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MULTIBODY ANALYSIS OF THE CONTROL ASSEMBLY DROP IN THE VVER 440/213 NUCLEAR REACTOR

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Summary: *Control assemblies used in nuclear reactors are commonly based on a certain motor driving a control rod composed of absorbers and fuel rods. They allow to control of a chain nuclear reaction in a reactor core. This paper is focused on the control assembly of the VVER 440/V213 nuclear reactor modelling and on the investigation of its dynamic response in the course of the drop and prescribed seismic excitation. The influences of the pressurized water have to be introduced in the MBS model because control rods are falling in a limited space and water resistance is not negligeable. Possible contacts of the falling control rod with adjoining structure are supposed. The multibody model including all special features was created in the* ***alaska*** *simulation toolbox.*

1. Introduction

As the nuclear reaction and radioactive materials, which can get out of hand, are viewed as a very dangerous phenomenon, the safety of nuclear power plants is under review and has to be properly tested. In case of various breakdown states, in the first place it is necessary to ensure immediate and reliable shut down of the reactor, i.e. the total stopping of the nuclear reaction. Various control mechanisms in dependence on the nuclear reactor type serve for that purpose. This paper deals with the importance of the proper functionality of such a control assembly in case of the breakdown state, which occurs during an earthquake. It is intended for the multibody modelling and analysis of a special control part of the VVER 440/V213 reactor called the control assembly.

The module spatial multibody model of the control assembly of the VVER 440/V213 NPP Paks nuclear reactor (Hungary) was generated in the **alaska** simulation toolbox. The multibody model is intended for the simulations of the control assembly operation in the AZ (”avarijnoj zaščity” in Russian, emergency stop) mode. It is possible to simulate the drop of the control assembly under the standard conditions or during the seismic event with it. From the point of view of dynamic calculations with the set seismic excitation both in horizontal and vertical direction the earlier used model described in Voldřich et al. (1997) is not sufficient. That is why the complex spatial control assembly drive model, which also considers the horizontal motion of the drive bodies and respects the possible contacts with the adjoining constructional parts

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inside the reactor, was generated. In the multibody model the presence of a liquid medium is considered, too.

2. VVER 440/V213 nuclear reactor and its control assembly

Fig. 1 shows the scheme of the VVER 440 reactor consisting of a reactor pressure vessel with an interior structure and a reactor upper block with control assemblies drives. The interior structure inside the vessel can be divided into three main parts. Under the vessel head with nozzles of the control drives there is the system of protective tubes that leads to the core with fuel assemblies (so called active zone). In the lower part of the reactor vessel a large volume is constructed to include the guide tubes for control assembly followers. The bottom of the guide tubes is fixed to an additional plate.

