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Modelling of nuclear fuel assemblies vibration in mutual interaction

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1. Introduction

The coolant pressure pulsations generated by the main circulation pumps in the coolant loops are one of the main sources of reactor excitation [1]. The vibrations of the VVER 1000-type reactor and its components caused by the coolant pressure pulsations was investigated in previous authors' research works on a linearized model of the reactor [2]. This model was later modified by the effect of the friction-vibration interactions in the reactor core barrel (CB) couplings with clearances [4]. The fuel assemblies (FAs) vibration without mutual interaction respecting new knowledge about excitation by coolant pressure pulsation measured at NPP Temelín [3] was published in [5]. The aim of the paper is to present an approach to the modelling of chosen FA vibration inside the reactor core with the possibility of interaction with the surrounding FAs.

2. A concept of modelling the FAs dynamic behavior

The general idea of the method is based on two-stage modelling concept depicted in Fig. 1. The first stage model represents the global nonlinear model of the reactor and the second stage model is model of the FAs group composed of the reference fuel assembly FA_i surrounded by up to six fuel assemblies FA_j (see Fig. 2).

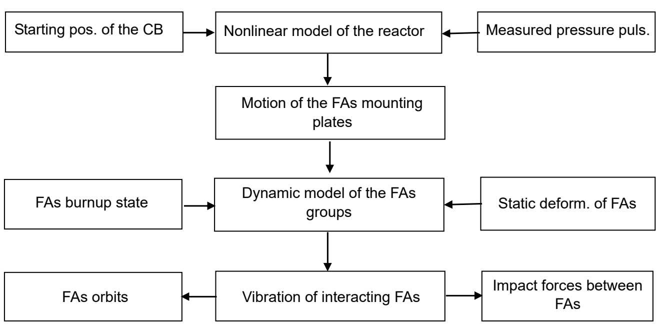

Fig. 1. A concept of modelling the FAs dynamic behavior

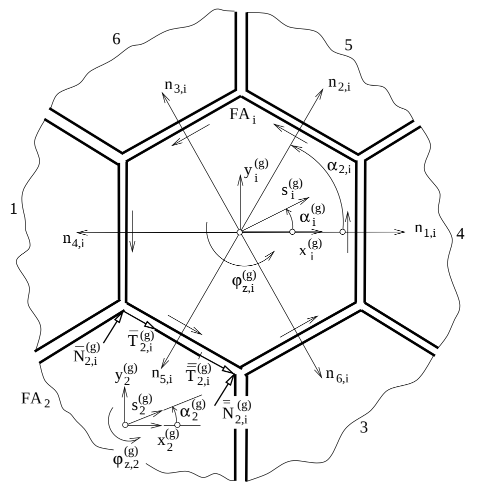

Fig. 2. A group of the FAs within the reactor core

Movement of FA mounting plates investigated on a global reactor model is the source of the FAs kinematics excitation. Interactions between FA_i and FA_j may arise as a result static deformation FAs. Static deformations are described by horizontal displacements $s_i^{(g)}$ and

$s_j^{(g)}$, $j \in \{1,\dots,6\}$ of the FA centers at the level of the spacer grids $g = 1,\dots,8$ from an ideal position. The directions of FAs static deformation are described by angles $\alpha_i^{(g)}$ and $\alpha_j^{(g)}$.

Contact of load-bearing skeleton of interacting hexagonal FAs can be assumed in the area of the vertices of the angles at the level of the spacer grids (Fig. 2). Which pair of vertices of the FA_j and FA_i angles on the contact line will be active depends on the relative transverse displacements. Relative displacements in the direction of the contact normal $n_{j,i}$, $j = 1,\dots,6$ of the vertices pairs on the common contact line can be described in the form

$$\bar{n}_{j,i}^{(g)}=s_j^{(g)}\cos(\alpha_{j,i}-\alpha_j^{(g)})-s_i^{(g)}\cos(\alpha_{j,i}-\alpha_i^{(g)})+(x_j^{(g)}-x_i^{(g)})\cos\alpha_{j,i}+(y_j^{(g)}-y_i^{(g)})\sin\alpha_{j,i}-h(\varphi_{z,j}-\varphi_{z,i}), \quad (1)$$

$$\bar{\bar{n}}_{j,i}^{(g)}=s_j^{(g)}\cos(\alpha_{j,i}-\alpha_j^{(g)})-s_i^{(g)}\cos(\alpha_{j,i}-\alpha_i^{(g)})+(x_j^{(g)}-x_i^{(g)})\cos\alpha_{j,i}+(y_j^{(g)}-y_i^{(g)})\sin\alpha_{j,i}+h(\varphi_{z,j}-\varphi_{z,i}), \quad (2)$$

