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Application of spectral tuning on the dynamic model of the reactor VVER 1000 support cylinder

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Abstract

The paper deals with the optimization of parameters of the dynamic model of the reactor VVER 1000 support cylinder. Within the model of the whole reactor, support cylinder appears to be a significant subsystem for its modal properties having dominant influence on the behaviour of the reactor as a whole. Relative sensitivities of eigenfrequencies to a change of the discrete parameters of the model were determined. Obtained values were applied in the following spectral tuning process of the (selected) discrete parameters. Since the past calculations have shown that spectral tuning by the changes of mass parameters is not effective, the presented paper demonstrates what results are achieved when the set of the tuning parameters is extended by the geometric parameters. Tuning itself is then formulated as an optimization problem with inequalities.
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1. Introduction

The tuning of the dynamic model was based on the values of eigenfrequencies that were computed on the FEM model, and could also be identified on the dynamic model. The computation model, that has been developed in Cosmos/M programming code, contains support cylinder with core barrel housing. The eigenfrequencies obtained by modal analysis of this model represent the objective values for the eigenfrequencies of the tuned dynamic model of the support cylinder.

The tuning of the discrete parameters of the dynamic model of the support cylinder body is the first step of identification of the parameters of the complete VVER 1000 reactor model. It was necessary to use identical boundary conditions for both models so that modal properties of the support cylinder would not be influenced by any other factor. In case of this model, it means that all stiffness parameters, including the gland flange stiffness, the bearing support stiffness and the stiffness of the toroidal pipes, were not considered. The only stiffness element which was considered was the contact stiffness of the support cylinder with the flange of the pressure vessel.

As the past calculations [3] showed, spectral tuning carried out only by changes of mass parameters has not appeared to be effective. Therefore it was necessary to add some other parameters for a new tuning process. It was found reasonable that geometric parameters (thickness of the support cylinder wall and its diameter) could be the suitable ones to extend the set of tuning parameters. The fact that the total weight of the new dynamic model should be approximately the same as the weight of the FEM model is also taken into account. This requirement is represented by two inequality constraints. Further, the changes of all discrete pa-

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rameters shouldn't be radical. This is provided by imposing appropriate lower and upper bound for each tuning parameter.

After the tuning of the discrete parameters of the support cylinder the dynamic model will be tested by modal analysis. Providing the desired results are achieved, the stiffness parameters mentioned above could be included. At the meantime, the core containing 163 fuel cassettes will be implemented, and next tuning processes will then follow.

2. Spectral tuning

The aim of tuning of a mathematical model of a mechanical system is to change the values of parameters (mass, stiffness, geometric) to new values that provide achieving required characteristic values. In case of spectral tuning they are represented by eigenfrequencies.

Mechanical system is assumed to be undamped. Mass, stiffness, or geometric parameters, that will be changed to tune the mathematical model, constitute a vector $\boldsymbol{p} = [p_j]$ where $j = 1, \ldots, s$ of tuning parameters. Characteristic values, which are selected eigenfrequencies in this case, and which are imposed some requirements, constitute a vector $\boldsymbol{l} = [l_i]$ where $i = 1, \ldots, k$. This vector is called a *vector of tuning*.

Selected tuned quantities depend (by means of coefficient matrices $\boldsymbol{M}$ and $\boldsymbol{K}$ of the mathematical model) on the selected tuning parameters. Thus, we may put $\boldsymbol{l} = \boldsymbol{l}(\boldsymbol{p})$ where $\boldsymbol{l}(\boldsymbol{p})$ is a transformation from a space R^s into a space R^k. Hence, the tuning problem can be formulated as a problem of finding a vector $\boldsymbol{p}^*$ which satisfies

$$\boldsymbol{l}(\boldsymbol{p}^*) = \boldsymbol{l}^*, \tag{1}$$

where $\boldsymbol{l}^*$ is a vector of required values of eigenfrequencies. Dimension of this vector is k.