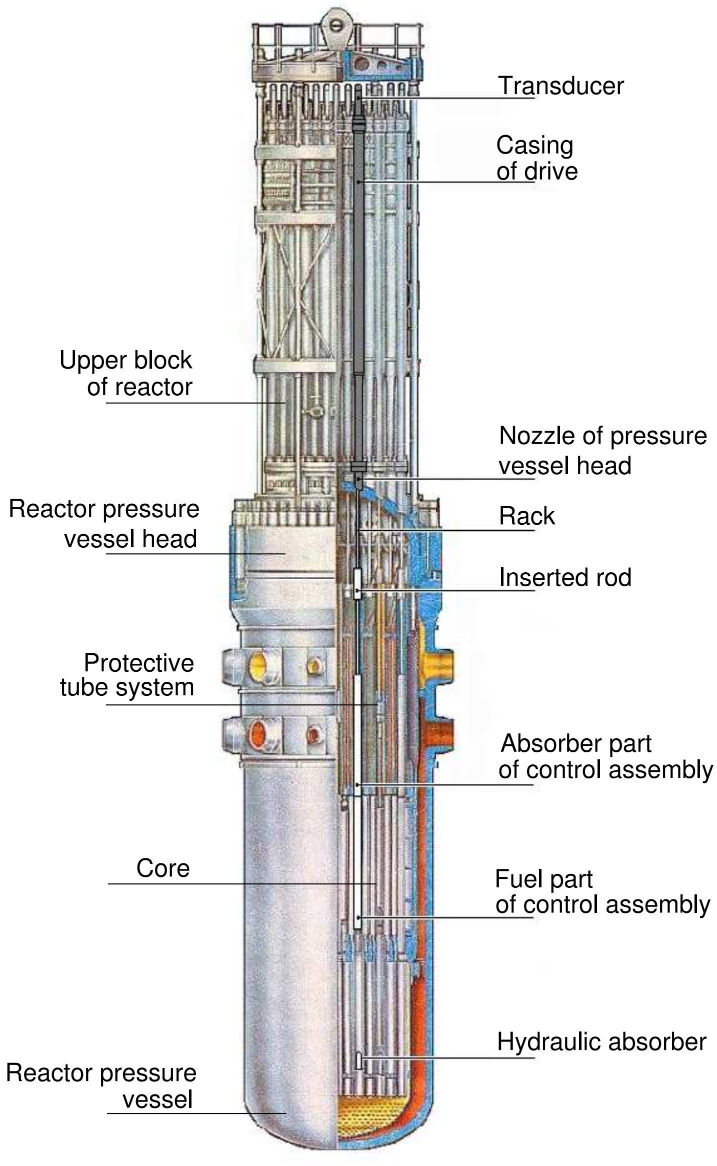

Fig. 1 Scheme of the VVER 440 reactor.

The core of the VVER 440 reactor contains 312 standard fuel assemblies and 37 control assemblies. Each control assembly has its control drive that is protected and closed by a drive casing screwed down on to the nozzle of the vessel head. The control assembly is of a hexagonal intersection and can move through the protective tube system, the core and the guiding tubes. When the control assembly reaches the reactor vessel bottom, a spindle, which has the function of a hydraulic shock absorber for the stop of the control assembly drop, is installed there. Seven out of 37 control assemblies are used for the regulation of the reactor power (to control nuclear reaction). Remaining 30 are still in one position, an absorber part is pulled out of the core, and in case of some accident they must drop down and stop the chain reaction.

The control assembly is twice as long as the standard fuel assembly. Its upper part is a hexagonal boron steel absorber. The lower part of the control assembly is the follower, which consists of fuel rods and which is similar to the normal fuel assembly. Each control assembly moves down during a reactor scram, the follower goes below the core and the absorber part

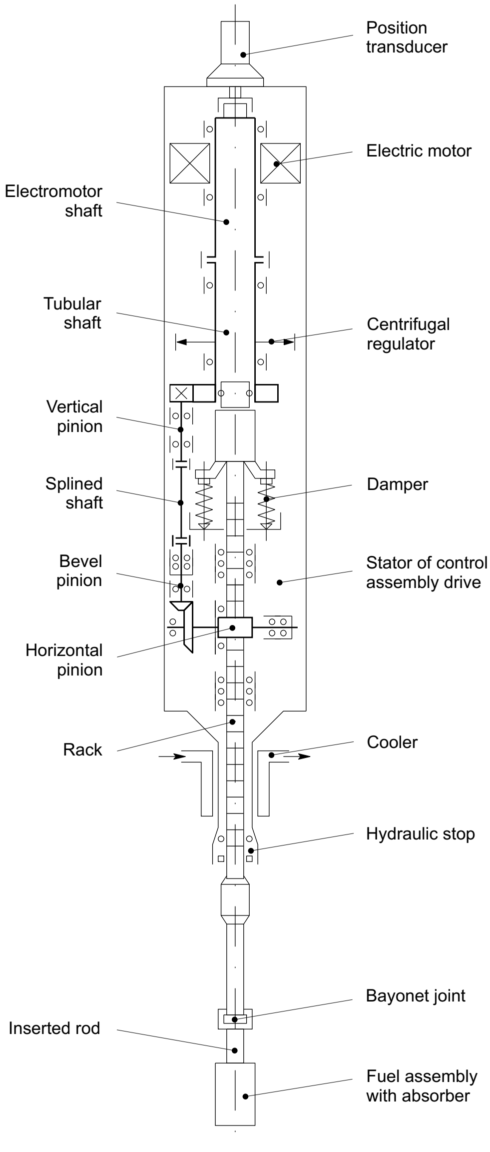

Fig. 2 Scheme of the control assembly without casing (not in a real scale factor).

enters the core from the top. Then the chain nuclear reaction in the core is stopped.

