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FRICTION FORCES AND FRETTING WEAR IN REACTOR CORE BARREL COUPLINGS

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Abstract: *The couplings key-groove between the lower part of core barrel and reactor pressure vessel in the nuclear VVER-type reactors show small assembling side clearances. Due to fretting wear the potential for increasing of the clearances exist. Reactor vibrations, caused by coolant pressure pulsations generated by main circulation pumps, produce impulse contact forces in the above mentioned couplings. These forces are used for calculation of friction forces in the slipping contact surfaces between the key and the groove and for their fretting wear prediction. Increasing of the clearances leads to decreasing of some reactor frequencies. Their changes present good tool for the interpretation of diagnostic measurements. The computational method with numerical results applied on VVER1000 type reactor is shown.*

Keywords: Nonlinear vibration, Nuclear reactor, Friction forces, Fretting wear.

1. Introduction

Vibration of VVER type nuclear reactors was investigated in previous author´s research works and papers in co-operation with Nuclear Research Institut Řež on linear models with proportional damping. The original linearized spatial model of the VVER1000/320-type reactor (Fig. 1), intended for dynamic response calculation excited by pressure pulsations generated by main circulation pumps, was derived (Zeman, 2008) as linear clearance-free model with 137 DOF number in the form

$$\mathbf{M}\ddot{\mathbf{q}}(t)+\mathbf{B}\dot{\mathbf{q}}(t)+\mathbf{K}\mathbf{q}(t)=\sum_{j=1}^{4}\sum_{k=1}^{3}F_{PV}^{(k)}\mathbf{f}_j\cos k\,\omega_j\,t\ . \tag{1}$$

Due to excitation by coolant pressure pulsation, this linear model was used for calculation of spatial vibration of all main reactor components including nuclear fuel assemblies (Hlaváč, 2013). The excitation vector in (1) is expressed by means of amplitudes $F_{PV}^{(k)}$ of k-th harmonic components of the hydrodynamic force acting on reactor pressure vessel generated by particular main circulation pumps with small different angular speeds ω_j. The vectors $\mathbf{f}_j$ of geometrical parameters correspond to main circulation loops $j=1,2,3,4$. The fluctuation of the pumps angular speeds is based on the measurement at NPP Temelín blocks.

The aim of this paper is an investigation of reactor nonlinear vibration, friction forces in the couplings key-groove between the lower part of core barrel (CB3) and reactor pressure vessel (PV) and fretting wear prediction in their contact surfaces in dependence on clearances.

2. Mathematical model of the reactor with clearances in couplings

The relative tangential displacement u_i (Fig. 3) of the one groove on CB3 from starting position compared to key on reactor PV can be written as

$$u_i=\mathbf{d}_i^T\mathbf{q}(t),\quad i=1,2,..,8\ , \tag{2}$$

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where $\mathbf{q}(t)$ is vector of generalized coordinates of dimension 137 detailed described in author's monograph (Hlaváč, 2013). Vector $\mathbf{d}_i$ corresponding to coupling i is defined by the centre mass position of the CB3 in reactor (see Fig. 1) and by the coupling key-groove position after core barrel circumference

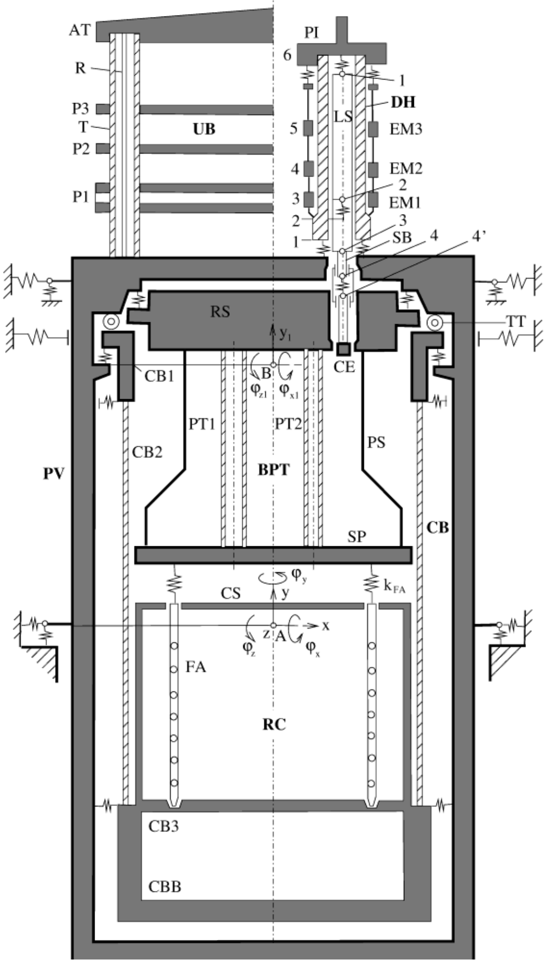

Fig. 1: Scheme of reactor model (PV- pressure vessel, CB3-lower part of core barrel).

