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Radek BULÍN*, Michal HAJŽMAN, Pavel POLACH*****

BASIC MODEL OF A CONTROL ASSEMBLY DROP IN NUCLEAR REACTORS

ZÁKLADNÍ MODEL PÁDU REGULAČNÍHO ORGÁNU V JADERNÝCH REAKTORECH

Abstract

This paper is focused on the modelling and dynamic analysis of a nonlinear system representing a control assembly of the VVER 440/V213 nuclear reactor. A simple rigid body model intended for basic dynamic analyses is introduced. It contains the influences of the pressurized water and mainly the effects of possible control assembly contacts with guiding tubes inside the reactor. Another approach based on a complex multibody model is further described and the suitability of both modelling approaches is discussed.

Abstrakt

Článek je zaměřen na modelování a dynamickou analýzu nelineárního systému, který reprezentuje regulační orgán jaderného reaktoru VVER 440/V213. Je představen jednoduchý model tuhého tělesa určený pro základní dynamické analýzy. Model zahrnuje vliv stlačené vody a zejména vliv možných kontaktů regulačního orgánu s vodicími trubkami uvnitř reaktoru. Dále je popsán jiný přístup k modelování založený na komplexním multibody modelu a je diskutována vhodnost obou přístupů k modelování.

1 INTRODUCTION

Nuclear reactors are important parts of electric power systems in many countries. As the nuclear reaction and radioactive materials are viewed as very dangerous phenomena, the safety of nuclear reactors is under review and has to be properly tested. In case of various breakdown states, it is necessary to ensure immediate and reliable shut down of the reactor, i.e. the total stopping of the nuclear reaction. With respect to different types of nuclear reactors, different control systems composed of various mechanical parts and transmissions can be distinguished. Generally they can be simplified to the typical problem of a long thin rod moving through guide tubes and driven by a motor. Then the modelling approach depends on the chosen mode of operation, which can be operation (regulation) under normal conditions or a certain emergency state. In both cases, influences of contacts, influences of a coolant (water) surrounding the control assembly in the nuclear reactor and possible influences of seismic excitation would be considered in the mathematical model.

The problem of the mechanical behaviour of a control assembly during the emergency drop is not commonly studied in available literature and therefore the motivation for the investigation of this problem is straightforward. Some basic studies can be found in [1] or [2], but they are not focused on mechanical behaviour in sufficient detail. This paper deals with two possible approaches intended to

* Bc., Department of Mechanics, Faculty of Applied Sciences, University of West Bohemia, Univerzitní 22, Plzeň, tel. (+420) 377 632 301, e-mail: rbulin@students.zcu.cz
** Ing., Ph.D., Department of Mechanics, Faculty of Applied Sciences, University of West Bohemia, Univerzitní 22, Plzeň, tel. (+420) 377 632 311, e-mail: mhajzman@kme.zcu.cz
*** Dr. Ing., Materials and Mechanical Engineering Research, Výzkumný a zkušební ústav Plzeň s.r.o., Tylova 1581/46, Plzeň, tel. (+420) 379 852 246, e-mail: polach@vzuplzen.cz

the modelling and analysis of the control assembly of the VVER 440/V213 nuclear reactor. Detailed description of this control assembly can be found in [3].

2 SIMPLIFIED MODEL OF A CONTROL ASSEMBLY

The control assembly is simplified as one rigid body, which is moving in a guiding tube. This tube is inside the active zone of the nuclear reactor and is filled with pressurized water. The space between the assembly and the tube is very small, so contacts may occur and they must be included in the mathematical model. Due to the symmetry of the control assembly the simplified model is considered to move in a plane with three degrees of freedom, which are translations x and y and rotation φ. The scheme of the system is in Fig. 1, where the assembly is simplified as a rectangle. Other essential influences, which affect the control assembly emergency drop, are water resistance forces, the braking force produced by a centrifugal speed brake and the inertia torque of a rotating driving mechanism.