Vertical motion of the control assembly through internal parts of the reactor is controlled by an electric motor with a joined position transducer. The rotating motion of the motor is transformed by means of a geared transmission system to the vertical sliding motion of a rack. The control assembly (fuel assembly with absorber part) is coupled by the rack with an inserted rod. These couplings are realized by bayonet joints.

The transmission system is composed of several shafts mutually coupled by gearings and joined with the stator using ball bearings. The detailed scheme of the transmission system is shown in Fig. 2 (the objects in this figure are not displayed in a real scale factor). An important part of the drive system is a centrifugal brake, which regulates the rotating motion of the tubular shaft in dependence on its angular velocity. Other functional subsystems plotted in Fig. 2 do not influence the dynamic behaviour during the studied control assembly drop.

3. Multibody model of the control assembly

The model was created in the **alaska** simulation toolbox (Maisser et al., 1998) on the basis of the technical documentation and drawings provided by the control assembly producer ŠKODA JS a.s. It is intended mainly for the simulations of the control assembly drop during the seismic event, where the significant measured and computed quantity is the total time of the drop.

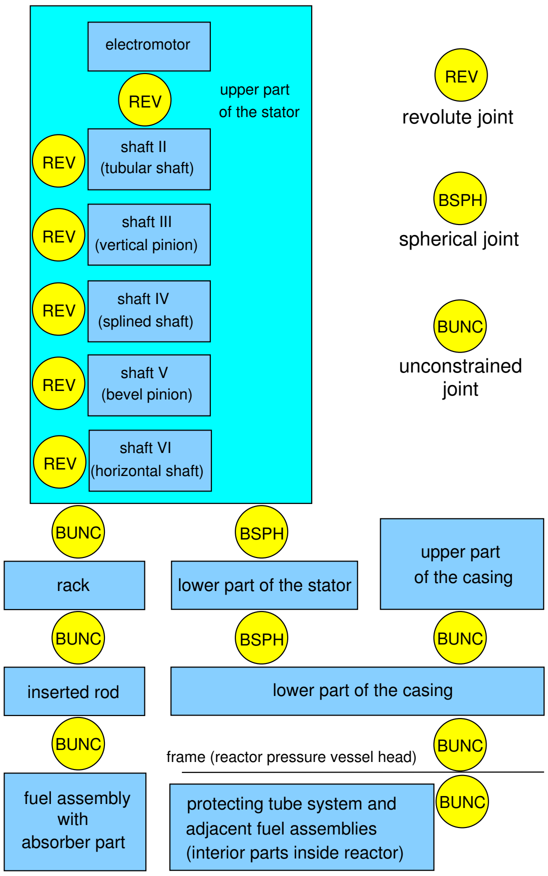

Fig. 3 Kinematic scheme of the control assembly multibody model.

Therefore some dynamical aspects of the control assembly that do not influence the drop time could be neglected. 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. The report Polach & Hajžman (2004) describes the control assembly model in detail.

The presented multibody model is the first control assembly model that should be the initial state to start the detailed study of the control assembly behaviour. The multibody model creation including coolant influences, seismic excitation and impacts was limited by the usage of the **alaska** simulation toolbox. Not all influences and specific behaviour could be considered in the model, but it is supposed that some aspects of the control assembly will be studied in more details in future works. The kinematic scheme and all the special features of the control assembly model are described in this paper.

The kinematic scheme of the control assembly multibody model is shown in Fig. 3, where circles represent kinematic joints (BUNC — unconstrained, BSPH — spherical, REV — revolute) and the quadrangles represent rigid bodies. In the computational model, the rigid bodies are described by their mass and inertia properties computed analytically for simple shapes or by means of the COSMOS/M software (SRAC, 1999) based on the finite element method. In order to introduce particular flexible behaviour of bodies, chosen parts of the control assembly (namely the stator and the drive casing) are divided into two bodies. Artificial stiffnesses are added in the kinematic couplings between two divided bodies. These stiffnesses are computed on the basis of finite element modelling of the whole body in the COSMOS/M system and allow to consider the first bending vibration modes. As this work is not focused on the modelling and analysis of the drive high frequency vibrations, each shaft in the gear transmission system (see Fig. 3) is modelled as one rigid body coupled with stator by revolute joint. Bending properties of the rack are also represented by the variable artificial torsional stiffness added in the kinematic coupling with the stator in dependence on the rack length ejected out of the stator. Due to the limited types of kinematic joint in the **alaska** some joints with redundant degrees of freedom, e.g. unconstrained joint, are used. But the **alaska** simulation toolbox allows to suppress these redundant degrees of freedom. The complete list of limited kinematic joints can be found in Polach & Hajžman (2004).

