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Investigation of falling control rods in deformed guiding tubes in nuclear reactors using multibody approaches

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ABSTRACT — *One of the interesting applications of multibody dynamics is the analysis of control assemblies or control rods used for the nuclear reaction control and emergency stops. Generally, control assemblies can be simplified to the typical problem of a long thin rod moving through guide tubes and driven by a motor. Two different approaches to the modelling of control assemblies for nuclear reactors are introduced in this paper. The first approach is based on the usage of a complex multibody model consisting of rigid bodies while the second approach employs the absolute nodal coordinate formulation. Both models are used for numerical simulations of falling control rods in deformed guiding tubes during the emergency reactor shut-down.*

1 Introduction

Multibody approaches can be successfully employed for the modelling of nonlinear motion and dynamical analysis in nuclear engineering. An interesting application of multibody dynamics is the analysis of control assemblies or control rods used for the nuclear reaction control and emergency stops [1]. Typically after the emergency signal, control assemblies should fall inside their guiding tubes into the active zone and it leads to higher absorption of neutrons and finally to stop the nuclear reaction. This paper is dedicated to the modelling and dynamical analysis of a falling control assembly of the VVER 1000 nuclear reactor [2]. The study is mainly aimed at the dynamic behaviour affected by the deformed guiding tubes.

The nuclear industry is bound by many regulations and standards which put high demands on design of components, quality of used material and detailed documentation. This leads to a need of a clear proofing of a nuclear power plant (NPP) safety operation. According to the safety class of various components of NPP, the evaluation of integrity and stability of the component must be performed for different load cases, such as normal operation conditions (including pressure and temperature loadings), seismic loadings, loss of coolant accident (LOCA) and others. Many of these evaluations must be performed computationally, since experimental validation is not possible. The computational evaluation of a NPP component is always subjected to a computational error caused by discretization issues, numerical method error etc. In order to lower the influence of computational error to the safety operation of NPP component, it is always appropriate to choose conservative approach and made conservative assumptions. For example, a conservative estimation of friction coefficient is employed in this work.

The motivation for this work results from the requirements for the safe shutdown of a nuclear reactor. The time limit for the control assembly full drop to the active zone in the investigated reactor is 3.5 seconds. In ideal conditions the real drop time is about 1.4 seconds. But it is common that a permanent transverse deformation of guiding tubes may arise during the operation of the nuclear reactor due to temperature and radiation. Since there is a relatively small gap between the control rods and the guiding tubes, the control assembly might get stuck before the full drop because of tube deformation. This state can be dangerous for the successful nuclear reaction shutdown. Our goal is to investigate the influence of the guiding tube deformation to the successful control assembly drop. The results may help to approximately determine the maximal allowed tube deformation without the need of difficult experimental proofing.