Let's assume that the transformation $\boldsymbol{l}(\boldsymbol{p})$ is differentiable in the neighbourhood of the starting point $\boldsymbol{p_0}$. Let's define a Jacobi matrix of the transformation $\boldsymbol{l}(\boldsymbol{p})$ as

$$\boldsymbol{L}(\boldsymbol{p}) = \begin{bmatrix} grad^T l_1(\boldsymbol{p_0}) \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ grad^T l_k(\boldsymbol{p_0}) \end{bmatrix} = \left[\frac{\partial l_i}{\partial p_j}(\boldsymbol{p_0}) \right], \quad \begin{array}{l} i = 1, \ldots, k; \\ j = 1, \ldots, s. \end{array} \tag{2}$$

The Jacobi matrix $\boldsymbol{L}$ is called a *matrix of sensitivity*. Generally, it is a rectangular matrix of dimension (k,s) where its element in the i-th row and in the j-th column determines the rate of a change of a quantity l_j with respect to a unit change of a quantity p_j. It expresses the sensitivity of a change of the i-th tuned quantity (eigenfrequency Ω_i) to a change of the j-th tuning parameter. Thus, we deal with *absolute sensitivity* having its dimension corresponding to the dimension of the model parameters.

However, more useful information is provided when *relative sensitivity* is used. The advantage of relative sensitivity is that it is related to unit frequency and unit parameter p_j, therefore it enables the comparison of particular sensitivities. For the relative sensitivity l_{ij} of the changes of the i-th eigenfrequency to a change of the j-th parameter we may write

$$l_{ij} = \frac{\partial \Omega_i}{\partial p_j} \cdot \frac{p_j}{\Omega_i}. \tag{3}$$

3. Tuning as an optimization problem

The (selected) tuned parameters form a vector of tuning $\boldsymbol{l} = [l_i]_{i=1}^{k}$, the selected tuning parameters form a vector $\boldsymbol{p} = [p_i]_{i=1}^{s}$, and the requirements constitute the vector $\boldsymbol{l}^* = [l_i^*]_{i=1}^{k}$. According to [1], the tuning problem can be formulated by the k-criterion function expressed as

$$\psi(p) = \sum_{i=1}^{k} g_i \left[1 - \frac{l_i(p)}{l_i^*}\right]^2, \tag{4}$$

where g_i is a weight of the i-th parameter. Each tuning parameter p_i must lie in a permissible close range. Values of p_i^d (lower bound of the i-th tuning parameter), and p_i^h (upper bound of the same parameter), are chosen appropriate while the starting point must lie in this region. Incidence with a permissible parameter range is determined by $2s$ inequalities

$$p_i^d \le p_i \le p_i^h, \qquad i = 1, \ldots, s. \tag{5}$$

From the definition (4), it is apparent that $\psi(p) \ge 0$. See that if all requirements are met, then the value of the objective function is zero. If k-multiplicity of the function (4) is not suitable for $k > 1$, then it is possible to choose a preferable (most important) i_0-th requirement of which fulfilment is to be optimized, and the remaining requirements are included in the inequality limitations. Then the objective function of the optimization problem is given by

$$\psi(p) = \left[1 - \frac{l_{i_0}(p)}{l_{i_0}^*}\right]^2. \tag{6}$$

In addition to the limitation (5), the permissible region will also be specified by the limitations

$$l_i^d \le l_i(\boldsymbol{p}) \le l_i^h, \qquad i = 1, \ldots, k; \qquad i \ne i_0, \tag{7}$$

while the bounds l_i^d and l_i^h are suitably chosen.

4. Dynamic model of the reactor VVER 1000 support cylinder

At the Department of Mechanics of the University of West Bohemia in Pilsen, the mathematical model of the reactor VVER 1000 installed in the Temelin NPP has been developed. The evolution of the methodology which has been applied in the modelling of the vibrations of the reactor or the reactor components is documented in [4]. Within this model, the reactor is composed of eight subsystems which are: pressure vessel, support cylinder and core with fuel cassettes, guide tube block, upper block support system, control rod drives housings, block of electromagnets, and drive assemblies. Each subsystem is modelled in a suitably chosen configurational space of one of other subsystems, and coupling stiffnesses are discretized by translational and rotational stiffness elements.

