

Veronika VALAŠKOVÁ¹, Jozef MELCER²MUTUAL COMPARISON BETWEEN THE TWO COMPUTATIONAL MODELS OF
INTERACTION SYSTEM VEHICLE- PAVEMENT**Abstract**

Dynamic interaction between vehicle and pavement is a current problem which is solving in many workplaces around the world. This article is focused on the interaction model creation and principles of the solution for two numerical models. Numerical models of the interaction system vehicle-pavement were constructed in the computer software ADINA, which is based on the Finite Element Method.

Keywords

Vehicle-Pavement Interaction, Finite Element Method, Half-Part Model, Lorry Tatra 815, Numerical Model.

1 INTRODUCTION

Pavements are structures that are exposed to the direct dynamic effect of the moving vehicles. Unevenness of the pavement surface is the main source of the kinematic excitation for the vehicle. They have significant influence on the magnitude of the contact forces between the pavement surface and the vehicle tires. The amplitude is the variable of the time and the frequency domain. There are two approaches how to obtain a required data – computational or experimental methods. The verification of the reliability of the transport structures loaded by the heavy traffic needs a detailed analysis using vehicle-pavement interaction simulations [1, 2].

There are many possibilities how to create the computational model of the vehicle-pavement interaction. Two interaction models of 2D half-part model of the vehicle Tatra 815 and the ground were created and results of the comparison of the outputs of these models are presented in this paper. The first numerical model of the interaction vehicle-pavement assumes the unevenness of the pavement. The unevenness is modelled as a surface with offsets- lifting penetration of the contact. The second interaction model was prepared with perfectly smooth pavement. The theoretical solution is based on the Finite Element Method (FEM). FEM computational numerical software ADINA was used for these simulations. FEM methods were more widely used since computer calculations became part of the modelling tools. In this case, simulations are non-stationary dynamic actions and they are described by the following differential equation:

$$[M] \cdot \{\ddot{u}(t)\} + [C] \cdot \{\dot{u}(t)\} + [K] \cdot \{u(t)\} = \{F(t)\} \quad (1)$$

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where $[M]$, $[C]$ and $[K]$ are mass, damping and stiffness matrices describing the spatial properties of the vehicle and pavement interaction.

2 NUMERICAL MODEL OF VEHICLE

One of the most important tasks is to prepare adequate model of the vehicle. For this purpose, the vehicle lorry Tatra 815 was selected (Fig.1). A discrete model of the vehicle with finite degrees of freedom simplifies the mathematical solution of the problem. This assumption transforms partial differential equations to the ordinary differential equations [3].

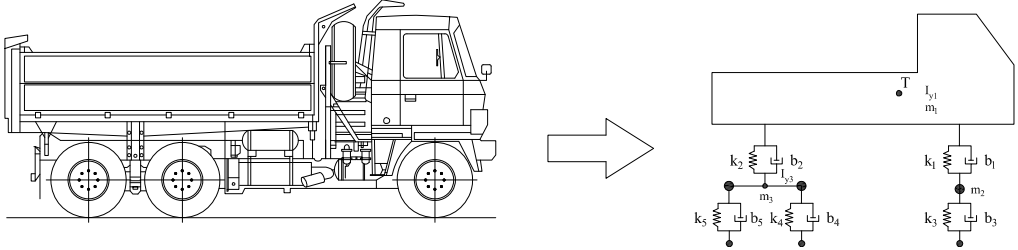


Fig. 1: Half-part model of the lorry Tatra 815

The main characteristics of the half-part model are defined by the three diagonal matrices – mass $\{m\}$, stiffness $\{k_i\}$ and damping $\{b_i\}$ matrices, which contain experimentally measured values [1].