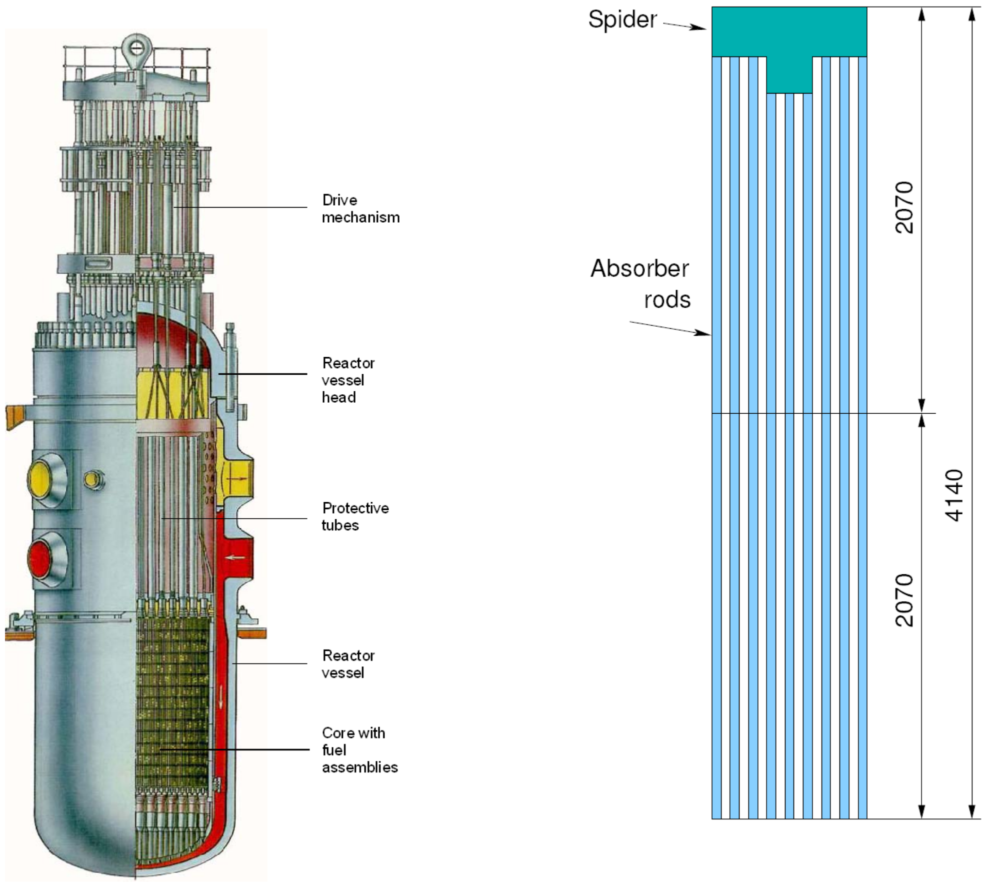

Fig. 1: Scheme of the VVER 1000 nuclear reactor (left) and its cluster of control rods (right)

Concerning modelling of the control assembly of the VVER 1000 nuclear reactor, two different approaches are introduced in this paper. The first approach is based on the usage of a complex multibody model consisting of rigid bodies while the second approach employs the absolute nodal coordinate formulation. Each following section includes the chosen results of numerical simulations.

2 Complex multibody model using rigid bodies

The VVER 1000 nuclear reactor is a pressurized water-cooled and water-moderated reactor used in many countries (mainly in the central and eastern Europe). The reactor consists of a reactor pressure vessel with an interior structure and a reactor upper block with control assembly drives (see the scheme in Fig. 1 on the left). Under the vessel head with nozzles of the control assembly drives there is a block of protective tubes, which is above the core with fuel assemblies (so called active zone with running nuclear reaction). The VVER 1000 reactor contains 163 fuel assemblies and 61 control assemblies [2]. A moveable part of the control assembly, i.e. the rod control cluster assembly (this part is the necessary condition for the stopping of nuclear reaction), is composed of a suspension bar, a spider and 18 long thin absorber rods.

A functional scheme of the control assembly is shown in Fig 2 (rectangles represent parts of the mechanism that are coupled by elastic elements with possible clearances). The suspension bar (driven by a linear stepper motor) is divided into an upper and a lower part with a bayonet joint for connecting with a spider of the control element (i.e. the rod control cluster assembly). In case of an emergency state the lifting system mechanism is set off and the rod control cluster assemblies can drop down through the protective tubes to the reactor core with fuel assemblies and stop the nuclear reaction. When the absorber rods reach the lower part of the core they pass through the guide channel narrowing, which has the function of hydraulic shock absorbers for stopping the rod