Support cylinder (SC) is modelled in a configurational space of pressure vessel (PV). Its model consists of two stiff bodies (SC1 and SC3) which are connected by one-dimensional beam-type continuum (SC2). The body SC1 is denied relative transverse displacements at the location of its hanging on the pressure vessel flange, and relative rotations about the reactor axis relative to pressure vessel. SC1 can both move longitudinally (vertically), and rotate by bending motion – generalized coordinates y_1, φ_{x_1}, φ_{z_1}. SC2 is divided into two elements by a node at its centre. Plane section passing through the node is enabled general spatial motion - generalized coordinates x_2, y_2, z_2, φ_{x_2}, φ_{y_2}, φ_{z_2}. SC3 can also move by general spatial motion - generalized coordinates x_3, y_3, z_3, φ_{x_3}, φ_{y_3}, φ_{z_3}. The model of the support cylinder has 15 degrees of freedom. Vector of generalized coordinates of the support cylinder then has a following form:

$$q_{SC} = \left[y_1, \varphi_{x_1}, \varphi_{z_1}, x_2, y_2, z_2, \varphi_{x_2}, \varphi_{y_2}, \varphi_{z_2}, x_3, y_3, z_3, \varphi_{x_3}, \varphi_{y_3}, \varphi_{z_3} \right]. \tag{8}$$

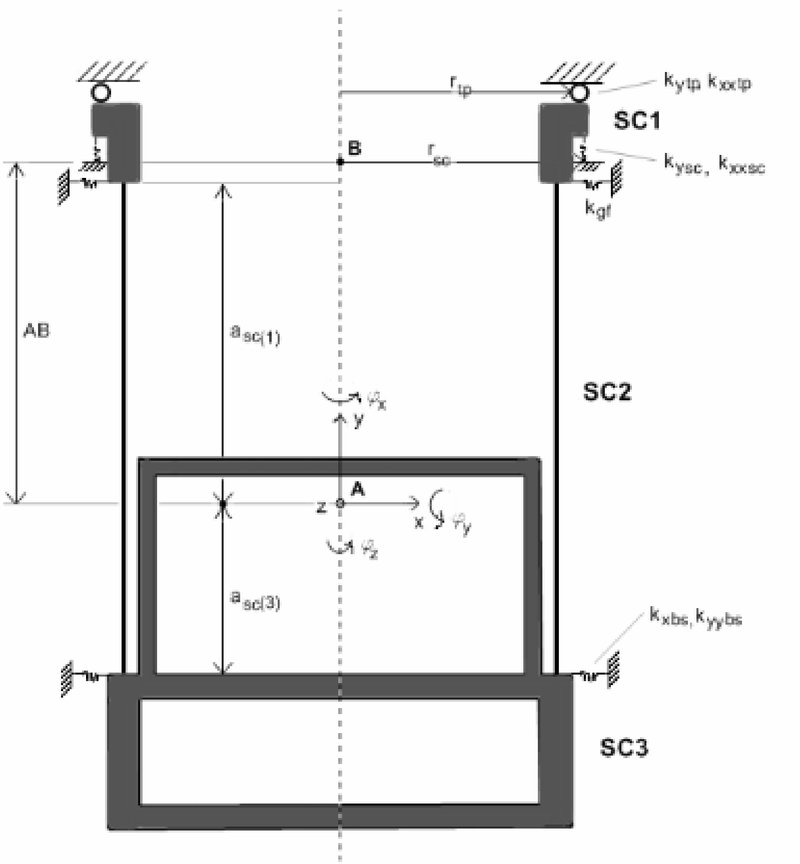

Fig. 1. Scheme of the dynamic model of the support cylinder.