The special rigid body substituting interior parts in the reactor (see Fig. 1) in the multibody model is important to specify contact and impact conditions during the control assembly drop. The motion of this special body is defined on the basis of the whole reactor dynamic analysis.

The spur gear couplings between the shafts of the control assembly drive as well as between the rack and the pinion (shaft VI) are modelled on the basis of the expression of forces and torques transmitted by the gearings. Meshing stiffness on a gear mesh line is considered as constant mean stiffness, which can be approximately expressed (Slavík et al., 1997) by

$$k_G = 2 \cdot 10^{10} \text{ [N/m]}, \tag{1}$$

where b is width of the gearing. The meshing stiffness is not constant in a real gear couplings, but it is complex periodic function dependent on the tooth pairs in the gear mesh and on the position of the gear mesh point. The variable meshing stiffness is neglected in the multibody model of the control assembly, because it has the minimal dynamic effect on the control assembly drop. Due to the same reason the high frequency excitation by the gear kinematic transmission errors in gear couplings is not considered either. If angular rotations of the two wheels joined by gear coupling are described by angular deflections φ_1 and φ_2, the force F_G transmitted by the working tooth faces can be written in the form

$$F_G = k_G(r_1\varphi_1 - r_2\varphi_2). \tag{2}$$

The torques M_1 acting on the first wheel from the second wheel and M_2 acting on the second wheel from the first wheel are then

$$M_1 = k_G(r_1\varphi_1 - r_2\varphi_2)r_1 \qquad \text{and} \qquad M_2 = k_G(r_1\varphi_1 - r_2\varphi_2)r_2. \tag{3}$$

This approach allows to use the applied torques in the **alaska** simulation toolbox for the modelling of gear couplings between two rotating shafts with spur gears and similarly with internal spur gears (for splined shaft) and rack and pinion drive.

Possible contacts and impacts of the moving parts with the drive stator and with the adjacent structural parts inside the reactor are very important and significant aspects of the control assembly drop modelling. This is the topical issue in the modern multibody dynamics and many publications were released studying this field, e.g. Vukobratovic & Potkonjak (1999), Klisch (1998), Schiehlen & Seifried (2004), Kecskeméthy et al. (1999). However it was necessary to use some simple contact-impact model of the rigid bodies applicable in the **alaska** simulation toolbox.

The problem can be divided into two steps — the first one is the determination of the contact event and contact position and the second one is the calculation of the impact force acting on the bodies.

The possible bodies in contact were specified on the basis of technical documentation and drawings. Since the clearances between the falling bodies (the fuel assembly with absorber, the inserted rod, the rack) and adjacent structures (stator, protecting tube system, other fuel assemblies) are relatively small — 0.5 to 10 millimetres — the contacts occur frequently. Three types of contacts in the multibody model can occur according to the body-hole intersection. The simple geometrical consideration can decide if the contact of the body intersection boundary curves occurs or not. For the case illustrated in Fig. 4 of the body with circular intersection

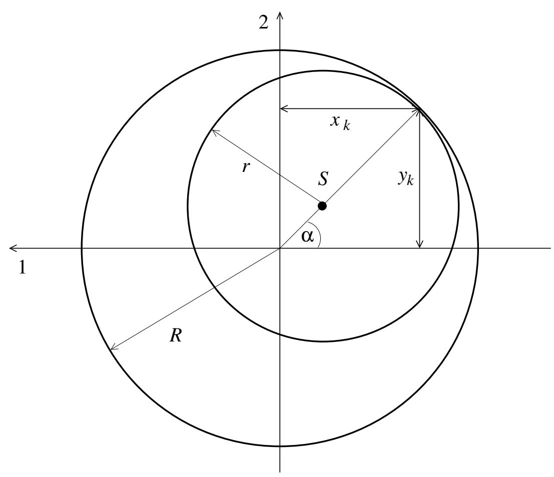

Fig. 4 The contact of the body with circular intersection moving through the circular hole.