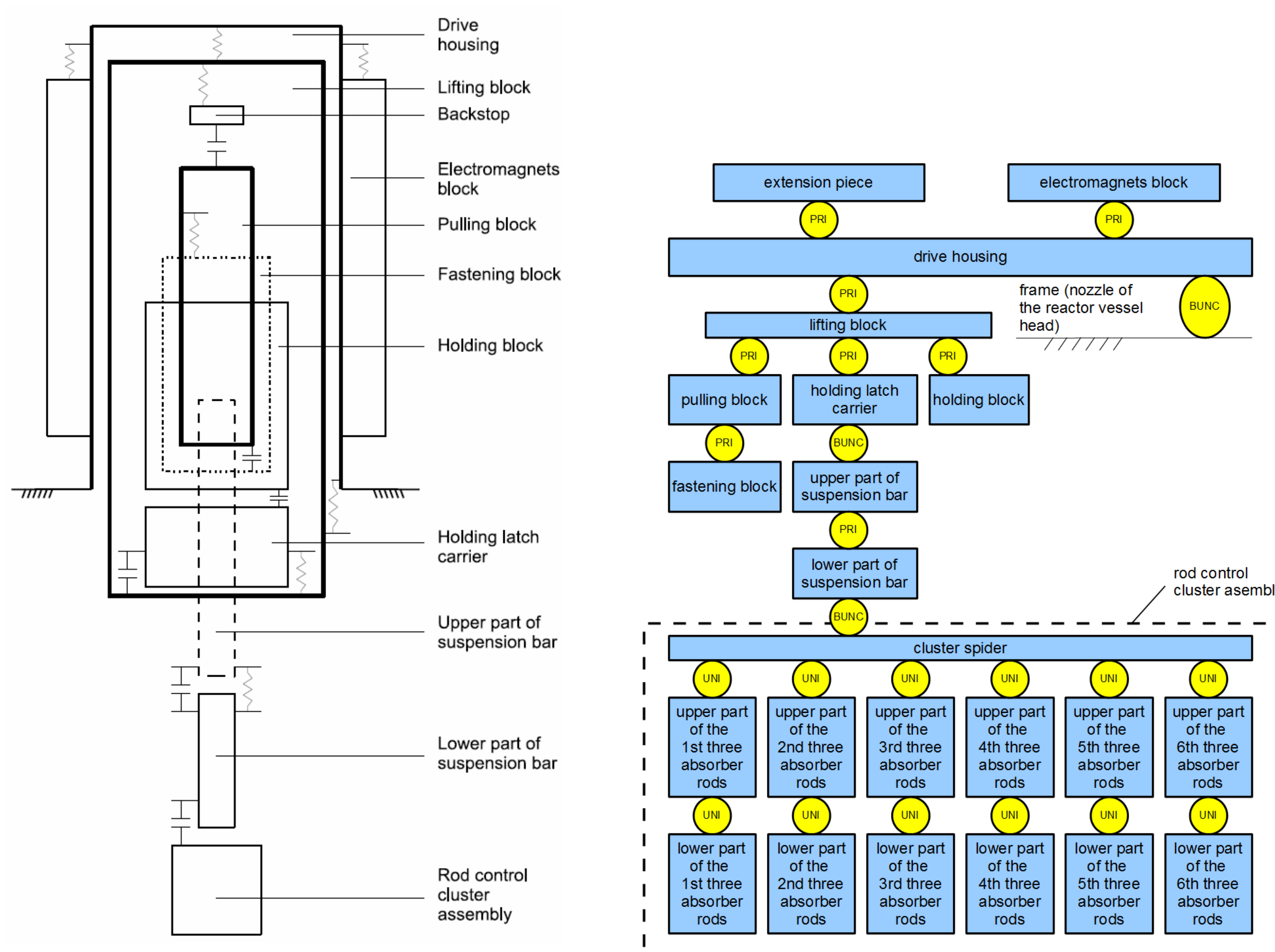

Fig. 2: Functional scheme of the control assembly of the VVER 1000 nuclear reactor (left, not in the real scale) and its kinematical scheme (right)

control cluster assemblies drop.

The first presented model is a complex multibody model of the LKP-M/3 control assembly of the VVER 1000 nuclear reactor created in the alaska simulation tool [3]. It is composed of 22 rigid bodies coupled by 22 kinematic joints. See Fig. 2 for the kinematical scheme, where rectangles represent rigid bodies and circles represent kinematic joints. The number of its degrees of freedom is 45. All bodies can perform spatial motion. The influences of the pressurized water have to be introduced in the multibody model because the rod control cluster assemblies are falling in a limited space and water resistance is not negligible.

