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COMPUTER ANALYSIS OF INFLUENCE OF THE FLEXIBLE BODY IN MULTIBODY SYSTEM OF THE RAIL VEHICLE BOGIE ON OUTPUTS PARAMETERS

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КОМП'ЮТЕРНИЙ АНАЛІЗ ВПЛИВУ НА ВИХІДНІ ПАРАМЕТРИ НАЯВНОСТІ ПРУЖНОГО ЕЛЕМЕНТА В БАГАТОКОМПОНЕНТНІЙ СИСТЕМІ ВІЗКА РЕЙКОВИХ ЕКІПАЖІВ

Діжо Я., Блатніцкий М., Ноженко О.С., Кравченко К.О.

Using computer analyses and simulations of rail vehicles we can carry out static analyses of individual parts of rail vehicles and dynamic analyses of substructure or complete rail vehicle. The Finite Element Method is most frequently used for stress analyses of structures. On the other hand dynamic behaviours and properties are analysed, investigated and evaluated by different approach called Multibody System. Connection of these two procedures considerably extents the possibilities of computer analyses of rail vehicles under various operational conditions. This contribution presents an influence of including a flexible body into the multibody system of a freight wagon bogie on its running behaviour. The flexible multibody system of freight wagon bogie was created and as a flexible body the bogie frame was used. After numerical simulation selected parameters were evaluated in order to assess the flexible body influence on the ride properties of a wagon bogie.

Keywords. *Finite Element Method, Multibody System, Vehicle bogie, Flexible body.*

Introduction. Computer aided modelling and simulations are nowadays widely employed in investigating rail vehicles properties. These include e.g. track interaction and study of track forces, detection and prediction of the mechanism of deterioration and causes of accidents. Therefore it is necessary to develop adequate virtual models of rail vehicles.

Rail vehicle design has to meet the requirements of the vehicle application. Rail vehicles manufacture is consists of several stages. The manufacturing stage and operation of rail vehicles is closely linked to economic factors. Results of simulation calculations contribute significantly to the estimation and prediction of rail vehicles behaviour. However, this requires creation of a representative virtual model. Dynamic simulations of rail vehicles can be performed by means of commercial software working with a rail vehicle model and a system of rigid or deformable bodies which are connected by linking elements.

Motivation for investigation. The properties of rail vehicles as mechanical systems can be designed, studied, evaluated, verified and diagnosed by means of experimental methods [1] and measurements [2 and 3], simulation calculations and optimization using computer software [4, 5 and 6] or also by special equipment in laboratories [7].

In investigating dynamic properties and behaviour of rail vehicles we model and describe these vehicles by means of multibody system dynamics.

A standard multibody system of a rail vehicle contains rigid bodies that are connected by ideal joints, coupling elements [8], contact elements, suspension and spring elements [9] and force elements. Rail vehicle dynamics also involves the phenomena of wheel/rail contact [10 - 13], which significantly influences the rail vehicle properties and wheel/rail contact stress conditions.

Rail vehicle analysis includes applications, where deformations of individual bodies have to be considered as well and taken into account in calculations. Therefore, the rail vehicle multibody system is extended with flexible bodies. Generally, the Finite Element Method is most often used for flexible bodies' implementation into the rail vehicle multi-body system [14]. This however means that a large number of degrees of freedom would be introduced into the rail vehicle model. Therefore we need the so-called reduction of linear degrees of freedom, which represents the principal step for efficient simulation of a rail vehicle multibody system with a flexible body in MBS software. The following Figure 1 gives an overview of the workflow when working with flexible bodies.

Principles of flexible multibody dynamics. The formulation of the finite element method uses a coordinate system firmly fixed to the body to describe the de-formation field of each body.

Flexible bodies and rigid bodies of the rail vehicle multibody system are represented by a set of Cartesian coordinates and have their relative motion restrained by a set of kinematic constraints. There are also other formulations of multibody systems, such as natural coordinates, which can be used with the finite element description of the large motion of flexible bodies. Nevertheless, we need another set of coordinates to define the kinematic constraints between the rigid and flexible bodies of the multibody system.

