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Nonlinear vibration of the nuclear reactor with clearances in core barrel couplings

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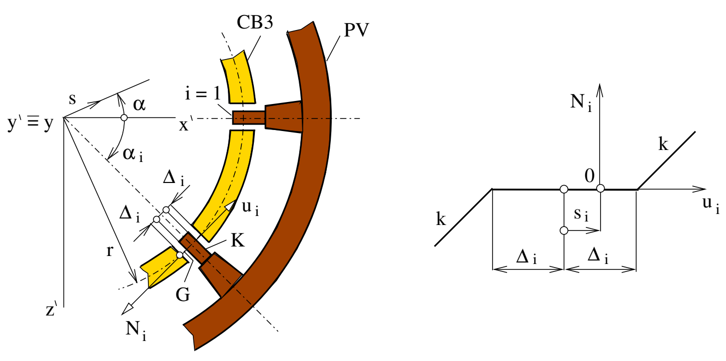
The original mathematical model of the VVER-type reactor excited by coolant pressure pulsations [2] was derived as the linear clearance-free model in couplings. Assembly clearances Δ_i in the key-groove (K-G) couplings between the lower part of core barrel (CB3) and the reactor pressure vessel (PV) (Fig. 1) produce nonlinear vibration of reactor components. Friction-vibration interactions in the above mentioned couplings cause the fretting wear on their contact surfaces [1]. The aim of this contribution is an investigation of the VVER 1000 type reactor nonlinear vibration respecting the assembling side clearances and friction in eight K-G couplings uniformly deployed to circumference between CB3 and PV. Relative tangential displacements $u_i \, (i = 1, \dots, 8)$ of the K-G contact surfaces from the general starting position generate the normal contact forces

$$N_i(u_i) = k[(u_i + \Delta_i + s_i)H(-u_i - \Delta_i - s_i) + (u_i - \Delta_i + s_i)H(u_i - \Delta_i + s_i)] \,, \tag{1}$$

where k is the stiffness in tangential direction of one key connected with PV by means of the cantilever. Small shifts s_i of the grooves with respect to keys in direction of displacements u_i from the ideal central position of CB3 was detailed investigated in a context of the K-G coupling fretting wear on the simplified reactor model in [3]. Heaviside function H in (1) is zero when the contact is interrupted. The slide of K-G contact surfaces in contact phases (when $H = 1$) causes radial $T_{i,r}$ and axial $T_{i,ax}$ components of friction forces

$$T_{i,r} = f(c_i)N_i(u_i)\frac{c_{i,r}}{c_i} \,, \; T_{i,ax} = f(c_i)N_i(u_i)\frac{c_{i,ax}}{c_i} \,, \; i = 1, \dots, 8 \,, \tag{2}$$



(a) (b)

Fig. 1. Key-groove layout in contact plane between lower part of core barrel (CB3) and reactor pressure vessel (PV) (a) and stiffness characteristic of one coupling (b)

where friction coefficient f depends on relative slip velocity c_i, $c_{i,r}$ and $c_{i,ax}$ are its components in radial and axial directions. All contact forces $N_i(u_i)$, $T_{i,r}$, $T_{i,ax}$, $i = 1, \ldots, 8$ transmitted by K-G couplings are expressed by means of the vectors of generalized coordinates $\boldsymbol{q}(t)$ and speeds $\dot{\boldsymbol{q}}(t)$ in the new global reactor model

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

The vector of elastic forces $\boldsymbol{K}_C\boldsymbol{q}(t)$ in all clearance-free and smooth K-G couplings included in vector $\boldsymbol{K}\boldsymbol{q}(t)$ of the original reactor model [2] is replaced by nonlinear force vector $\boldsymbol{f}(\boldsymbol{q}, \dot{\boldsymbol{q}})$. The reactor dynamic response excited by coolant pressure pulsations generated by four main circulation pumps (the first member on right-hand side) is investigated by a numerical integration of the nonlinear motion equations (3) in time domain.

For illustration, Fig. 2 shows the time behaviour of the normal contact force N_3 and relative velocity c_3 calculated for same clearances $\Delta_i = 25\,[\mu\text{m}]$ in all eight K-G couplings, the central starting position CB3 ($s = 0$, $\alpha = 0$) and the Coulomb friction with friction coefficient $f = 1$. The presented method is applied to sensitivity analyses focused on variation in the friction characteristic and clearances in K-G couplings lead on as possible to reduce the contact forces and fretting wear.

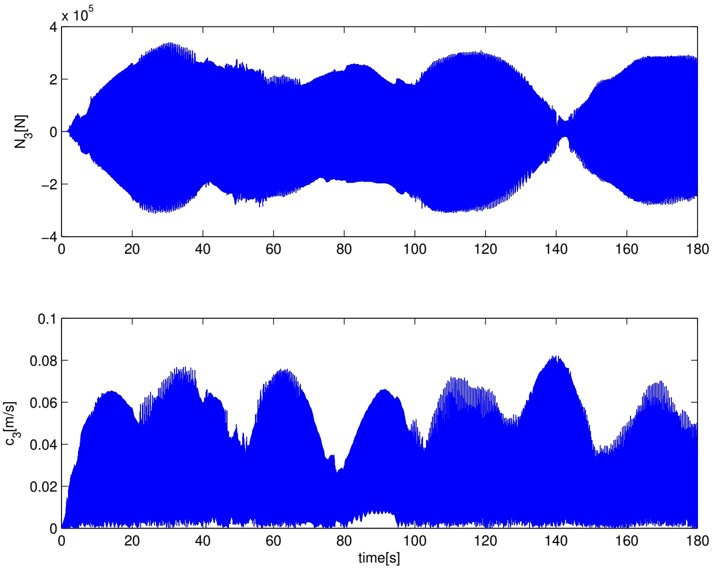


Fig. 2. Time behaviour of normal contact force N_3 and relative velocity c_3 in coupling 3

Acknowledgement

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