Model of the Fuel Assembly

In order to model, the hexagonal type FA (Fig. 1 and Fig. 2) is divided into subsystems – six identical rod segments s = 1, 2, …, 6, centre tube (CT) and load-bearing skeleton (LS). Each rod segment of the TVSA-T FA (on Fig. 2 drawn in lateral FA cross section and circumscribed by triangles) is composed of 52 fuel rods with fixed bottom ends in lower piece (LP) and 3 guide thimbles (GT) fully restrained in lower and head pieces (HP). The fuel rods and guide thimbles are linked by transverse spacer grids $g = 1, 2, \ldots, 8$ of three types (SG1-SG3) inside the segments. All FA components are modelled as one dimensional continuum of beam type with nodal points in the gravity centres of their cross-sections on the level of the spacer grids.

The mathematical model of the rod segment s was derived in the coordinate system (Hlaváč and Zeman, 2013)

$$\mathbf{q}_s = \left[\mathbf{q}_{1,s}^T, \ldots, \mathbf{q}_{r,s}^T, \ldots, \mathbf{q}_{55,s}^T\right], \quad r = 1, \ldots, 55, \; s = 1, \ldots, 6, \tag{1}$$

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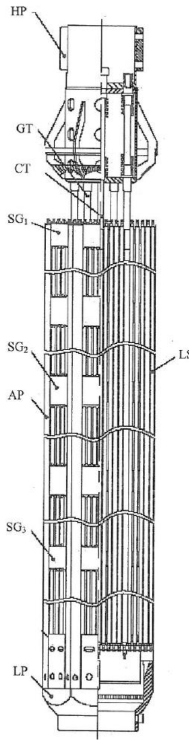

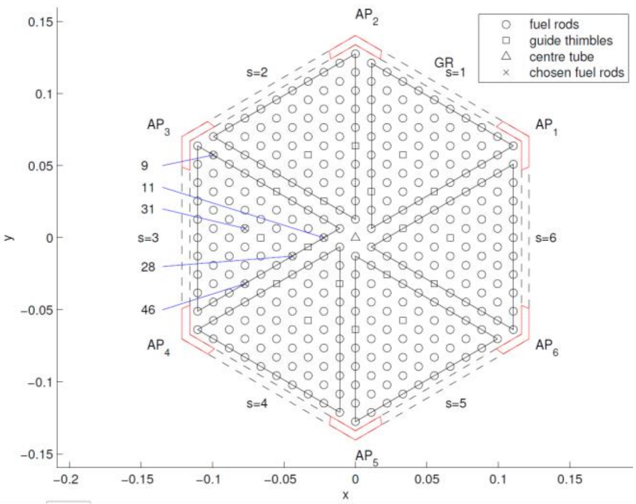

Fig. 1: Fuel assembly.

Fig. 2: Fuel assembly cross-section.

where $\mathbf{q}_{r,s}$ is vector of absolute lateral and bending displacements in nodal points of one rod r (fuel rod or guide thimble) in segment s on the level of all spacer grids $g = 1, \ldots, 8$. The other subsystems – centre tube (CT) and load-bearing skeleton (LS) assembled from six angle pieces (AP) coupled by grid rims (GR) – are modelled similarly as one dimensional continua. The vectors $\mathbf{q}_s$ of generalized coordinates of the subsystems loosed in kinematical excited nodes fixed by means of LP and HP into lower (L) and upper (U) support plates, can be partitioned in the form

$$\mathbf{q}_s = \left[\left(\mathbf{q}_L^{(s)}\right)^T, \left(\mathbf{q}_F^{(s)}\right)^T, \left(\mathbf{q}_U^{(s)}\right)^T\right]^T, \quad s = 1, 2, \ldots, 6, \ CT, \ LS. \tag{2}$$