level A – emplacement of the pressure vessel in the reactor concrete pit

level B – hanging of the support cylinder on the pressure vessel flange

2.1. Geometric parameters of the model

- AB = 4.72 m – distance between A and B,
- $a_{SC(1)}$ = 4.02 m – distance between the upper node of the tube SC2 and the horizontal plane passing through A,
- $a_{SC(3)}$ = 2.56 m – distance between the lower node of the tube SC2 and the horizontal plane passing through A,

- r_{SC} = 1.82 m – distance between the centre of the contact surface of the hanging of the support cylinder on the pressure vessel flange and the reactor axis,
- r_{tp} = 1.8 m – distance between the contact curve of the toroidal pipes with the support cylinder and the reactor axis.

2.2. Mass parameters of the model

- $m_1 = 1.32\cdot 10^4$ kg – weight of SC1,
- $I_1 = 2.69\cdot 10^4$ kgm^2 – moment of inertia of SC1 about the transversal axis passing through the centre of gravity,
- $m_3 = 7.97\cdot 10^4$ kg – weight of SC3,
- $I_3 = 2.31\cdot 10^5$ kgm^2 – moment of inertia of SC3 about the transversal axis passing through the centre of gravity,
- $I_{o3} = 9.94\cdot 10^4$ kgm^2 – moment of inertia of SC3 about the vertical axis of the reactor.

2.3. Stiffness parameters of the model

The stiffness parameters which are the axial gland flange stiffness k_{gf}, the axial and the torsional bearing support stiffness k_{xbs} and k_{xxbs}, the stiffness of the toroidal pipes during the vertical motion, during the bending motion respectively, k_{ytp}, k_{xxtp} respectively, were not considered so that boundary conditions can be identical with those that were considered in the FEM model. The value of the contact stiffness, the bending stiffness respectively, of the hanging of the support cylinder on the pressure vessel flange k_{ySC}, k_{xxSC} respectively, was taken sufficiently high to represent support.

5. Sensitivity of eigenfrequencies to a change of discrete parameters

The behaviour of the conservative mathematical model of the support cylinder is determined by the matrix equation of motion

$$\boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{K}\boldsymbol{q} = \boldsymbol{0}. \tag{9}$$

Concrete form of the symmetric, positively definite mass matrix $\boldsymbol{M}$ and symmetric matrix $\boldsymbol{K}$ is derived from the kinetic and deformation energy of the system after the substitution into the Lagrange equations of the 2nd order.

5.1. Sensitivity of eigenfrequencies to a change of mass parameters

According to [4], for the relative sensitivity of the i-th eigenfrequency Ω_i to a change of the j-th mass parameter (which has no influence on the stiffness matrix $\boldsymbol{K}$), we can write

$$l_{ij} = -\frac{m_j}{2}\boldsymbol{v}_i^{\boldsymbol{T}}\frac{\partial \boldsymbol{M}}{\partial m_j}\boldsymbol{v}_i, \tag{10}$$

where $\boldsymbol{v}_i$ is an eigenvector related to an eigenfrequency Ω_i, and which is normalized by matrix $\boldsymbol{M}$, so it satisfies the equation

$$\boldsymbol{v}_i^{\boldsymbol{T}}\boldsymbol{M}\boldsymbol{v}_i = 1. \tag{11}$$

The quadratic forms containing the matrix $\frac{\partial \boldsymbol{M}}{\partial m_j}$ have dominant role in the expression (10). Within the mathematical model, such matrix can be expressed very easily. For the discrete parameters of the support cylinder, we obtain

$$\boldsymbol{v}_i^T \frac{\partial \boldsymbol{M}}{\partial m_1} \boldsymbol{v}_i = v_{1i}^2 + b_1^2 \left(v_{2i}^2 + v_{3i}^2 \right), \tag{12}$$

$$\boldsymbol{v}_i^T \frac{\partial \boldsymbol{M}}{\partial I_1} \boldsymbol{v}_i = v_{2i}^2 + v_{3i}^2, \tag{13}$$