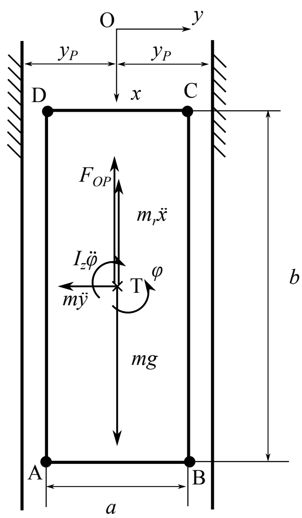

Fig. 1 Scheme of the simplified control assembly model

The overall mathematical model is formed by three ordinary differential equations

$$
\begin{aligned}
&m\ddot{x} + F_{red} - F - F_{OP} + F_r = F_{TA} + F_{TB} + F_{TC} + F_{TD}, \\
&m\ddot{y} + \operatorname{sign}(\dot{y})F_f = F_{NA} - F_{NB} - F_{NC} + F_{ND}, \\
&I_z\ddot{\varphi} = M_{NA} - M_{NB} + M_{NC} - M_{ND} - M_{TA} + M_{TB} + M_{TC} - M_{TD},
\end{aligned}
\tag{1}
$$

where $m\ddot{x}$, $m\ddot{y}$, $I_z\ddot{\varphi}$ are inertia effects related to generalized coordinates, F_{red} is force caused by driving mechanism inertia, F is gravity force together with buoyancy force caused by water, F_{OP} is force caused by over-pressurized water, F_r is force caused by centrifugal speed brake. Force $\operatorname{sign}(\dot{y})F_f$ expresses fluid resistance that acts against horizontal motion. Forces F_{Ni} and F_{Ti} are normal and friction contact forces, M_{Ni} and M_{Ti} are related torques in potential contact point i ($i = A, B, C, D$). The control assembly drop time and average and maximum velocities of the drop are the important quantities. The main forces that affect the dynamics of the control assembly are described in next paragraphs.

2.1 Influence of water

Since the control assembly moves in tubes filled by water, its motion is greatly affected. In vertical direction there is buoyancy force F_b which is given by well known Archimedes law. It says, that this force is equal to the weight of the fluid displaced by the object. This force is constant and can be deducted from gravitational force F_g. Then constant force F acting in vertical direction is expressed

$$F = F_g - F_b = mg - m_w g = mg\left(1 - \frac{\rho_w}{\rho_{ca}}\right), \tag{2}$$

where $m = \rho_{ca} V_{ca}$ represents the weight of the control assembly given by density of the control assembly material ρ_{ca} and its volume V_{ca}, g is gravitational acceleration and $m_w = \rho_w V_{ca}$ is the weight of displaced water given by density of water ρ_w and the volume of assembly which is fully submerged.

Force F_{OP} is caused by over-pressurized water in the tube and acts up in vertical direction. It is given by pressure differences of water Δp and by effective cross-section S of the control assembly.

The water affects the motion of the control assembly also in horizontal direction, but due to a very small space between tube and assembly it is very difficult to properly describe this problem. In this work, a standard formula for fluid resistance force F_f given by equation

$$F_f = \frac{1}{2} C \rho_w S v^2 \tag{3}$$

is used, where S is cross section area, C is the drag coefficient dependent on the shape and Reynolds number, v is the relative horizontal velocity.

2.2 Modelling of contact forces

As it was written before, the space between the control assembly and the guiding tube is very small (about $2,5$ mm on each side), so contacts may occur. The contact forces are of short duration, but they cause to large changes of velocity. There are many approaches how to describe these forces [4], in this paper a dissipative model is used. The normal contact force is given by

$$F_N = K\delta^n + D\dot{\delta}, \tag{4}$$

where δ is relative penetration of bodies, $\dot{\delta}$ is normal relative velocity of bodies, $n = 1.5$ for circular contacts, K is contact stiffness and D represents damping in contact. Coefficients K and D are dependent on shape and material properties of bodies. Hunt a Crossley [4] made further improvements of this model and they expressed damping D to be dependent on relative penetration

$$D = \chi\delta^n, \tag{5}$$

where χ is hysteresis factor given by

$$\chi = \frac{3K(1 - c_r)}{2\dot{\delta}^{(i)}}, \tag{6}$$

where $\dot{\delta}^{(i)}$ represents initial relative velocity of contact bodies and c_r is restitution coefficient. The final expression for normal contact force is

$$F_N = K\delta^n \left[1 + \frac{3(1 - c_r)}{2\dot{\delta}^{(i)}}\dot{\delta}\right]. \tag{7}$$