The displacements of free subsystem nodes (uncoupled with support plates) are integrated in vectors $\mathbf{q}_F^{(s)} \in R^{n_s}$. The transformation between displacements of the all kinematical excited nods of the subsystems and support plates in their gravity centres can be expressed in the global matrix form

$$\mathbf{q}_X^{(s)} = \mathbf{T}_X^{(s)} \mathbf{q}_X, \quad s = 1, 2, \ldots, 6, \ CT, \ LS, \quad X = L, U. \tag{3}$$

The vectors $\mathbf{q}_X$ of support plates $X = L, U$ absolute displacements result from seismic response of the reactor global model (Hlaváč and Zeman, 2010), where the fuel assemblies are replaced by beams.

The conservative mathematical models of the loosed subsystems in the decomposed block form corresponding to partitioned vectors according to (2) can be written as

$$\begin{bmatrix} \mathbf{M}_L^{(s)} & \mathbf{M}_{L,F}^{(s)} & \mathbf{0} \\ \mathbf{M}_{F,L}^{(s)} & \mathbf{M}_F^{(s)} & \mathbf{M}_{F,U}^{(s)} \\ \mathbf{0} & \mathbf{M}_{U,F}^{(s)} & \mathbf{M}_U^{(s)} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{q}}_L^{(s)} \\ \ddot{\mathbf{q}}_F^{(s)} \\ \ddot{\mathbf{q}}_U^{(s)} \end{bmatrix} + \begin{bmatrix} \mathbf{K}_L^{(s)} & \mathbf{K}_{L,F}^{(s)} & \mathbf{0} \\ \mathbf{K}_{F,L}^{(s)} & \mathbf{K}_F^{(s)} & \mathbf{K}_{F,U}^{(s)} \\ \mathbf{0} & \mathbf{K}_{U,F}^{(s)} & \mathbf{K}_U^{(s)} \end{bmatrix} \begin{bmatrix} \mathbf{q}_L^{(s)} \\ \mathbf{q}_F^{(s)} \\ \mathbf{q}_U^{(s)} \end{bmatrix} = \begin{bmatrix} \mathbf{f}_L^{(s)} \\ \mathbf{f}_C^{(s)} \\ \mathbf{f}_U^{(s)} \end{bmatrix}, \tag{4}$$

where letters $\mathbf{M}\ (\mathbf{K})$ correspond to mass (stiffness) submatrices of the subsystems. The force subvector $\mathbf{f}_C^{(s)}$ expresses the coupling forces between subsystem s and adjacent subsystems transmitted by spacer grids. The force subvectors $\mathbf{f}_L^{(s)}$ and $\mathbf{f}_U^{(s)}$ express the forces acting in kinematical excited nodes.

The detailed model of FA has to large DOF number for calculation of seismic response excited by FA support plate seismic motion. Therefore we assemble the FA condensed model with reduced DOF number. The vectors $\mathbf{q}_F^{(s)}$ of dimension n_s, corresponding to free nodes of subsystems, can be approximately transformed in the form

$$\mathbf{q}_F^{(s)} = {}^m\mathbf{V}_s\ \mathbf{x}_s\,,\ \mathbf{x}_s \in R^{m_s} \quad s = 1,\ 2,\ ...,\ 6,\ CT,\ LS\,, \tag{5}$$

where ${}^m\mathbf{V}_s \in R^{n_s\, m_s}$ are modal submatrices compound out of chosen m_s master eigenvectors of subsystems fixed in kinematical excited nodes. The second set of equations extracted from (4) for each subsystem can be rewritten using (5) and orthonormality conditions

$${}^m\mathbf{V}_s^T\ \mathbf{M}_F^{(s)}\ {}^m\mathbf{V}_s = \mathbf{E},\quad {}^m\mathbf{V}_s^T\ \mathbf{K}_F^{(s)}\ {}^m\mathbf{V}_s = {}^m\mathbf{\Lambda}_s\,,\quad s = 1,\ 2,\ ...,\ 6,\ CT,\ LS \tag{6}$$