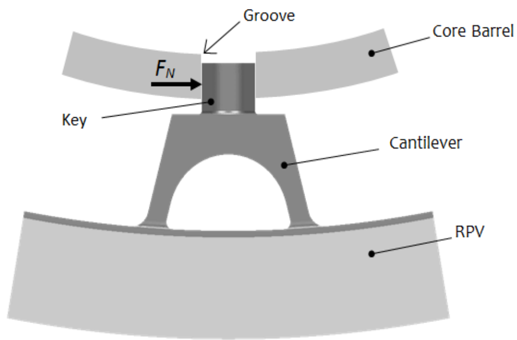

Fig. 2: Coupling key-groove between core barrel and reactor pressure vessel.

(radius r and angle α_i) depicted In Fig. 3. The tangential (normal) force transmitted by coupling i for general starting position of the CB3 centre relative to the reactor PV, defined by shift s in direction determined by angle α (see Fig. 3), can be expressed in the form

$$N_i(u_i)=k\{(u_i+\Delta_i-s_i)H(-u_i-\Delta_i+s_i)+(u_i-\Delta_i-s_i)H(u_i-\Delta_i-s_i)\},\ i=1,2,..,8, \qquad (3)$$

where k is contact stiffness in one clearance-free coupling and Δ_i is half clearance in the corresponding coupling i. The small shift s_i of the groove with regard to key in tangential direction from starting position is

$$s_i = s\sin(\alpha+\alpha_i),\ \alpha_i=\frac{\pi}{4}(i-1),\ i=1,2,..,8. \qquad (4)$$

The Heaviside function H in (3) is zero when the key contact with groove in coupling is interrupted $(|u_i|<\Delta_i-s_i)$. The all coupling forces $N_i(u_i)$ must be transformed in the reactor configuration space $\mathbf{q}$ into mass centre CB3 and solid reactor PV. This operation has an effect on mathematical model (1) which is rearranged into reactor nonlinear model

$$\mathbf{M}\ddot{\mathbf{q}}(t)+\mathbf{B}\dot{\mathbf{q}}(t)+[\mathbf{K}-\mathbf{K}_C(t)]\mathbf{q}(t)=\sum_{j=1}^{4}\sum_{k=1}^{3}F_{PV}^{(k)}\mathbf{f}_j\cos k\omega_j t+\mathbf{f}(\mathbf{q}). \qquad (5)$$

Elastic forces $\mathbf{K}_C(0)\,\mathbf{q}(t)$ of all clearance-free coupling (for $\Delta_i=0$) in model (1) are replaced by the nonlinear force vector

$$\mathbf{f}(\mathbf{q}) = -\sum_{i=1}^{8} N_i(u_i)\mathbf{d}_i \ . \tag{6}$$

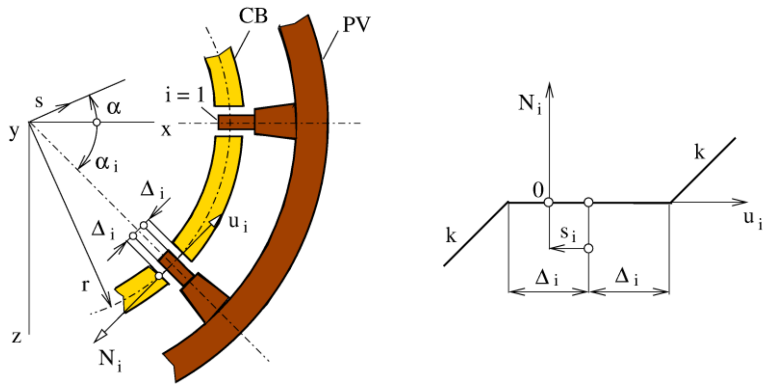

Fig. 3: The couplings between the lower part of core barrel (CB) and reactor pressure vessel (PV) and their stiffness characteristic.

3. Fretting wear of the contact surfaces

Due to fretting wear of the contact surfaces between the key and the groove the potential for increasing of the clearances there has been. For an assessment of this phenomenon the friction coefficient f and the fretting wear parameter $\mu[g/J]$ (i.e. loss of mass in one contact surface generated by the work of friction force $W = 1[J]$ at the excited frequency $\omega \approx \omega_j$) are experimentally obtained (Pečínka et al., 2016). The sliding velocity of the groove in the central contact points on radius r (see Fig. 3) as a result of CB3 and reactor PV vibration can be written by means of radial and axial components

$$c_{r,i} = \mathbf{d}_{r,i}^T \dot{\mathbf{q}}, \quad c_{ax,i} = \mathbf{d}_{ax,i}^T \dot{\mathbf{q}}, \quad i = 1, 2, .., 8 \ , \tag{7}$$

where vectors of geometrical parameters $\mathbf{d}_{r,i}$ and $\mathbf{d}_{ax,i}$ are defined by the centre mass position of CB3 in reactor model and by parameters r, α_i corresponding to concrete coupling i. The criterion of the fretting wear of contact surfaces can be expressed using the work of friction forces (Zeman et al., 2016) during the representative time interval $\langle t_1, t_2 \rangle$ as

$$W_i = \int_{t_1}^{t_2} |P_i(t)| \, dt, \quad P_i(t) = f \, N_i(u_i)\sqrt{c_{r,i}^2 + c_{ax,i}^2} \, , \quad i = 1, 2, .., 8 \ , \tag{8}$$

where $P_i(t)$ is friction power. The fretting wear in grams in particular contact surfaces during the interval $\langle t_1, t_2 \rangle$ can be expressed as

$$\Delta m_i = \mu \int_{t_1}^{t_2} |P_i(t)| \, dt \, , \quad i = 1, 2, .., 8 \ . \tag{9}$$