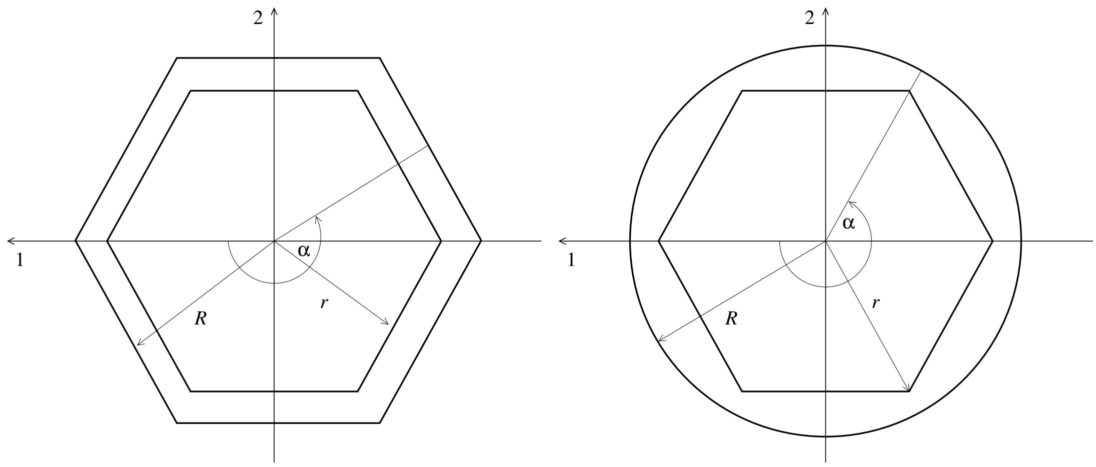

Fig. 5 The body with hexagonal intersection moving through the hexagonal hole and the circular hole.

moving through the circular hole it holds

$$R - \sqrt{x_S^2 + y_S^2} - r \leq 0 \tag{4}$$

if the body is in contact with the structure. Coordinate system axes are designated by numbers "1" and "2" in agreement with the **alaska** simulation toolbox, R is the hole radius, r is the radius of the body intersection, x_S and y_S are vertical displacements of the body center. If the condition (4) is fulfilled angle $\alpha = \arctan \frac{y_S}{x_S}$ can be computed and the relative deformation d of the contact surfaces can be expressed

$$d = R - \sqrt{x_k^2 + y_k^2}, \quad \text{where} \quad x_k = (x_S + r)\sin\alpha \quad \text{and} \quad y_k = (y_S + r)\cos\alpha. \tag{5}$$

Variable d is used in the impact force evaluation. Fig. 5 shows other possible contact cases in the control assembly multibody model.

Simple nonlinear Hertzian law (Flores et al., 2004)

$$F = kd^n \tag{6}$$

is used for the impact force evaluation, where k is the generalized stiffness and n is the constant coefficient for given materials. The contacts are coupled with vertical motion and therefore the friction force

$$F_t = fN, \tag{7}$$

where f is the friction coefficient and N is the actual normal force in the contact, is introduced. The impact forces are realized in the control assembly multibody model as the applied forces (command `aforce` of the **alaska 2.3** simulation toolbox). Their history is described by functions `bistop` and `step` (Maisser et al., 1998)

The most problematic factor in the control assembly multibody model is the influence of the pressurized coolant that flows through the reactor interior structure and acts against the control assembly motion. Like in the case of the contacts and impacts this issue is frequently studied in the theoretical way (e.g. Feireisl, 2002; Møller et al., 2005) but the simple practical approach was necessary in case of modelling such a complex system in the **alaska** simulation toolbox. It is clear that the main influence of coolant is the hydraulic resistance and friction slowing down the rigid body motion.

If $m_k = \rho_k V_i$ is the fluid mass pushed up by the body with volume $V_i = \frac{m_i}{\rho_m}$ static uplift pressure is respected in the corrected gravity force

$$G_i = m_i g - m_k g = m_i g \left(1 - \frac{\rho_k}{\rho_m}\right), \tag{8}$$

where m_i is the body mass, g is the gravity acceleration, ρ_m is the body material density and ρ_k is the coolant density.