$$\boldsymbol{v}_i^T \frac{\partial \boldsymbol{M}}{\partial m_3} \boldsymbol{v}_i = v_{1i}^2 + v_{10i}^2 + v_{11i}^2 + v_{12i}^2 + b_3^2 \left(v_{2i}^2 + v_{3i}^2 \right) + 2\left[v_{1i} v_{11i} + b_3 \left(v_{3i} v_{10i} - v_{2i} v_{12i} \right) \right], \tag{14}$$

$$\boldsymbol{v}_i^T \frac{\partial \boldsymbol{M}}{\partial I_3} \boldsymbol{v}_i = v_{2i}^2 + v_{3i}^2 + v_{13i}^2 + v_{15i}^2 + 2\left(v_{1i} v_{13i} + v_{5i} v_{15i} \right), \tag{15}$$

$$\boldsymbol{v}_i^T \frac{\partial \boldsymbol{M}}{\partial I_{03}} \boldsymbol{v}_i = v_{14i}^2. \tag{16}$$

5.2. Sensitivity of eigenfrequencies to a change of geometric parameters

Generally, the relative sensitivity of the *i*-th eigenfrequency Ω_i to a change of the *j*-th parameter is determined by the following expression:

$$l_{ij} = \frac{1}{2} \left[\frac{p_j}{\Omega_i^2} \boldsymbol{v}_i^T \frac{\partial \boldsymbol{K}}{\partial p_j} \boldsymbol{v}_i - p_j \boldsymbol{v}_i^T \frac{\partial \boldsymbol{M}}{\partial p_j} \boldsymbol{v}_i \right]. \tag{17}$$

Since the investigated geometric parameters influence only the segments of the matrices $\boldsymbol{M}$ and $\boldsymbol{K}$ which are related to those two elements modelling the middle part of the support cylinder, one may write

$$\frac{\partial \boldsymbol{X}}{\partial p_j} = \sum_{e=1}^{2} \boldsymbol{T_e}^T \frac{\partial \boldsymbol{x_e}}{\partial p_j} \boldsymbol{T_e}, \tag{18}$$

where $\boldsymbol{X} = \boldsymbol{M}, \boldsymbol{K}$, and the corresponding $\boldsymbol{x_e} = \boldsymbol{m_e}, \boldsymbol{k_e}$ are mass and stiffness matrices of the *e*-th shaft element of the annular cross-section with 12 degrees of freedom. $\boldsymbol{T_e}$ is a matrix of transformation between the global and the local coordinates of the *e*-th shaft element. The detail structure of the matrix $\boldsymbol{T_e}$ is described in [4].

6. FEM model of the reactor VVER 1000 support cylinder

In fig. 2, there is a computation model of the support cylinder which was developed in Cosmos/M programming code as a thin-shell tank, and to which the fuel cassettes will be implemented in the future.

The support cylinder body consists of 14 segments of various diameters and thicknesses. The inlets for the cooling loop pipelines that are located in two different zones of the support cylinder were not modelled. Instead of that, the thicknesses in the support cylinder segments which contain these inlets were reduced in the rate of area of the wall with the inlets to the area of the "full" wall. Using this simplification that was already applied in the calculation [2], the bending stiffness should not change dramatically.

Core barrel, of which total height is 4.07 m, consists of two horizontal slabs and six rings. The shape of their outer shell enables to insert 163 fuel cassettes of regular hexagonal outer cross-section with the diameter of inscribed circle equal to 0.236 m. Five upper rings are 0.705 m high while the bottom ring is 0.545 m high. These six rings are bolted together by six hollow screws (outer diameter 0.125 m, inner diameter 0.1 m) with the thread in the slab. Twelve bolts by which the bottom ring is anchored to the lower slab were not included in the model. The thickness of the upper and lower slab of the core barrel is 0.1 m. The model also contains 163 pipes connecting the lower slab of the core barrel with the bottom of the support cylinder.