Several methods have been developer for kinematic description of the motion of a flexible body performing large displacements such as [15, 16] floating frame of reference, convected coordinate system, finite segment method, large rotation vector, and absolute nodal coordinate formulation.

The floating frame of reference formulation is a method that is currently the most frequently used in computer simulation of multibody systems with flexible bodies, and is implemented in commercial multibody computer software [16, 17].

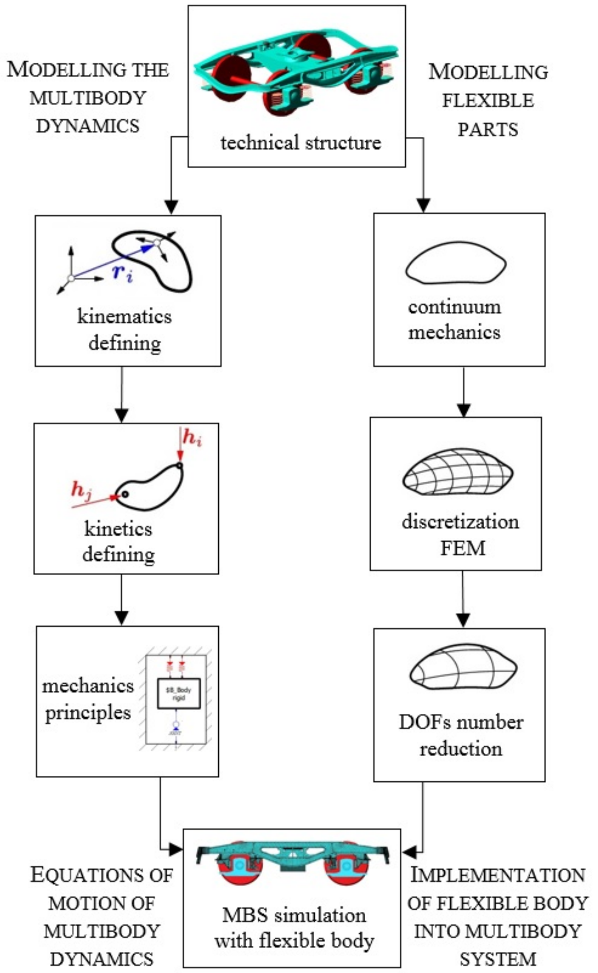

Fig. 1. Workflow procedure in flexible multibody system preparation

In this formulation, the configuration of a flexible body is described by two set of coordinates. One set of coordinates is used for location and orientation of the selected body coordinate system and the other set is used the body deformation with respect to its coordinate system. Using this approach, the global position vector of the flexible body $\boldsymbol{B}^i$ (Fig. 2) can be written as:

$$\boldsymbol{r}_P = \boldsymbol{r}_i + \boldsymbol{R}_{iP} + \boldsymbol{u}_P \tag{1}$$

All vectors in eq. (1) are in Fig. 2; vectors represent the following: $\boldsymbol{r}_p$ – position vector of the point $\boldsymbol{P}$, $\boldsymbol{r}_i$ – nonlinear motion of the reference frame $\boldsymbol{K}_i$, $\boldsymbol{R}_{iP}$ – the position of the point $\boldsymbol{P}$ in the nondeformed state, $\boldsymbol{u}_p$ – superposed linear elastic deformation.

Using the above-described dynamic description we can use the principle of virtual work in dynamics of Lagrange's equations of motion to symmetrically develop the dynamic equation of motion of the flexible body that is undergoing large reference displacements. In this formulation, the equations of motion are expressed in terms of a coupled sets of reference and elastic coordinates. The location and orientation of a selected body are defined by the reference coordinates, and the body deformation with respect to its reference state is defined by the elastic coordinates.