Hydraulic resistance force for the motion of the body in certain fluid can be written (Giles, 1962) in the form

$$F = \frac{1}{2} C \rho_k S v^2. \tag{9}$$

The relative velocity is designated v, S is the body effective surface and C is the hydraulic coefficient depending on the shape of the body. In this case the coolant significantly influences the fuel assembly with the absorber part that has the biggest effective surface. But due to the complexity of the surface the hydraulic resistance coefficient is difficult to be determined accurately by the simple computation. Also the fact, that control assembly falls in the limited space where the coolant cannot run outside, makes the estimation more difficult.

Since the aim of this control assembly modelling problem is to study the worst case, it was sufficient to consider the vertical hydraulic resistance force as

$$F_V = \Delta p S_e, \tag{10}$$

where Δp is the change of the hydraulic pressure (dynamic component of the hydraulic pressure) in the reactor and S_e is the effective control assembly surface perpendicular to the motion direction. For the horizontal motion the hydraulic force in the form (9) is considered.

The centrifugal brake acting on the tubular shaft significantly regulates the control assembly drop. It is set to obtain the given control assembly drop velocity in the interval of 0.2 m/s to 0.3 m/s. The constant velocity of this interval has to be reached approximately in time 0.7 s. The braking torque of the centrifugal regulator is zero when the tubular shaft angular velocity is under a certain value and when this value is exceeded the braking torque can be written (Voldřich et al., 1997; Polach & Hajžman, 2004)

$$M_{reg} = A\omega_{II}^2 - B, \tag{11}$$

where ω_{II} is the tubular shaft angular velocity, A and B are specific constants that depend on a regulator setting.

4. Numerical simulations

Besides the creation of the control assembly multibody model including the drive, the main aim of the work was to simulate the control assembly drop in the course of seismic excitation. The drop without seismic excitation was also simulated. Numerical simulations were performed in the **alaska** simulation toolbox using the Shampine-Gordon integration method (Maisser et al., 1998).

Various standards and prescripts for the estimation of a nuclear power plants safety define the character of typical earthquakes in the locality of a nuclear power plant. The prescribed excitation is mostly defined by acceleration response spectra (acceleration of the base versus frequency). The common practise in linear seismic engineering is to use the response spectra method (Levy & Wilkinson, 1976) to determine the response of an investigated system. However, the presented problem of the control assembly drop is strongly nonlinear, mainly due to the presence of contact and impact forces, and the numerical integration of the equations of motion have to be used. The best way how to introduce seismic excitation in the **alaska** model is to use absolute displacements. It was necessary to recompute the acceleration spectra to the time history of absolute displacements.

The linear simplified dynamic model of the VVER 440/V213 NPP Paks nuclear reactor including primary circuit loops modelled by finite element method was used for this purpose. This model was developed by Department of Mechanics, University of West Bohemia in Pilsen. The interior parts of the reactor were simplified in this model. The reactor and loops were excited by the acceleration spectra of the base and the time histories of displacements of chosen points during the seismic excitation were obtained. The time histories of the absolute displacements of the pressure vessel head nozzle (see Fig. 1) and the time histories of the interior structural parts inside the reactor are the inputs of the control assembly multibody model.

Tab. 1 Summary of the computed control assembly drop times for all simulations.

Set velocity [m/s]	Simulation type	Drop time [s]
0.3	without seismic excitation	8.666
0.3	with seismic excitation	9.272
0.2	without seismic excitation	12.77
0.2	with seismic excitation	13.38

The computed times of the control assembly drop with seismic excitation are compared with the results of the simulations without seismic excitation in Tab. 1. The set velocity means the velocity of the control assembly drop, for which the centrifugal regulator was set. Fig. 6 shows the relative displacement between the control assembly lower end and the bottom of the reactor vessel computed without and with seismic excitation for centrifugal regulator set to velocity 0.3 m/s. Relative velocities of the control assembly drop on the bottom of the reactor vessel for the same cases are plotted in Fig. 7.

The studied multibody model is very complicated and strongly nonlinear due to the influences of the coolant, the contacts with the adjacent parts, the centrifugal regulator and possible seismic excitation. The complexity and nonlinearities cause the unstability in numerical integration. Further some used coefficients cannot be measured and have to be estimated on the basis of appropriate literature. Numerical sensitivity analyses with respect to the most problematic values of model parameters were performed to find out the stability of the model. The illustration of the sensitivity analysis with respect to the values of the contact stiffness used in the bayonet joints with clearance is shown in Fig. 8.