Possible contacts of the falling rod control cluster assembly with adjacent structural parts inside the reactor were supposed. The problem can be divided into two steps – the first one is the determination of the contact occurrence 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 (parts of the rod control cluster assembly) and adjacent structures (protective tubes, fuel assembly guide tubes) are relatively small – 1 to 7.5 millimetres – the contacts occur frequently. In all cases the contact of a body of circular cross-section with a circular hole (the body moves through the hole) can occur in the multibody model. Relative penetration of the geometries was used in the impact force evaluation and additionally the simple Coulomb's friction model was considered.

The shape of the fuel assembly guide tubes deformation was specified by a control assembly manufacturer and a reactor operator. Horizontal deformation $\Delta(z)$ is described parametrically as a function of vertical coordinate z

$$\Delta(z) = P\delta(z), \tag{1}$$

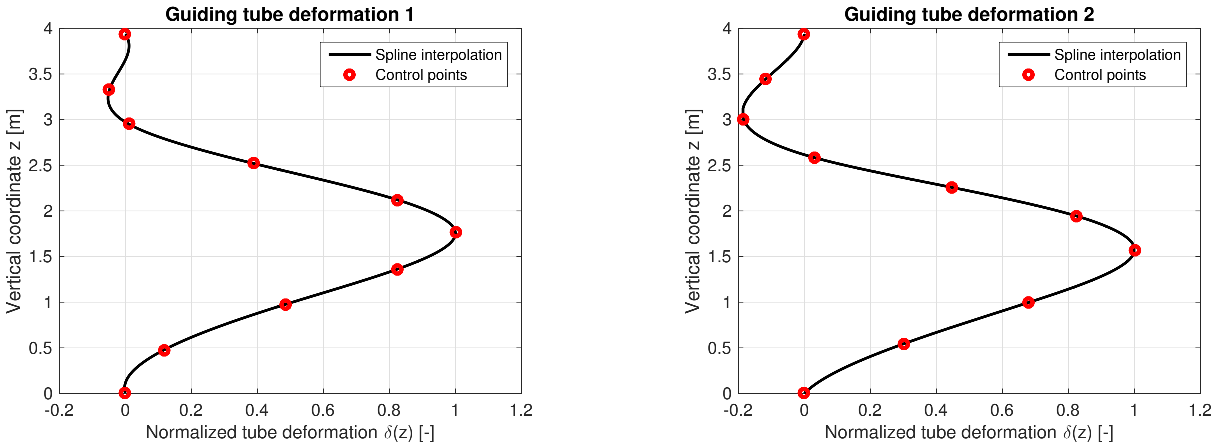

Fig. 3: Predefined normalized deformation of guiding tubes in the active zone

where $\delta(z)$ is the normalized deformation curve of the guide tubes obtained as the spline interpolation between defined control points, see Fig. 3, P is the parameter corresponding to the maximal tube deformation. As it is shown in Fig. 3, two shapes of the tube deformation were investigated.

As an example of the complex multibody model results, two cases of the control assembly drop with deformation 2 were chosen. In Fig. 4 the time histories of vertical position and velocity of the control assembly successful drop are shown. In this case, the tube deformation was small (5.4 mm). In case of higher deformations an unsuccessful drop can be reached as it is shown in Fig. 5.

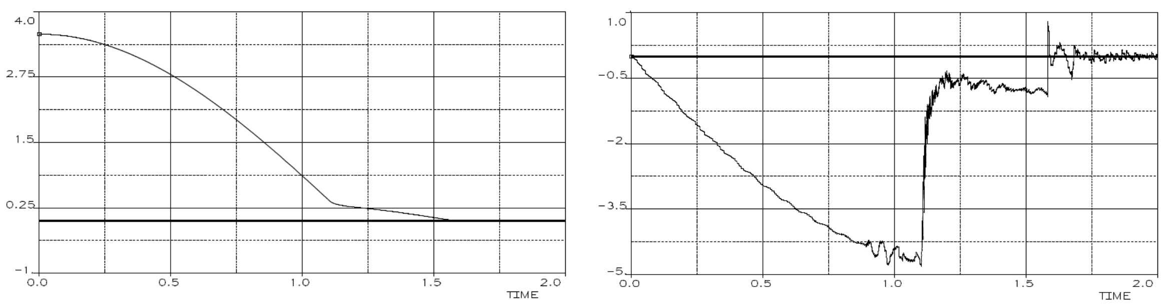

Fig. 4: Successful control assembly drop: time histories of distance [m] of the lower end of absorber rods from the mechanical stop (left) and vertical velocity [m/s] of the control rod