Application

The presented method has been applied to vibration analysis and fretting wear calculation of the side contact surfaces in couplings depending on clearances. The basic excitation frequency ω corresponds to mean rotational speed of main circulation pumps $n = 996 rpm$, contact stiffness in one clearance-free coupling is k = 1.2.10^9 *N/m* and design values of clearances in all couplings 2Δ are in interval $\langle 0{,}05; 0{,}17 \rangle mm$. All geometrical parameters correspond to design parameters of VVER1000/320 type reactor. Reference values of the fretting wear parameters are f = 1 and μ = 10^{-9} *g/J*.

As an illustration, time behaviour of the normal contact force N_2 and friction power P_2 calculated according to (3) and (8) for same clearances $\Delta_i = 75 \mu m$ in all eight couplings and for the central starting position CB with respect to reactor PV $(s_i = 0)$ are shown in the Fig. 4. The time interval $\langle 0;100\rangle s$ of numerical simulations includes the long period of the beating vibration caused by slightly different main circulation pumps revolutions (Zeman, 2008). Corresponding fretting wear of the side contact surfaces of coupling $i = 2$ in this time interval, according to (9) $\Delta m_2 = 3.014 \cdot 10^{-4}\ g$.

4. Conclusion

The main objective of this contribution is to present the new basic method of fretting wear prediction in the reactor core barrel couplings with clearances. The method is based on mathematical remodelling of the original linear clearance-free reactor model into the nonlinear model and computer simulation of nonlinear vibration of the reactor and its components—reactor pressure vessel and lower part of core barrel linked by key-groove nonlinear couplings. The coolant pressure pulsations generate impulse forces between contact surfaces of key-groove and may result in fretting wear and increasing clearances. The developed software in MATLAB code is conceived in such a way that is enables to choose an arbitrary design clearances, starting position of core barrel with respect to reactor pressure vessel and operating mode of main circulation pumps. The presented method was applied for the VVER1000/320 type reactor in Czech NPP Temelín.

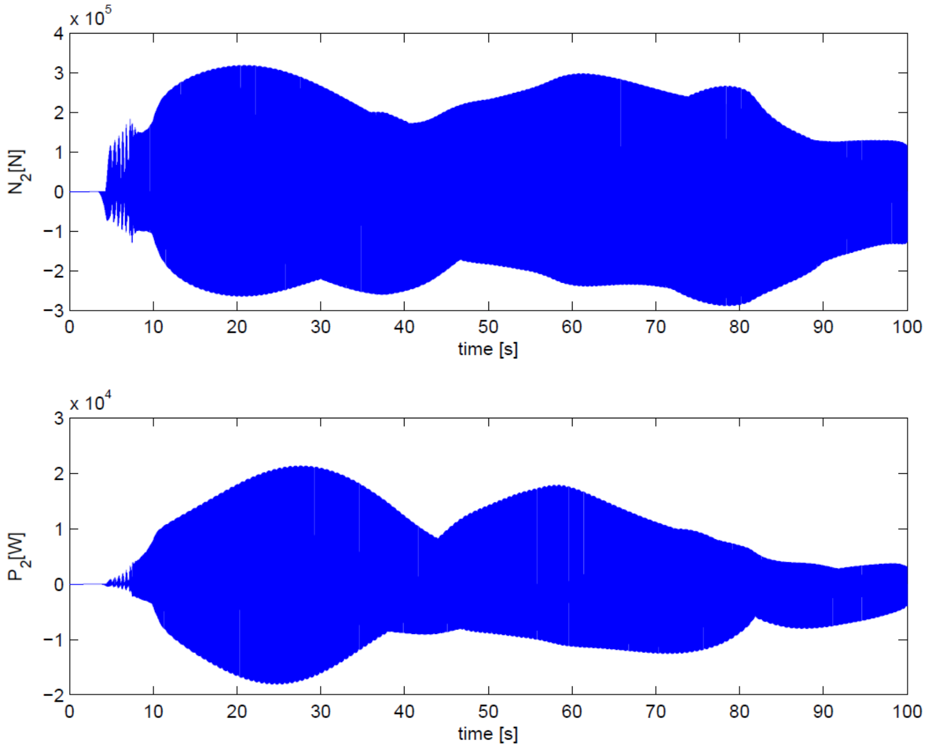

Fig. 4: Time behaviour of the normal contact force N_2 and friction power P_2 in coupling $i = 2$ for clearances $\Delta_i = 75\ \mu m$.

Acknowledgement

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