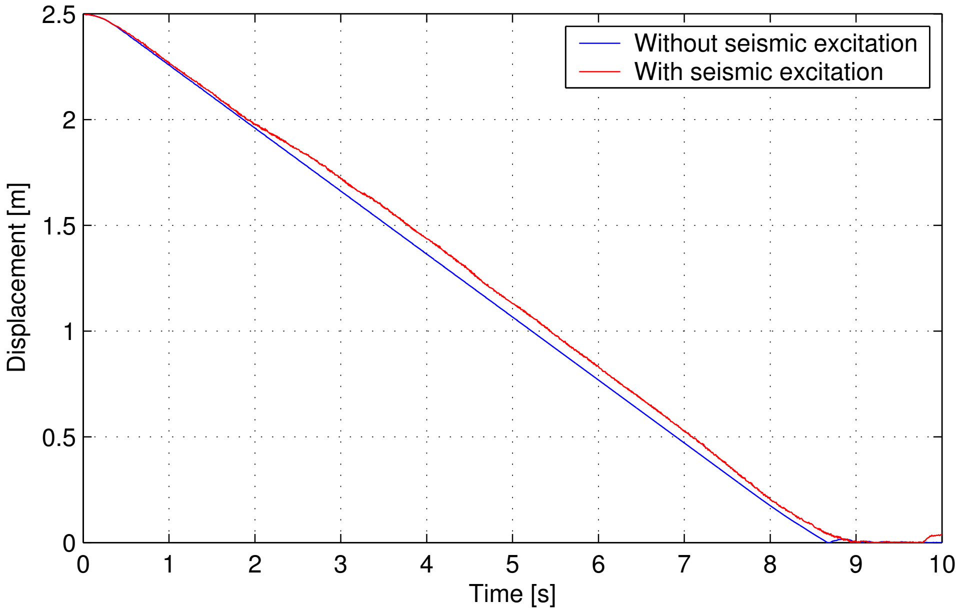

Fig. 6 Relative displacement of the control assembly lower end and the bottom of the reactor vessel (without and with seismic excitation, velocity set to 0.3 m/s).

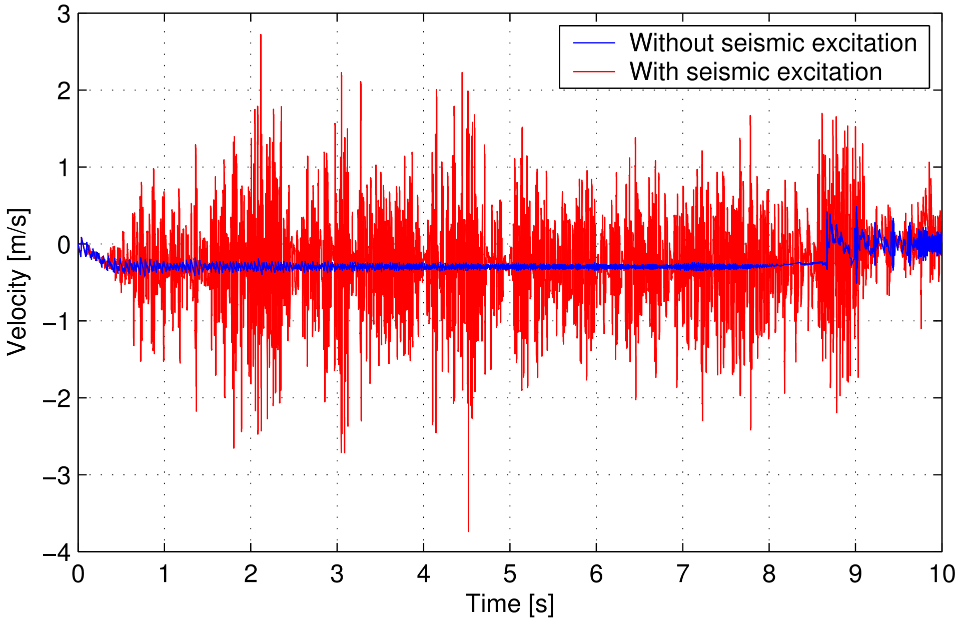

Fig. 7 Relative velocity of the control assembly drop on the bottom of the reactor vessel (without and with seismic excitation, velocity set to 0.3 m/s).