When the assembly and the tube are in contact, there is also friction force between them. This force can be described in vector notation as

$$\mathbf{F}_T = -f_f F_N \frac{\mathbf{v}_t}{v_t}, \tag{8}$$

where f_f is friction coefficient, $\mathbf{v}_t$ is vector of relative tangential velocity and v_t is its magnitude.

The simplified model, as it is presented, has four potential contact points, in Fig. 1 marked as A, B, C and D. In every time step during calculation it is tested if the contact occurs in some of these potential contact points, then the contact forces and related torques are introduced in the equations of motion.

2.3 Influences of the drive

The centrifugal regulator (brake) is a part of the driving mechanism. It produces braking torque depending on speed of rotation. It helps to reach required constant drop velocity, which is usually between 0.2 m·s^{-1} and 0.3 m·s^{-1}. The model of braking force is expressed as

$$M_r = [a_1 + a_2(0.3 - v_{req})](\omega_m^2 - \omega_{tr}^2), \tag{9}$$

where a_1 and a_2 are experimentally obtained coefficients, v_{req} is the required constant (maximum) drop velocity, ω_m is rotation speed of the driving mechanism and ω_{tr} is the threshold value, when the braking torque starts to act. The ratio between driving mechanism rotation speed and drop velocity is $\omega_m = p_{v\omega} v_{ca}$ and the resulting braking force is

$$F_r = M_r \cdot p_{v\omega}. \tag{10}$$

The inertia of the driving mechanism particular parts is not insignificant, so it must be also implemented in the model. The inertia of driving mechanism is reduced to the vertical motion x of the simplified control assembly using the equality of kinetic energies and it results in

$$m_{red} = (I_e + I_{II})p_{v\omega}^2, \quad F_{red} = m_{red}\ddot{x}, \tag{11}$$

where m_{red} is reduced mass of the driving mechanism, I_e is inertia torque of an engine and I_{II} is inertia torque of a tubular shaft (see Fig. 5). Inertia properties of other rotating parts can be neglected.

3 RESULTS OBTAINED USING THE SIMPLIFIED MODEL

The presented simplified model was implemented in the MATLAB system for particular parameters of the VVER 440/V213 nuclear reactor. Contact model coefficients correspond with a contact of two rigid steel sphere bodies. Equations of motion (1) were solved using numerical integration with initial conditions $[x,\ \dot{x},\ y,\ \dot{y},\ \varphi,\ \dot{\varphi}] = [0,\ 0,\ 0,\ 0.05,\ 0.0005,\ 0]$ and corresponding illustrative results are shown in this paper.

Time histories of vertical translation x and velocity $v_x = \dot{x}$ of the control assembly are shown in Fig. 2. Maximum speed related to the centrifugal regulator was set to 0.2 m·s^{-1}. The normal contact forces became smaller in time mainly due to the considered damping in contact, therefore also friction forces affected the drop mainly in the early phase of the motion. Time histories of horizontal translation y and velocity $v_y = \dot{y}$ are shown in Fig. 3, where the impacts of the control assembly with the tube can be clearly seen. Time histories of rotation φ and angular velocity $\omega = \dot{\varphi}$ are shown in Fig. 4.