where $\alpha_{j,i}$ are the angles of the contact normals and h is the half length of one contact line. Relative displacements of both pairs in the marked directions of the contact line are

$$t_{j,i}^{(g)}=s_j^{(g)}\sin(\alpha_{j,i}-\alpha_j^{(g)})-s_i^{(g)}\sin(\alpha_{j,i}-\alpha_i^{(g)})+(x_j^{(g)}-x_i^{(g)})\sin\alpha_{j,i}-(y_j^{(g)}-y_i^{(g)})\cos\alpha_{j,i}-\sqrt{3}h(\varphi_{z,j}-\varphi_{z,i}). \quad (3)$$

Rigid plate bodies of the FAs load-bearing skeleton (spacer grids parts of the angles in width at the rims) perform a spatial motion arround the statically deformed FAs described by vector of generalized coordinates

$$\boldsymbol{q}_j = [\dots, x_j^{(g)}, y_j^{(g)}, z_j^{(g)}, \varphi_{x,j}^{(g)}, \varphi_{y,j}^{(g)}, \varphi_{z,j}^{(g)}, \dots]^T \in R^{330},\ j = 1,\dots,6,\ g = 1,\dots,8 \quad (4)$$

and $\boldsymbol{q}_i$ respectively. Index g indicates the order of spacer grids. Transverse coordinates $x_i^{(g)}$, $y_i^{(g)}$, $z_i^{(g)}$, $y_j^{(g)}$ and torsion coordinates $\varphi_{z,i}^{(g)}$, $\varphi_{z,j}^{(g)}$ of the load-bearing skeleton affect the total (static and dynamic) relative displacements at possible contact points, see equations (1) – (3).

The contact forces between the interacting FAs, due to the mounting transverse clearances δ between neighboring FAs, have an impact character. Normal components $\bar{N}_{j,i}^{(g)}$ and $\bar{\bar{N}}_{j,i}^{(g)}$ of contact forces on one contact line and at the level of the grid g (see Fig. 2 for $j = 2$) can be written in the form

$$\bar{N}_{j,i}^{(g)} = k_C(n_{j,i}^{(g)} - \delta)H_1(n_{j,i}^{(g)} - \delta)H_2(t_{j,i}^{(g)})\,,\ \bar{\bar{N}}_{j,i}^{(g)} = k_C(n_{j,i}^{(g)} - \delta)H_1(n_{j,i}^{(g)} - \delta)H_2(-t_{j,i}^{(g)})\,, \quad (5)$$

where k_C is the contact stiffness between angles of the load-bearing skeleton. A necessary condition for the activation of any of the 96 normal contact forces (for $j = 1,\dots,6$ and $g = 1,\dots,8$) is a positive argument of the Heaviside function H_1. A sufficient condition is at the same time a positive argument of the Heaviside function H_2, which decides on the activation of one of the pairs of normal contact forces on the same contact line. Activated normal contact forces generate friction forces

$$\bar{T}_{j,i}^{(g)} = f(\dot{t}_{j,i}^{(g)})\bar{N}_{j,i}^{(g)} \text{ or } \bar{\bar{T}}_{j,i}^{(g)} = f(\dot{t}_{j,i}^{(g)})\bar{\bar{N}}_{j,i}^{(g)}\,. \quad (6)$$

The friction coefficient $f(\dot{t}_{j,i}^{(g)})$ is approximated by smooth function on the resulting sliding velocity $\dot{t}_{j,i}^{(g)}$ [4].

3. Mathematical model of the FAs group within the reactor core

The mathematical model of the group of seven FAs (see Fig. 2) can be written in the form

$$\mathrm{diag}[\boldsymbol{M}_{PS},..,\boldsymbol{M}_{PS}]\begin{bmatrix}\ddot{\boldsymbol{q}}_i\\ \ddot{\boldsymbol{q}}_1\\ \vdots\\ \ddot{\boldsymbol{q}}_6\end{bmatrix}+\mathrm{diag}[\boldsymbol{B}_{PS},..,\boldsymbol{B}_{PS}]\begin{bmatrix}\dot{\boldsymbol{q}}_i\\ \dot{\boldsymbol{q}}_1\\ \vdots\\ \dot{\boldsymbol{q}}_6\end{bmatrix}+\mathrm{diag}[\boldsymbol{K}_{PS},..,\boldsymbol{K}_{PS}]\begin{bmatrix}\boldsymbol{q}_i\\ \boldsymbol{q}_1\\ \vdots\\ \boldsymbol{q}_6\end{bmatrix}=\begin{bmatrix}\boldsymbol{f}_i^{KE}\\ \boldsymbol{f}_1^{KE}\\ \vdots\\ \boldsymbol{f}_6^{KE}\end{bmatrix}+\begin{bmatrix}\sum_{j=1}^{6}\boldsymbol{f}_{j,i}^{C}\\ \boldsymbol{f}_{i,1}^{C}\\ \vdots\\ \boldsymbol{f}_{i,6}^{C}\end{bmatrix}, \quad (7)$$