The support cylinder is inserted in the pressure vessel in the vertical axial direction (y axis), and hung on the flange. At the location of the contact which is between the first and the second segment of support cylinder wall, the corresponding circumferential nodes were imposed the zero displacement for all axial directions.

The reactor VVER 1000 support cylinder is made of the steel material 08X18H10T. In accordance with the past calculations, the average operational temperature of the support cylinder is 305 ^{o}C. The corresponding value of Young's modulus of elasticity $E = 1.894 \cdot 10^{11}$. Poisson's ratio and material density do not practically depend on the temperature. The material properties for modal analysis are summarized in tab. 1.

Density ρ **[kg/m^3]**	**Young's modulus** E **[Pa]**	**Poisson's ratio** υ
7850	$1.894.10^{11}$	0.3

Tab. 1. Material properties.

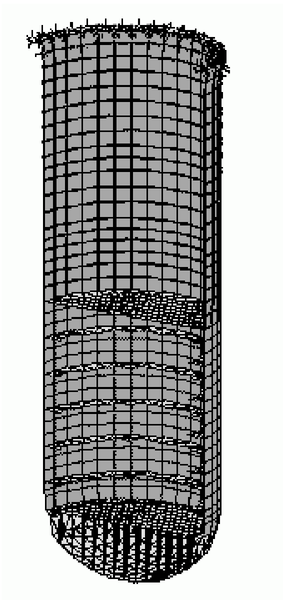

Fig. 2. FEM model of the support cylinder.

7. The tuning process

The values of the first eight eigenfrequencies computed on both models are listed in tab. 2. Those eigenfrequencies that were found the most suitable for the tuning process are bold marked (the frequencies of the FEM model define the objective functions). They represent the first bending, torsional, and longitudinal mode.

As was already mentioned, the spectral tuning carried out by changes of mass parameters has not provided satisfying results. Therefore in the next step, the geometric parameters were also included in the set of tuning parameters. The relative sensitivities of the dominant frequencies to a change of the mass parameters of the reactor VVER 1000 support cylinder are listed in tab. 3, and to the change of the geometric parameters (together with the sensitivities to the material constants) are listed in tab. 4.

DYNAMIC MODEL			**FEM MODEL**		
Order of frequency	**Eigenfrequency *f* [Hz]**	**Mode shape**	**Order of frequency**	**Eigenfrequency *f* [Hz]**	**Mode shape**
1	**25.84**	**bending**	1	**13.45**	**bending**
2	**25.84**	**bending**	2	**13.45**	**bending**
3	**69.02**	**torsional**	3	**43.75**	**torsional**
4	**73.14**	**longitudinal**	4	**49.93**	**longitudinal**
5	104.47	bending	5	66.18	core barrel
6	104.47	bending	6	69.90	bending
7	291.93	torsional	7	70.08	bending
8	427.54	longitudinal	8	81.58	shell

Tab. 2. Eigenfrequencies of the reactor VVER 1000 support cylinder.

Order of frequency	m_1	I_1	m_3	I_3	I_{o3}
1	$-1.1901\cdot10^{-11}$	$-2.1180\cdot10^{-11}$	$-3.6483\cdot10^{-1}$	$-7.4932\cdot10^{-2}$	$-2.4663\cdot10^{-24}$
2	$-1.1901\cdot10^{-11}$	$-2.1180\cdot10^{-11}$	$-3.6483\cdot10^{-1}$	$-1.9349\cdot10^{-6}$	$-4.4523\cdot10^{-24}$
3	$-1.7087\cdot10^{-31}$	$-2.1379\cdot10^{-33}$	$-2.8553\cdot10^{-21}$	$6.6924\cdot10^{-23}$	$-3.5740\cdot10^{-1}$
4	$-3.0493\cdot10^{-11}$	$-2.6731\cdot10^{-33}$	$-4.3464\cdot10^{-1}$	$8.1098\cdot10^{-12}$	$-2.3254\cdot10^{-21}$

Tab. 3. Relative sensitivity to a change of the mass parameters of the reactor VVER 1000 support cylinder.