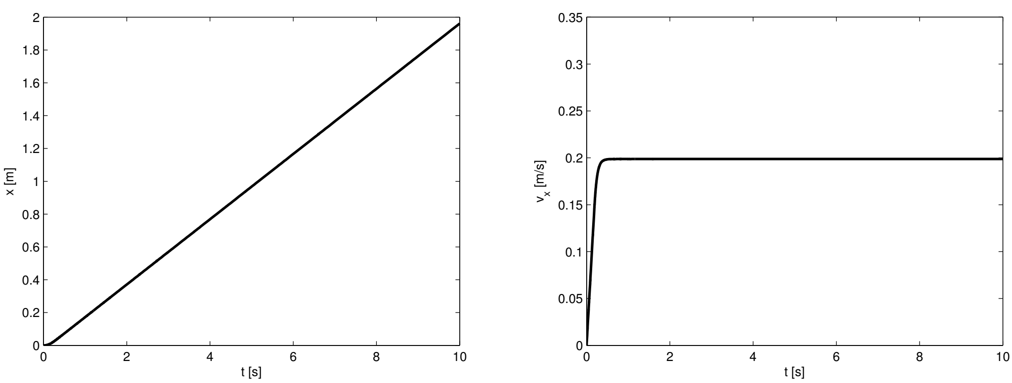

Fig. 2 Translation x and velocity $v_x = \dot{x}$ in time

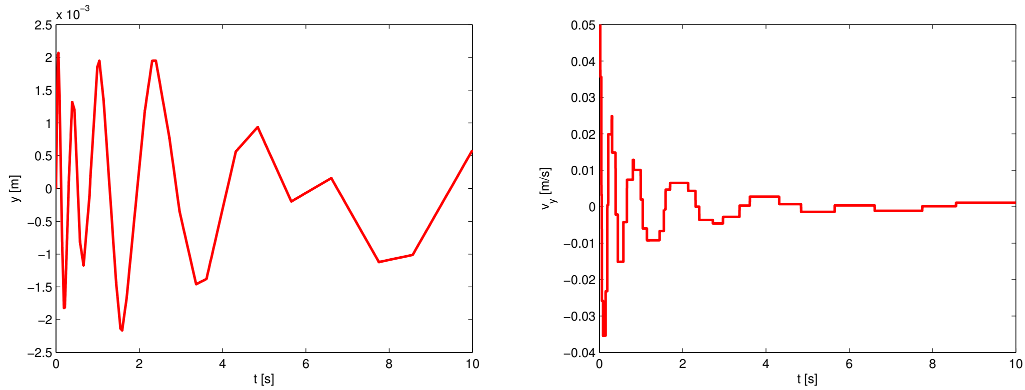

Fig. 3 Translation y and velocity $v_y = \dot{y}$ in time

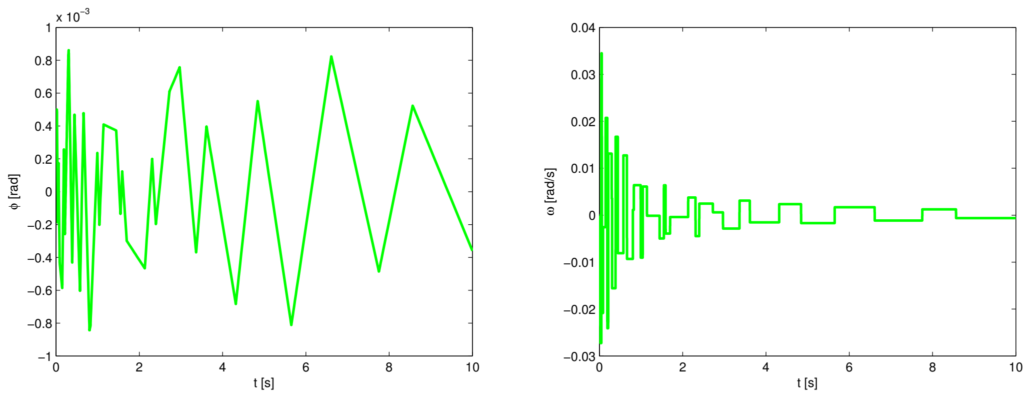

Fig. 4 Rotation φ and rotation velocity $\omega = \dot{\varphi}$ in time

4 COMPLEX MODELLING

Another possibility of the control assembly modelling is the usage of general multibody approaches [5]. The complex multibody model (see Fig. 5) of the VVER 440/V213 control assembly was implemented in the **alaska** simulation tool [3]. It is intended mainly for the simulations of the control assembly drop during the seismic event. The spatial multibody model of the whole control assembly is composed of 14 rigid bodies coupled by 14 kinematic constraints and has 48 degrees of freedom.