in the form

$$\ddot{\mathbf{x}}_s(t) + {}^m\mathbf{\Lambda}_s\,\mathbf{x}_s(t) = -{}^m\mathbf{V}_s^T \sum_{X=L,U}\left[\mathbf{M}_{F,X}^{(s)}\ \mathbf{T}_X^{(s)}\ \ddot{\mathbf{q}}_X + \mathbf{K}_{F,X}^{(s)}\ \mathbf{T}_X^{(s)}\,\mathbf{q}_X\right] + {}^m\mathbf{V}_s^T\ \mathbf{f}_C^{(s)}\ , \tag{7}$$

where spectral submatrices ${}^m\mathbf{\Lambda}_s \in R^{m_s,\, m_s}$ correspond to chosen master eigenvectors in ${}^m\mathbf{V}_s$. The model (7) of all subsystems can be written in the configuration space $\mathbf{x} = [\mathbf{x}_s]$ of dimension $m = \sum m_s$ as

$$\ddot{\mathbf{x}}(t) + \left(\mathbf{\Lambda} + \mathbf{V}^T\,\mathbf{K}_C\,\mathbf{V}\right)\mathbf{x}(t) = -\mathbf{V}^T \sum_{X=L,U}\left[\mathbf{M}_X\ \ddot{\mathbf{Q}}_X(t) + \mathbf{K}_X\ \mathbf{Q}_X(t)\right], \tag{8}$$

where global vector of coupling forces between subsystems is $\mathbf{f}_C = \left[\mathbf{f}_C^{(s)}\right] = -\mathbf{K}_C\,\mathbf{q}_F$. Matrix $\mathbf{K}_C$ is stiffness matrix of all couplings between subsystems derived in monograph Hlaváč and Zeman (2013) for Russian TVSA-T fuel assembly and $\mathbf{q}_F = \left[\mathbf{q}_F^{(s)}\right] = \mathbf{V}\ \mathbf{x}(t)$. Matrices $\mathbf{\Lambda} = diag\left[{}^m\Lambda_s\right] \in R^{n,m}$, $\mathbf{V} = diag\left[{}^m\mathbf{V}_s\right] \in R^{n,m}$, $\mathbf{M}_X = diag\left[\mathbf{M}_{F,X}^{(s)}\ \mathbf{T}_X^{(s)}\right]$, $\mathbf{K}_X = diag\left[\mathbf{K}_{F,X}^{(s)}\ \mathbf{T}_X^{(s)}\right] \in R^{n,\,48}$, $n = \sum n_s$, $X = L,U$ are block diagonal, composed from corresponding matrices of subsystems. Vectors $\mathbf{Q}_X = \left[\mathbf{q}_X^T,\ ...,\ \mathbf{q}_X^T\right]^T \in R^{48},\ X = L,U$ are assembled for eight times repeating support plate displacement vectors.

In consequence of slightly damped FA components we consider modal damping of the subsystems characterized in the space of modal coordinates $\mathbf{x}_s$ by diagonal matrices $\mathbf{D}_s = diag\left[2\,D_\nu^{(s)}\ \Omega_\nu^{(s)}\right]$, where $D_\nu^{(s)}$ are damping factors of natural modes and $\Omega_\nu^{(s)}$ are eigenfrequencies of the mutually uncoupled subsystems. The damping of spacer grids can be approximately expressed by damping matrix $\mathbf{B}_C = \beta\mathbf{K}_C$ proportional to stiffness matrix $\mathbf{K}_C$. The conservative condensed model (8) can be completed in the form

$$\ddot{\mathbf{x}}(t) + \left(\mathbf{D} + \beta\,\mathbf{V}^T\mathbf{K}_C\,\mathbf{V}\right)\dot{\mathbf{x}}(t) + \left(\mathbf{\Lambda} + \mathbf{V}^T\mathbf{K}_C\,\mathbf{V}\right)\mathbf{x}(t) = -\mathbf{V}^T \sum_{X=L,U}\left[\mathbf{M}_X\ \ddot{\mathbf{Q}}_X(t) + \mathbf{K}_X\ \mathbf{Q}_X(t)\right], \tag{9}$$

where $\mathbf{D} = diag\left[\mathbf{D}_s\right]$ is block diagonal matrix composed from damping matrices of subsystems.