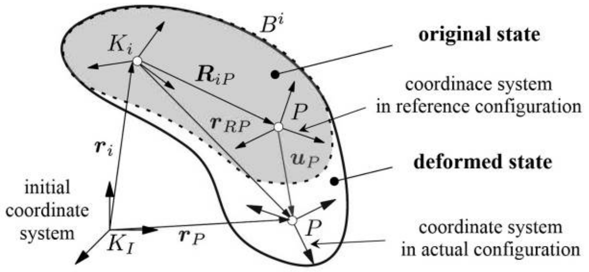

Fig. 2. Representation of a flexible body kinematics

The equations of motion of a flexible body in a rail vehicle multibody system can be written in a general form:

$$\boldsymbol{M}^i \ddot{\boldsymbol{y}}^i + \boldsymbol{K}^i \boldsymbol{y}^i = \boldsymbol{q}_e^i + \boldsymbol{q}_v^i + \boldsymbol{q}_c^i \tag{2}$$

The subscript i indicates the number of bodies, $\boldsymbol{M}$ is the mass matrix, $\boldsymbol{K}$ is the stiffness matrix, $\boldsymbol{y}$ is the vector of the system of generalized coordinates, and vectors $\boldsymbol{q}_e$, $\boldsymbol{q}_v$, and $\boldsymbol{q}_c$ are vectors of externally applied forces, Coriolis and centrifugal forces and constraint forces, respectively. The vector qc can also be rewritten as the vector of Lagrange multipliers $\boldsymbol{\lambda}$:

$$\boldsymbol{q}_c^i = -\boldsymbol{Q}^{iT} \boldsymbol{\lambda} \tag{3}$$

where $\boldsymbol{Q}$ represents the Jacobian matrix of the kinematic constraint equations defining the joint constraints and trajectories of the corresponding motion. The equations of motion (2) can also be expressed with a small modification as:

$$\boldsymbol{M}\ddot{\boldsymbol{y}} + \boldsymbol{K}\boldsymbol{y} = \boldsymbol{q}_e + \boldsymbol{q}_v + \boldsymbol{q}_c \tag{4}$$

If we write the coordinates vector $\boldsymbol{y}$ in the following form:

$$\boldsymbol{y} = \left[y_r^T, y_f^T \right]^T, \tag{5}$$

then the matrix form of the equations of motion of the multibody system with a flexible body will be as follows:

$$\begin{bmatrix} \boldsymbol{M}_{rr} & \boldsymbol{M}_{rf} \\ \boldsymbol{M}_{fr} & \boldsymbol{M}_{ff} \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{y}}_r \\ \ddot{\boldsymbol{y}}_f \end{bmatrix} + \begin{bmatrix} \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{K}_{ff} \end{bmatrix} = \\ = \begin{bmatrix} (\boldsymbol{q}_e)_r \\ (\boldsymbol{q}_e)_f \end{bmatrix} + \begin{bmatrix} (\boldsymbol{q}_v)_r \\ (\boldsymbol{q}_v)_f \end{bmatrix} + \begin{bmatrix} (\boldsymbol{q}_c)_r \\ (\boldsymbol{q}_c)_f \end{bmatrix} \tag{6}$$

The subscript r indicates reference coordinates and the subscript f indicates elastic coordinates [16].

Using the floating frame of reference method for the reduction of flexible bodies leads to a highly nonlinear mass matrix due to the inertia coupling between the reference motion and the elastic deformation, but the stiffness matrix remains the same as the stiffness matrix in structural dynamics. This is because the elastic coordinates are defined with respect to the coordinate system of the body [16].

Procedure of modelling and simulation of the freight wagon bogie with flexible body. Implementation of the flexible body into the multibody system of rail vehicle requires performing some pre-processing steps to obtain a reduced flexible body. Flexible body reduction can be carried out using FEM software. The general procedure to integrate a flexible body into a multibody system of the rail vehicle bogie can be divided into these main steps:

1. Creating a FE model of the rail vehicle bogie component,
2. Integrating the FE model of the rail vehicle bogie component into the software for multibody system dynamics,
3. Establishing the multibody system of the rail vehicle bogie with a flexible body.