where $\boldsymbol{M}_{PS}$, $\boldsymbol{B}_{PS}$, $\boldsymbol{K}_{PS}$ are the matrices of mass, damping and stiffness of one linearized FA. The kinematic excitation vectors $\boldsymbol{f}_i^{KE}$ and $\boldsymbol{f}_j^{KE}$ differ in cooordinates describing the position of their axes in the reactor core. Vectors of contact forces $\boldsymbol{f}_{j,i}^{C}$ and $\boldsymbol{f}_{i,j}^{C}$, $j = 1, \ldots, 6$, $g = 1, \ldots, 8$ are expressed by means of normal componnets $\bar{N}_{j,i}^{(g)}$, $\bar{\bar{N}}_{j,i}^{(g)}$ and friction forces $\bar{T}_{j,i}^{(g)}$, $\bar{\bar{T}}_{j,i}^{(g)}$. If, based on the calculation of the arguments of the Heaviside functions H_1 and H_2 in (5), the normal components are not activated at any spacer grid level, the corresponding vectors $\boldsymbol{f}_{j,i}^{C}$ and $\boldsymbol{f}_{i,j}^{C}$ are zero.

The dimension of global vectors of generalized coordinates of all FAs in a group (specifically $7 \cdot 330 = 2310$) is too large. Therefore, it is expedient to use the modal reduction of generalized coordinates of individual FAs. If the reference FA_i is not surrounded by any of the FA_j or if contact with any of the FA_j can be excluded, corresponding block line in model (7) is deleted.

4. Result of numerical simulations

To demonstrate the presented method, dynamic response of the three configurations of hexagonal FA_2 and FA_5 (see Fig. 3) statically deformed in the shape of a "banana" applied in the VVER 1000-type reactor was analysed. Dynamic orbits of the reference FA_i centers in a short time interval at the level of the spacer grids 4, 5 for the configuration of Fig. 3b, they are shown in Fig. 4. The normal components of the impact forces between reference FA_i an surrounding FA_2 and FA_5 at the level of spacer grids 4 and 5 are shown in Figs. 5 and 6. The analysis of the different configurations of statically deformed FAs shows a large change in the dynamic behavior of interacting FAs.

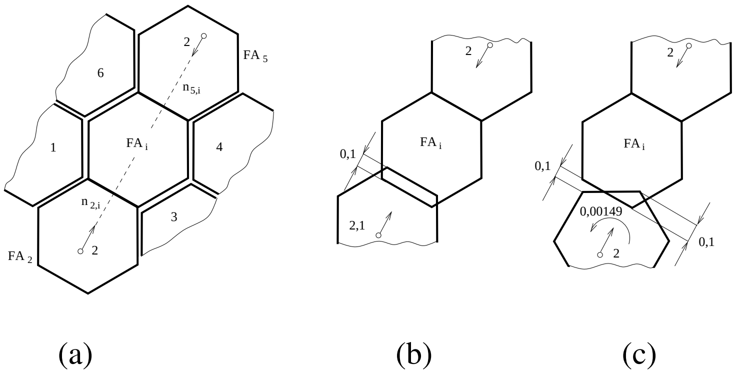

Fig. 3. Selected configurations of the statically deformed FA_2 and FA_5 (in mm) at the level of the grids 4 and 5