5. Conclusion

The contribution presents the VVER 440/V213 nuclear reactor control assembly multibody model created in the **alaska** simulation toolbox. The multibody model includes the influences of the fluid and the contacts and impacts with the interior parts inside the reactor. The model is

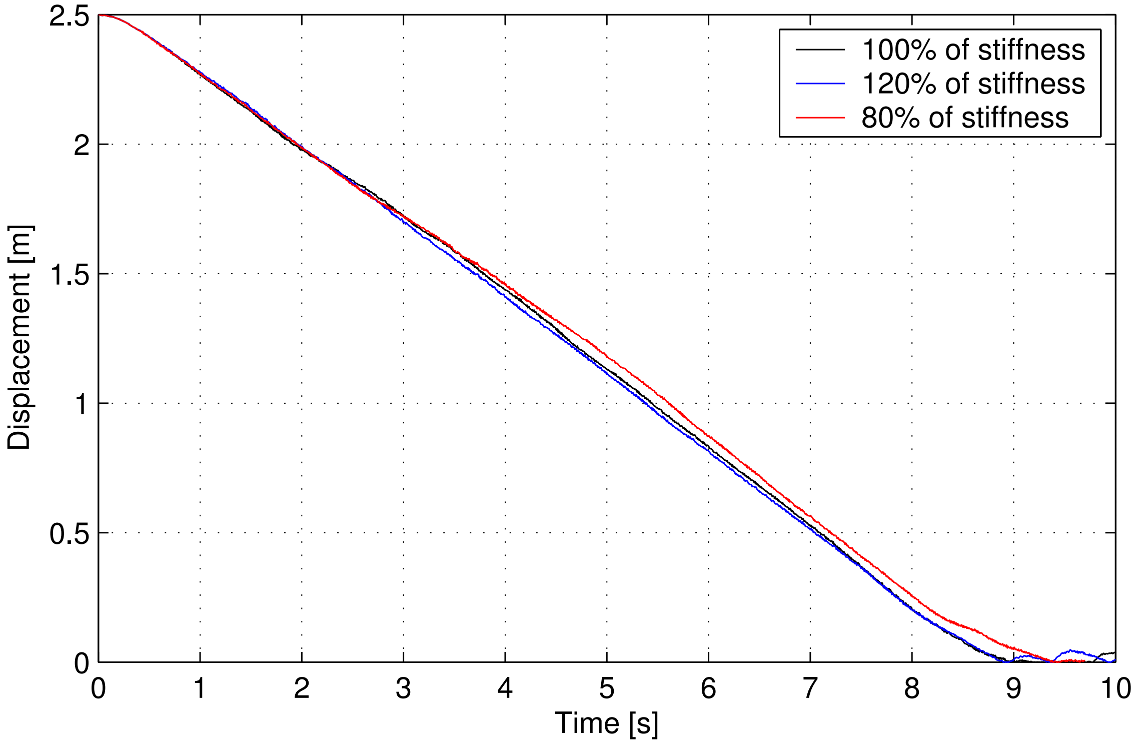

Fig. 8 Relative displacement of the control assembly lower end and the bottom of the reactor vessel for different values of stiffness in the bayonet joints (without and with seismic excitation, velocity set to 0.3 m/s).

used for the numerical simulations of the control assembly drop without and with the seismic excitation in Paks nuclear power plant.

The computed drop times summarized in Tab. 1 fulfil the prescribed limits given for nuclear power plants safety estimation. These times are necessary for immediate stop of the chain nuclear reaction in the reactor core in case of an earthquake.

The model with the considered influences should be understood as the introductory work on this topic. Various problems arised from the solving of this task will be studied in more detail in future work. Mainly the problems of the falling body that is in contact with other bodies and interacts with fluid (coolant) in limited space have to be investigated. The control assembly (the fuel assembly with the absorber part) is of a complex structure. It is composed of many fuel rods and the evaluation of the bending stiffness is difficult. The consideration of rigidity seems to be good assumption in the case of its drop but the problem of a falling flexible body in fluid with contacts has to be studied, too.

6. Acknowledgement

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