In previous chapters we used the collocation “flexible body reduction”. We thereby understand reduction of degrees of freedom of the FE model. Reduction of degrees of freedom of the FE model is performed in FEM software (step (1) above) and consists of several phases:

1. Defining location of the interface nodes. The flexible body is connected in these nodes to each other in the multibody system of the rail vehicle;
2. Setting up the interface nodes connection to the structure of the flexible body,
3. Defining the coupling nodes as retained nodes, and finally
4. Restricting degrees of freedom.

When the FE model of the rail vehicle bogie component is reduced, we can generate the input files, which are required for multibody software. This file contains all necessary information about flexibility and properties of the selected rail vehicle bogie component. Once the input data of the flexible body are imported into the multibody software, we can apply to the flexible body joints, constraints, force elements, etc. Deformations of the flexible body are caused by these boundary conditions and loads.

In this part of the paper, we introduce the FE model of the bogie frame. This bogie design is originally French, but today it is produced in several modifications and in several countries.

The procedure of the flexible body preparation includes several parts. First, we have to create a 3D model of the bogie frame using modern software existing for this purpose. This model can be imported into the FEM software, where we create a FEM mesh and perform modal analysis, which is necessary for evaluation of eigenfrequencies and eigenmodes, then we analyse the flexible body behaviour and finally reduce it. After that, the FE model of the bogie frame can be implemented into the multibody dynamic model of the freight wagon bogie.

As noted above, the flexible body reduction expects the interface nodes definition. These nodes have to appear in those locations where the other components of the freight wagon bogie (e.g. axle boxes, wheelsets, suspension, etc.) will be connected to the bogie frame. In our case, these locations are on axle guides, central pivots and side bearers. Inter-face nodes on axle guides serve for the interconnection with axle boxes and suspension elements, and interface nodes on the central pivot and side bearers allow connection of the bogie to wagon body. Figure 3 on the left side shows the FE model of the freight wagon bogie frame created in Ansys FEM software. After definition of interface nodes we imported the model into the MBS software Adams/Rail and set up the FMBS (flexible multibody system) of the freight wagon bogie Y25 (Fig. 3).

Fig. 3 Flexible multibody model of a freight wagon bogie

Once we have set-up the flexible multibody model of the freight wagon bogie, we can perform various simulations to verify the correctness of the model, assess the riding properties of the model, we can compare the results of simulation analyses of the freight wagon bogie with a flexible bogie frame with the outputs of dynamic behaviour of a freight wagon bogie with a rigid bogie frame, etc.

Following part of this work introduces the comparison of results for simulations analyses of the freight wagon bogie with a rigid bogie frame and a flexible bogie frame.

Simulation analyses were performed on a simple track. We chose the test track – S-curve with general parameters defined in the UIC code [18].

In our case, the S-curve comprises a curve and a reverse curve of R = 150 m separated by a section of straight track measuring 6 m in length. The length of curves is L = 100 m. The track has the normal rail gauge of 1435 mm with UIC60 rail profile. This track has no cant and no irregularities were used in the track model for our purposes.

Analyses were performed with one freight wagon bogie without load. The freight wagon bogie ran at the constant speed of 40 km/h. We analysed freight bogie running on the S-curve with both rigid and flexible bogie frames.

Results of analyses are shown in Figure 4.