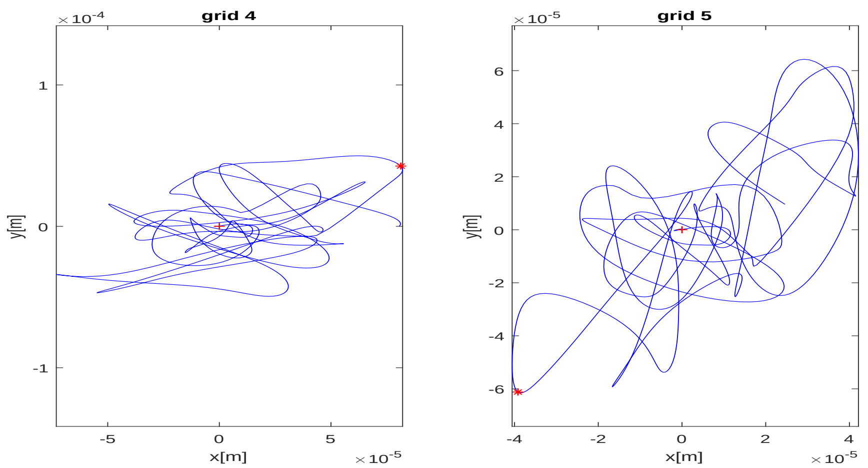

Fig. 4. Dynamic orbits of the reference FA_i centers at the level of grids 4,5 (+ origin, * extreme)

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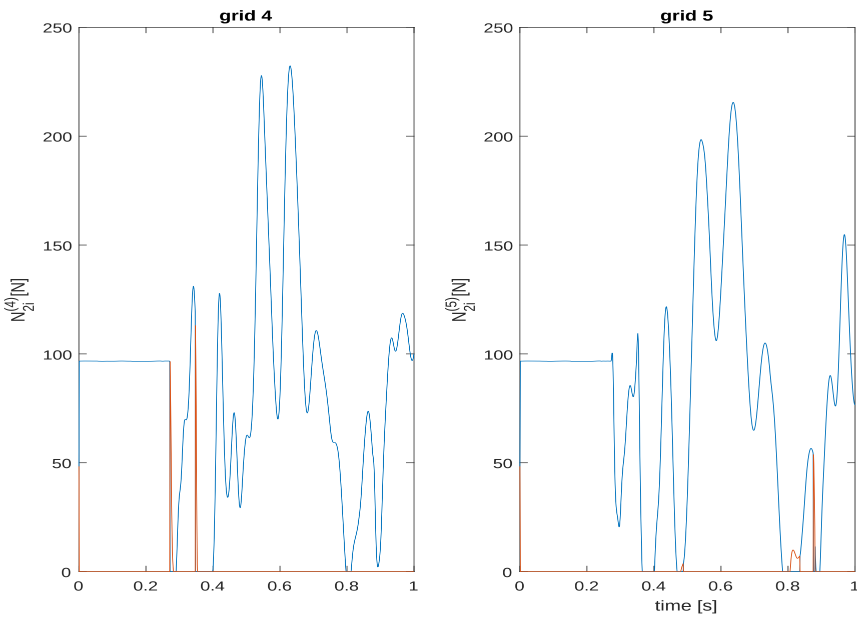

Fig. 5. Normal components of the impact forces between FA_i and FA_2 ($\bar{N}$ red, $\bar{\bar{N}}$ blue)

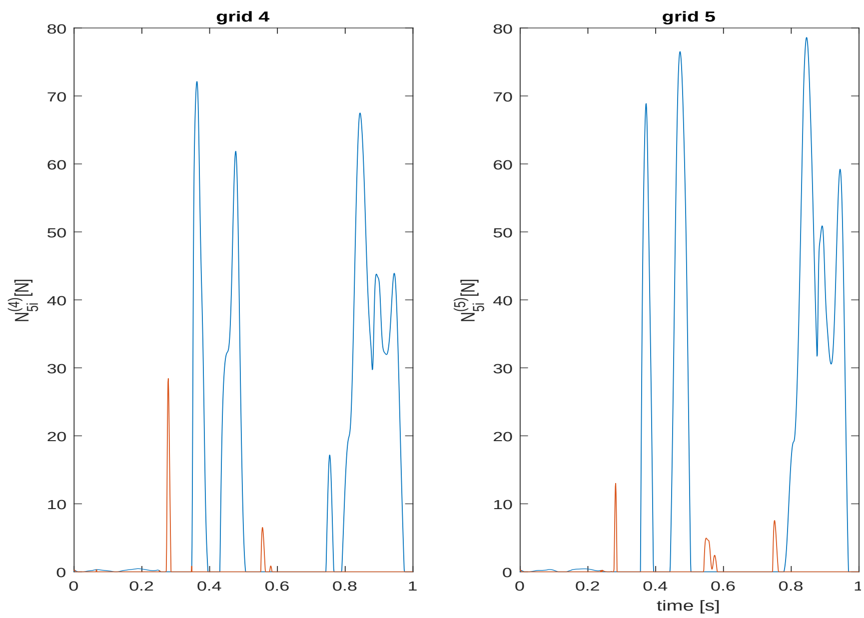

Fig. 6. Normal components of the impact forces between FA_i and FA_5 ($\bar{N}$ red, $\bar{\bar{N}}$ blue)

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