Order of frequency	r	h	ρ	E
1	$1.3965\cdot10^{0}$	$4.6394\cdot10^{-1}$	$-6.0233\cdot10^{-2}$	$4.9995\cdot10^{-1}$
2	$1.3965\cdot10^{0}$	$4.6394\cdot10^{-1}$	$-6.0233\cdot10^{-2}$	$4.9995\cdot10^{-1}$
3	$1.0539\cdot10^{0}$	$3.7567\cdot10^{-1}$	$-1.4260\cdot10^{-1}$	$5.0000\cdot10^{-1}$
4	$4.2730\cdot10^{-1}$	$4.4196\cdot10^{-1}$	$-6.5389\cdot10^{-2}$	$4.9999\cdot10^{-1}$

Tab. 4. Relative sensitivity to a change of the geometric parameters and material constants of the reactor VVER 1000 support cylinder.

According to the values of the relative sensitivities, the selected tuning parameters were: weight of SC3 m_3, moment of inertia of SC3 about the vertical axis of the reactor I_{o3}, and newly inner radius of the SC2 section of the support cylinder r, and thickness of the SC2 wall. Density of the support cylinder material ρ, and Young's modulus E remain unchanged.

While performing the tuning process, the value of the total weight of the support cylinder should be respected. Since the total weight found on the FEM model is 141.7 tones, the following two inequality constraints have been imposed:

$$135t \leq m_1 + m_2 + m_3 \leq 145t. \qquad (19)$$

What remains to be done is to determine appropriate values of the lower and upper bounds of the tuning parameters. The computations have shown that the most convenient results can be obtained when the bounds of the tuning parameters are as follows: (see tab. 5)

Parameter	Original value	Lower bound	Upper bound
m_3 [kg]	$7.97 \cdot 10^4$	$4.98 \cdot 10^4$	$1.28 \cdot 10^5$
I_{o3} [kgm^2]	$9.94 \cdot 10^4$	$5.23 \cdot 10^4$	$1.89 \cdot 10^5$
r [m]	1.75	1.61	1.90
h [m]	0.06	0.048	0.075

Tab. 5. Lower and upper bounds of the tuning parameters

The results of the tuning of the dynamic model of the support cylinder shown in tab. 6 where is the comparison of the eigenfrequencies of the model with the eigenfreqeuncies of the original model and the FEM model (objective values). The comparison of the new values of the tuning parameters with the original values is shown in tab 7.

Order of frequency	Mode shape	Frequency f [Hz]		
		Original dynamic model	New dynamic model	FEM model
1	bending	25.84	16.72	13.45
2	bending	25.84	16.72	13.45
3	torsional	69.02	43.72	43.75
4	longitudinal	73.14	49.94	49.93

Tab. 6. Effect of the spectral tuning on the eigenfrequencies of the reactor VVER 1000 support cylinder.

Parameter	Original value	New value
m_3 [kg]	$7.97 \cdot 10^4$	$1.28 \cdot 10^5$
I_{o3} [kgm^2]	$9.94 \cdot 10^4$	$1.87 \cdot 10^5$
r [m]	1.75	1.61
h [m]	0.06	0.048

Tab. 7. The changes of the tuning parameters.

Finally, let us check the total weight of the new model:

$$m_{SC} = m_1 + m_2 + m_3 = 13.2 + 3.24 + 127.52 = 143.96t. \qquad (20)$$

8. Conclusion

This work is an introduction to the research of which aim is to implement the model of the support cylinder with core and fuel cassettes to the dynamic model of the whole reactor. Including of the geometric parameters to the tuning process brought a significant improvement when the desirable modal properties were practically achieved. On the other hand, the achieving of this result was possible only by dramatic changes of the mass parameters of the dynamic model of the support cylinder. Therefore, application of this method in this case still remains questionable. Another approach, and more suitable, is to execute the condensation of the FEM model and to implement the condensed model into the dynamic model of the reactor. This will be the task for the next phase of the research.

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