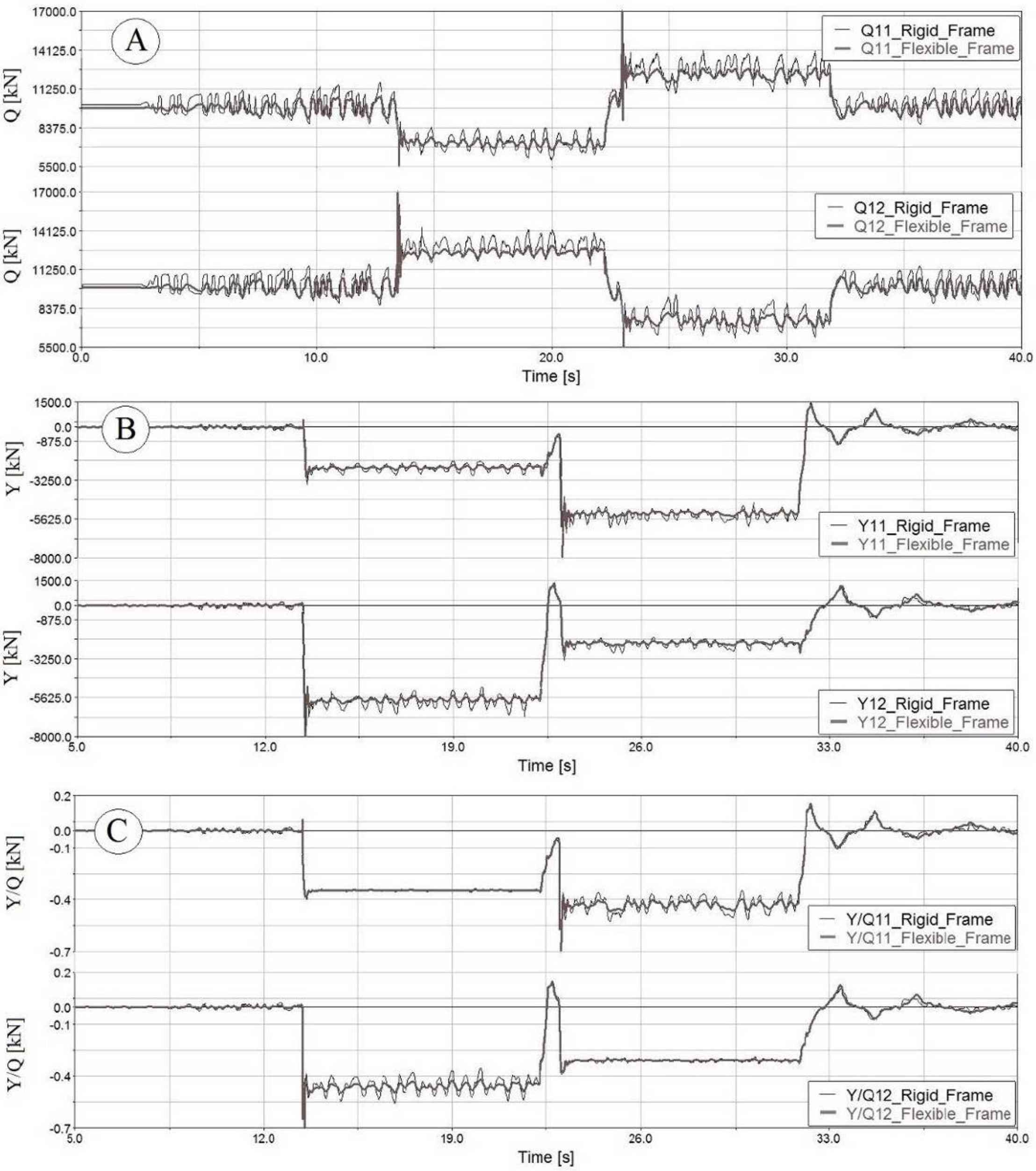

Fig. 4. Comparison of vertical wheel forces (A), lateral wheel forces (B) and derailment quotient (C) of the first wheelset for rigid and flexible bogie frame

In order to assess the riding properties of the freight wagon bogie running with flexible bogie frame, we selected the waveforms of the vertical wheel forces (Q), lateral forces (Y) and derailment quotient (Y/Q).

Moreover, each figure contains two waveforms, one for the rigid bogie frame (thinner curved) and one for the flexible bogie frame (thicker curve) and also details.

Let's have a look at Figure 4. When the bogie enters the curve, values of vertical wheel forces increase (Fig. 4A). In the straight track section, vertical wheel forces correspond to the gravitational load of the bogie.

Further from results we conclude (Fig. 4B) that lateral forces increase also when the bogie enters the curve. In the straight track section lateral forces achieve very small values compared to the values in curves.