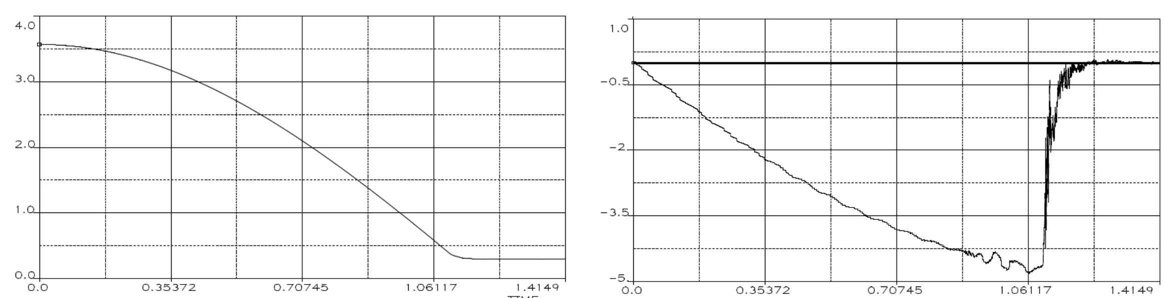

Fig. 5: Unsuccessful control assembly drop: time histories of distance [m] of the lower end of absorber rods from the mechanical stop (left) and vertical velocity [m/s] of the control rod

3 Falling rod modelling based on the absolute nodal coordinate formulation

The second presented approach is based on the flexible body modelling using the absolute nodal coordinate formulation (ANCF). Various ANCF beam elements such as those mentioned in [4, 5] can be used for thin rod modelling, however the simple gradient deficient spatial beam element was chosen because it includes axial and bending stiffness. This element does not consider torsional stiffness, but the control rods are not torsionally loaded during emergency drop. The ANCF elements were chosen because of large translational motion of the falling rod.

A simplified model of one control rod was created and tested. This simplified rod is 4.2 m long with the radius of 4.1 mm, mechanical parameters such as density and Young's modulus were set according to real values [3]. In order to represent the dynamics of the suspension bar and the spider in the most simplest way, these bodies are considered as rigid, the possible rotation of these bodies is neglected, since there is a small gap between other structural parts of the reactor, and they are represented as one point-mass. The point mass has three translational degrees of freedom and the weight is equal to 1/18 of the real weight of the simplified structural parts because there are 18 control rods in one control assembly and the weight distribution is assumed to be uniform. So the resultant model of the falling rod contains the thin flexible rod and the reduced mass of other falling parts.

Possible contacts and friction between the thin rod and the guiding tube are also included in the model. The normal contact force was defined according to Hertz's model with nonlinear damping [6]. The guiding tube radius is 5.5 mm, so the initial gap between the rod and the tube is 1.4 mm. Over the guiding tubes there are the protective tubes. The gap of 2.5 mm between the spider and the protective tubes is also included in the model. The Threlfall model of the friction force, which is based on the smoothened Coulomb's friction model, was used because of its efficiency [7]. The threshold relative speed was set to 0.01 $\text{m}\cdot\text{s}^{-1}$, lower threshold speed had almost none influence to the quality of results. The friction coefficient was conservatively set to 0.3.