3. Seismic Response of the Fuel Assembly Components

The FA seismic response in coordinates $\mathbf{x}(t)$ can be investigated by integration of motion equations (9) transformed into 2m differential equations of the first order using standard software (for example ODE45 in MATLAB code). We obtain the numerical values of the vector $\mathbf{x}(t_k)$ components in time steps. According to (5) we get the vector $\mathbf{q}_F^{(s)}(t_k) = {}^m\mathbf{V}_s\ \mathbf{x}_s(t_k)$ for select FA subsystem.

As an illustration, the time behaviour of lateral deformation of the chosen FR $r = 31$ in segment $s = 3$ on the level of the spacer grid $g = 8$ in the Russian TVSA-T FA of the WWER 1000/320 type reactors in

NPP Temelín (Hlaváč and Zeman, 2010) is presented in Fig. 3. The condensed FA model (9) with 650 DOF ($m_S = 100, m_{CT} = 20, m_{LS} = 30$) place of original model with 10 832 DOF ($n_S = 1760, n_{CT} = 32, n_{LS} = 240$), was used for numerical integration.

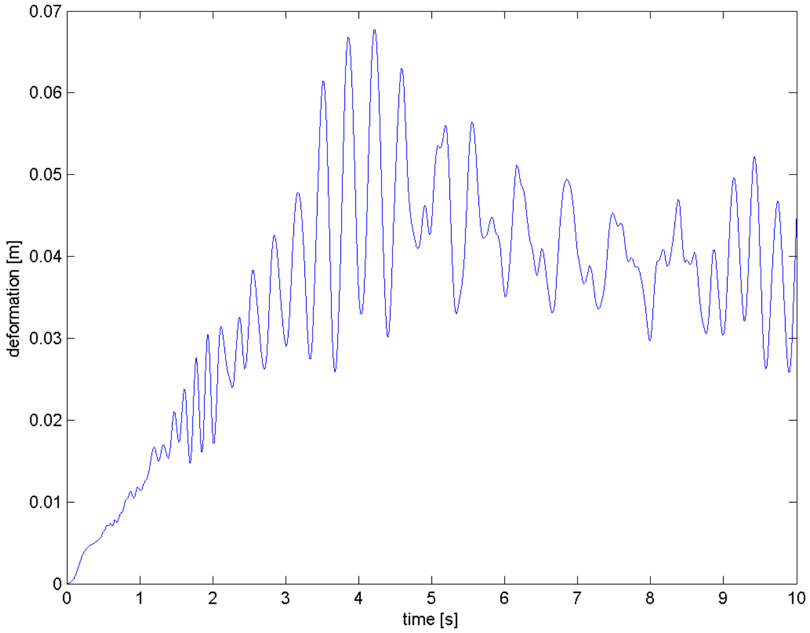

Fig. 3: Seismic deformation.

4. Conclusions

The described method, based on the FA decomposition and modal synthesis method with reduction of DOF number, enables to investigate effectively seismic response of the FA components. The FA seismic vibrations are caused by spatial motion of the supporting plates in the reactor core transformed into displacements of the kinematically excited nodes of the fuel assembly components – fuel rods, guide thimbles, centre tube and skeleton angle pieces – linked by spacer grids.

The developed methodology was used for seismic response of the Russian type nuclear fuel assembly. The developed software in MATLAB code is conceived in such a way that enables to calculation of the displacements and deformation of the arbitrary FA component on the arbitrary spacer grid level.

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