Finally, Figure 4C shows the derailment quotient values. Derailment quotient is the ratio of the lateral (Y) and vertical forces (Q), and it expresses safety of a rail vehicle running. As we can see, the maximum values are reached when the bogie is running in curves, similarly to the vertical and lateral wheel forces.

From comparison of the simulation of the freight wagon bogie running with rigid and flexible bodies we can observe the influence of the bogie frame flexibility on the monitored variables. Flexibility of the bogie frame causes a greater damping of vibration.

Conclusion. The aim of this paper is focused on the describtion of options of multibody system dynamics usage to analyse the rail vehicle containing flexible components. We presented the most commonly used approach to the reduction of the flexible body. Inclusion of flexible bodies into the rail vehicle multibody system provides advanced opportunities for evaluation of the rail vehicle properties and stress in the structure of the rail vehicle components under real operational conditions. It presents including the flexible frame into the freight wagon bogie multibody system, its simulations and evaluation and comparison of results of numerical calculations of the freight wagon bogie running. On one side we found out that the implementation of the flexible body into MBS better correspond to the real bogie behaviour during running but on the other side rising demands on user knowledges, computational time and computer capacity. In our future research we will use this flexible multibody system of a freight wagon bogie to assemble a complete freight wagon model and to perform various analyses for better assessment of the freight wagon riding properties.

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Діжо Я., Блатніцкий М., Ноженко О.С., Кравченко К.О. Комп'ютерний аналіз впливу на вихідні параметри наявності пружного елемента в багатокомпонентній системі візка рейкових екіпажів

Використання комп'ютерного аналізу і моделювання рейкових транспортних засобів дозволяє проводити статичний аналіз окремих частин рейкових транспортних екіпажів і динамічний аналіз субструктури або повного рейкового транспорту. Метод кінцевих елементів найбільш часто використовується для аналізу напружень в елементах конструкції. З іншого боку, динамічну поведінку і властивості аналізуються, досліджуються і оцінюються за допомогою іншого підходу - мультикомпонентні системи. Поєднання цих двох підходів значно розширює можливості комп'ютерних досліджень рейкових транспортних засобів в різних експлуатаційних умовах. Такий принцип побудови досліджень передбачає включення пружного тіла в багатокомпонентну систему і оцінку його впливу на роботу конструкції в цілому. Була створена пружна багатокомпонентна модель візка вантажного вагона, і в якості пружного тіла була використана рама візка. За результатами чисельного моделювання були обрані параметри для оцінки впливу пружного тіла на характеристики руху візка вагона.

Ключові слова: *метод кінцевих елементів, мультикомпонентна система, візок транспортного засобу, пружне тіло.*

Дижо Я., Блатницкий М., Ноженко Е.С., Кравченко Е.А. Компьютерный анализ воздействия на выходные параметры наличия упругого елемента в многокомпонентной системе тележки рельсовых экипажей.

Используя компьютерный анализ и моделирование рельсовых транспортных средств, мы можем проводить статический анализ отдельных частей рельсовых транспортных экипажей и динамический анализ субструктуры или полного рельсового транспорта. Метод конечных элементов наиболее часто используется для анализа напряжений в елементах конструкции. С другой стороны, динамическое поведение и свойства анализируются, исследуются и оцениваются с помощью другого подхода, называемого мультикомпонентной системы. Соединение этих двух подходов значительно расширяет возможности компьютерных исследований рельсовых транспортных средств в различных эксплуатационных условиях. Такой принцип построения исследований предполагает включение упругого тела в многокомпонентную систему и оценку его влияния на работу конструкции вцелом. Была создана упругая многокомпонентная модель тележки грузового вагона, и в качестве упругого тела была использована рама тележки. По результатам численного моделирования были выбраны параметры для оценки влияния упругого тела на характеристики движения тележки вагона.

Ключевые слова: *метод конечных элементов, мультикомпонентная система, тележка транспортного средства, упругое тело.*

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