The vector of contact forces is evaluated at Gaussian points of each element and can be expressed as

$$\mathbf{F}_C(x_i) = \mathbf{F}_N(x_i) + \mathbf{F}_T(x_i), \tag{2}$$

where x_i is the axial parameter of the beam that corresponds to Gaussian point i, $\mathbf{F}_N$ is the vector of normal contact force and $\mathbf{F}_T$ is the vector of friction force. The contact of the beam element with other bodies is distributed along the element length l_e. The vector of generalized contact forces acting on the element can be expressed using integration along the beam length as

$$\mathbf{Q}_{Ce} = \int_0^{l_e} \mathbf{S}^T(x)\mathbf{F}_C(x)\mathrm{d}x, \tag{3}$$

where $x = \langle 0,\ l_e \rangle$ is the axial parameter of the ANCF beam element and $\mathbf{S}$ is the matrix of element shape functions [5]. In order to evaluate expression (3), the Gaussian quadrature method is used. This leads to a simple evaluation of the vector of contact forces using shape functions matrix precomputed in Gaussian integration points during preprocessing and expression (2) as follows

$$\mathbf{Q}_{Ce} \approx \frac{l_e}{2} \sum_{i=1}^{n} w_i \mathbf{F}_C(x_i)^T \mathbf{S}(x_i), \tag{4}$$

where w_i are weights, n is the number of Gaussian point, in our case $n = 5$.

Since the guiding tube is filled with a water, a resistance force (drag) acting opposite to the relative motion of the rod is included in the model [3]. The drag coefficient was set according to experimental data from the control assembly manufacturer. The hydraulic damper is placed at the bottom of the guiding tube in order to reduce the impact on the bottom mechanical stop. The effect of hydraulic damper is modelled by increasing the drag coefficient.

The whole model is described by the following equation of motion

$$\mathbf{M}\ddot{\mathbf{q}}(t) + \mathbf{K}(\mathbf{q})\mathbf{q}(t) = \mathbf{Q}_C(\dot{\mathbf{q}},\ \mathbf{q}) + \mathbf{Q}_G + \mathbf{Q}_D(\dot{\mathbf{q}}), \tag{5}$$

where $\mathbf{M}$ is the constant mass matrix composed of the ANCF beam element mass matrices, $\mathbf{K}(\mathbf{q})$ is the nonlinear stiffness matrix composed of the ANCF beam element stiffness matrices, since the vector of elastic forces can be

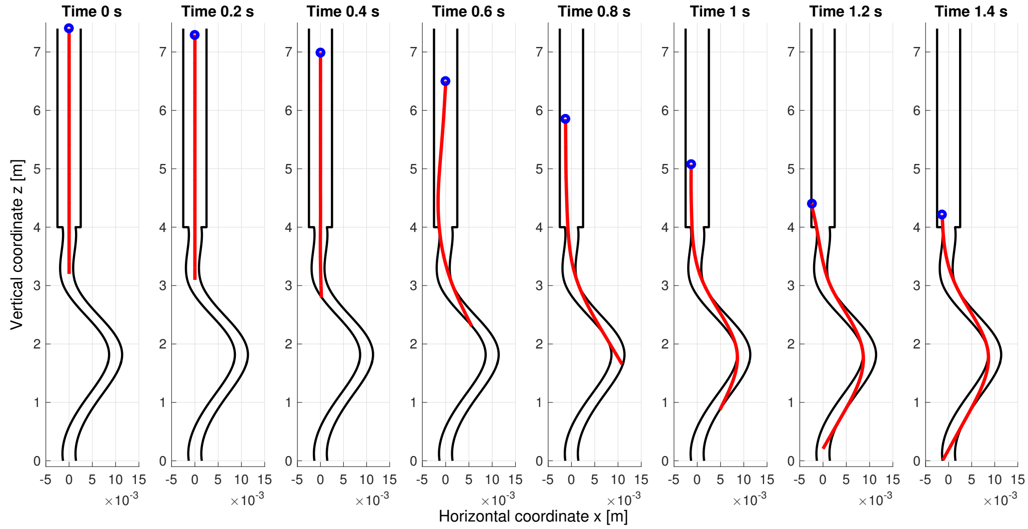

Fig. 6: Snapshots of the rod centerline (red), the contact boundaries (black) and the point-mass with reduced weight of the suspension bar (blue) in discrete time steps for deformation 1 and maximal deformation $P = 10$ mm