5 CONCLUSIONS

Two approaches to the modelling of control assemblies in the framework of nuclear reactors intended mainly for the dynamic analysis of the emergency drop were introduced in this paper. The simplified model can be advantageously used as the basic tool for the parameter and sensitivity studies. The second multibody model is more complex and can be used for detailed analyses, e.g. for the estimation of bearing load during seismic events.

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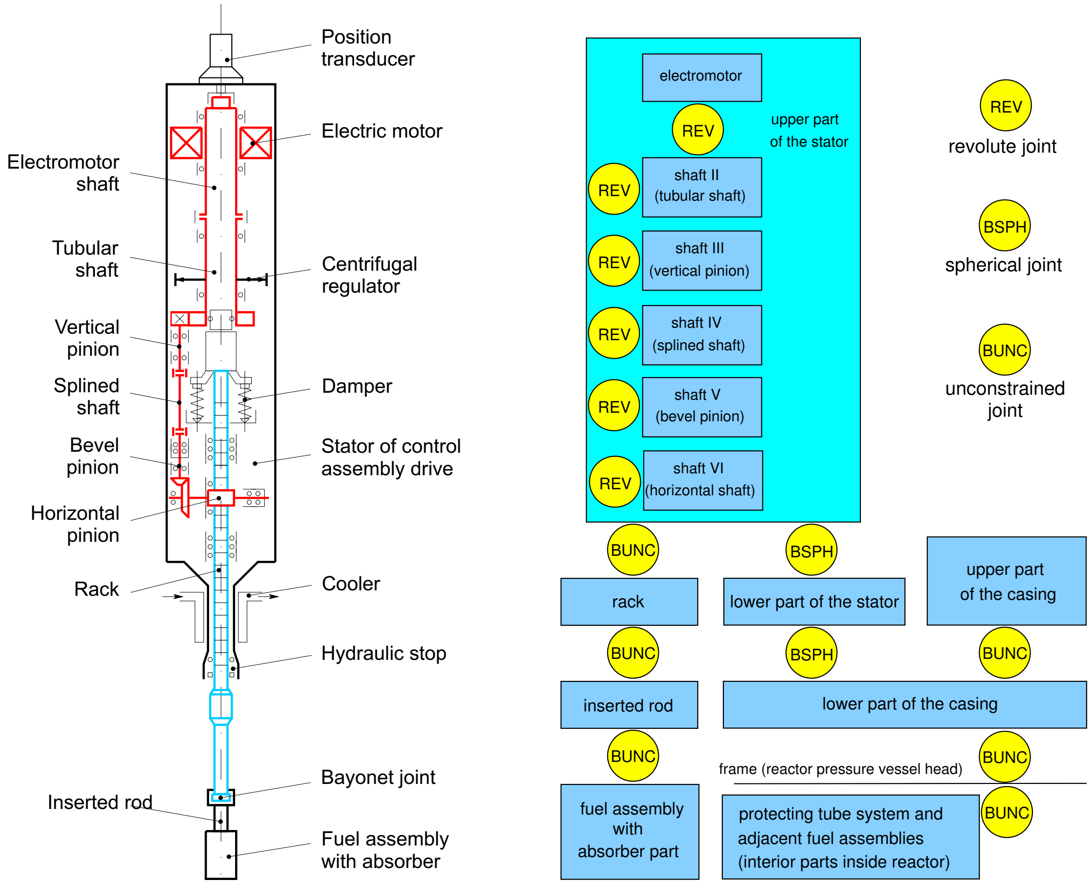

Fig. 5 Functional scheme of the control assembly and its kinematical scheme for the complex model

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