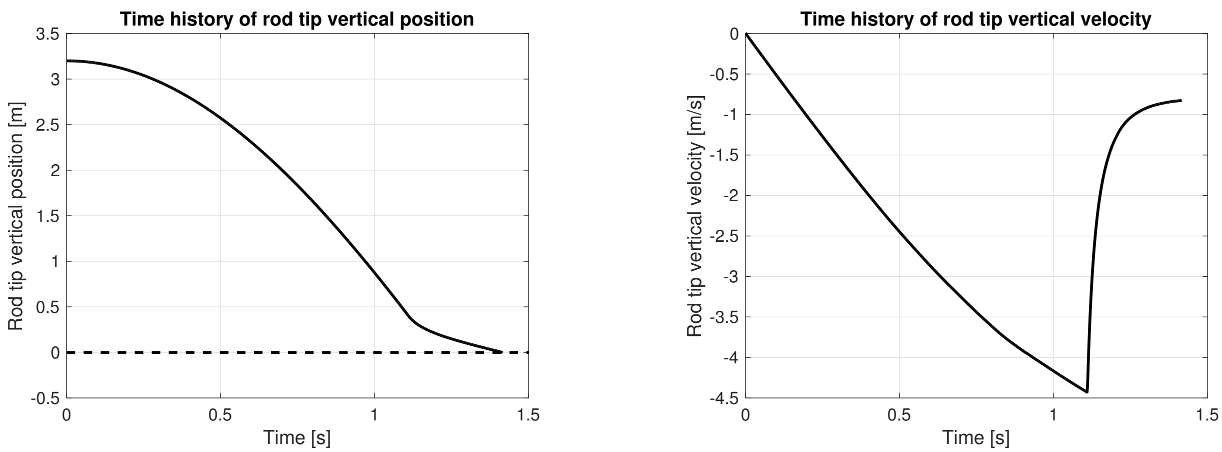

Fig. 7: Time history of vertical position (left) and velocity (right) of the control rod tip

rewritten to the form $\mathbf{Q}_e(\mathbf{q}) = \mathbf{K}(\mathbf{q})\mathbf{q}(t)$, expression $\mathbf{Q}_C(\dot{\mathbf{q}}, \mathbf{q})$ is the vector of the contact forces, $\mathbf{Q}_G$ is the vector of the gravitational forces and $\mathbf{Q}_D(\dot{\mathbf{q}})$ is the vector of the drag forces. This model can be extended by adding a damping. The proportional damping was selected in the form $\beta\mathbf{K}(\mathbf{q})\dot{\mathbf{q}}$, where $\beta = 0.0001$.

The whole model was implemented in the MATLAB system. Twenty elements were used for rod discretization. Snapshots of the successful drop are shown in Fig. 6, where the rod centerline is shown in red and its contact boundaries are shown in black. During this drop, the maximal deformation was $P = 10$ mm. Corresponding time histories of the rod tip vertical position and velocity are shown in Fig. 7. The time histories of both models (Fig. 4 and Fig. 7) are in a good agreement.

The parametric studies of the influence of the guiding tube deformation parameter P were performed for both deformation shapes. In Fig. 8) the drop times for various tube deformation are shown. As can been seen from the results, the limit deformation is approximately 43 mm for the first shape and 38.5 mm for the second shape. In case of higher deformations, the control rod got stuck and did not drop to the bottom of active zone. The example of time histories of vertical position and velocity of the control rod tip in case of the unsuccessful drop with deformation shape 2 is shown in Fig. 9). The maximal tube deformation was set to $P = 60$ mm, which is quite high for the tube of 4 m length and it should not be achieved during normal operating conditions. As can be seen, the time limit of 3.5 s for the drop was exceeded.

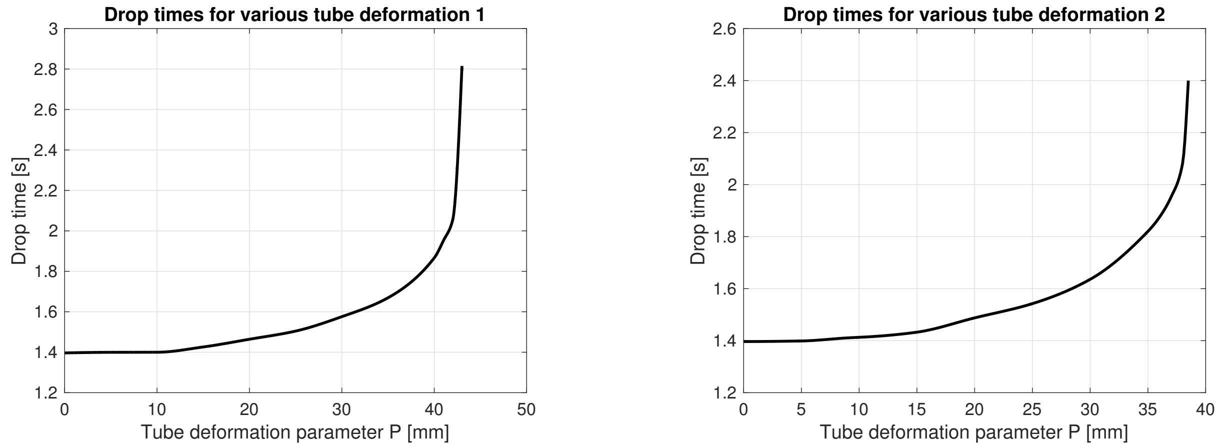

Fig. 8: Drop times dependency on the tube deformation parameter P for two deformation shapes

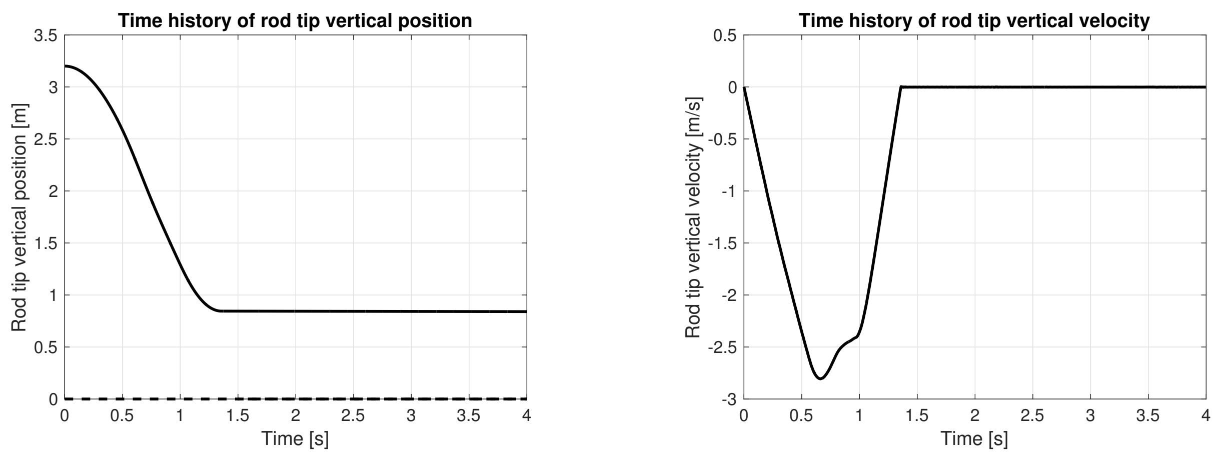

Fig. 9: Time history of vertical position (left) and velocity (right) of the control rod tip in case of the unsuccessful drop with deformation parameter $P = 60$ mm and deformation shape 2

4 Conclusions

Both presented modelling approaches of falling control assemblies in nuclear reactors can be considered complementary. The first approach is used to obtain a global response of the control assembly of the VVER 1000 nuclear reactor e.g. to the seismic loads, while the second approach is utilized for a detailed analysis of the interaction between the control rods and the deformed guiding tubes. However, the results from the second model are still indicative since several structural parts are simplified. In future work, the goal is to combine both model – the complex rigid body model with the control rods discretized using ANCF.

Acknowledgements

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