Matrices values for the lorry model have been determined:

$$\{m_i\}_D = \{m_1, I_{y1}, m_2, m_3, I_{y3}\}_D = \{11475; 31149; 455; 1070; 466\}_D, \quad (\text{kg, kg} \cdot \text{m}^2),$$

$$\{k_i\}_D = \{k_1, k_2, k_3, k_4, k_5\}_D = \{143716.5; 761256; 1275300; 2511360; 2511360\}_D, (\text{N} \cdot \text{m}^{-1}),$$

$$\{b_i\}_D = \{b_1, b_2, b_3, b_4, b_5\}_D = \{19228, 260197, 2746, 5494, 5494\}_D, \quad (\text{kg} \cdot \text{s}^{-1}).$$

The natural frequencies have also been determined:

$$\{f\} = \{f_{(1)}; f_{(2)}; f_{(3)}; f_{(4)}; f_{(5)}\} = \{1.13; 1.45; 8.89; 10.91; 11.71\} \quad (\text{Hz}).$$

3 NUMERICAL MODEL OF PAVEMENT

Properties for the asphalt pavement were assumed in the calculations. The pavement configuration is shown in Fig. 2. Three upper layers (asphalt concrete) are considered as the beam with the height of $h = 140$ mm and the width $b = 1.0$ m. The equivalent modulus of elasticity and cross section moment of inertia were calculated for these layers $E = 4800$ MPa and $I = 2.286667 \cdot 10^{-4}$ m⁴. Layers 4 – 6 are introduced into calculation as Winkler elastic half-space. Modulus of reaction K [MN/m³] was calculated in the program LAYMED [4]. The mass intensity of the beam μ is 310 kg/m. The damping is introduced using angular frequency $\omega_b = 0.1$ rad/s.

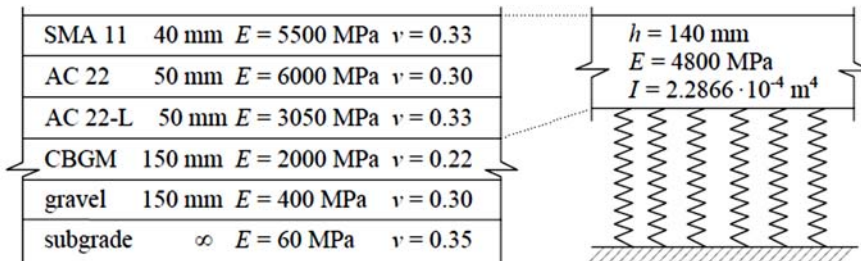


Fig. 2: Multi-layered model of the ground (left) and beam on the springs simplification (right) [4]

4 DESCRIPTION OF NUMERICAL SOFTWARE

ADINA is a commercial engineering simulation software that is used in industry and academia to solve structural, fluid and heat transfer, and electromagnetic problems. ADINA can also be used to solve multiphysics problems, including fluid-structure interactions and thermo-mechanical problems. ADINA is the acronym for Automatic Dynamic Incremental Nonlinear Analysis. The program consists of four core modules:

- ADINA Structures for linear and nonlinear analysis of solids and structures,
- ADINA Thermal for analysis of heat transfer in solids and field problems,
- ADINA CFD for analysis of compressible and incompressible flows, including heat transfer,
- ADINA EM for analysis of electromagnetic phenomena.

These modules can be used fully coupled together to solve multiphysics problems where the response of the system is affected by the interaction of several distinct physical fields (e.g. fluid-structure interaction, thermo-mechanical analysis, piezoelectric coupling, Joule heating, fluid flow-mass transfer coupling, electromagnetic forces on fluids and structures, etc.) [5].

4.1 Bathe calculation method

The Bathe calculation method, also known as a composite integration method, is commonly used in mathematic nomenclature. This method is combination of the Backward Euler explicit and Newmark implicit method. By the combining these two methods we can ensure the stabilization of the calculation procedure.

In Bathe method is necessary to divide time step into two sub-steps. The task is solved by the Newmark method in the first step and by the Euler method in the second step. The classic approach is that in the Bathe method is time step divided in the halves. This brings some non-linearity problems to the solution, but it is possible to divide time step variably. In this case, based on the stability calculation, allocate more of Newmark integration method and Euler's method is used as a numerical damping. The range of the time sub-step is defined by the parameter γ . This parameter is generally recommended to be greater or equal to 0.5. $\gamma = 0.5$, when we consider the classical Bathe method.

The following conditions for the first sub-step (Newmark) are established in calculation of the differential equation.

$$\{\dot{u}_{t_n} + \gamma \cdot h\} = \{\dot{u}_{t_n}\} + [(1-\delta) \cdot \{\ddot{u}_{t_n}\} + \delta \cdot \{\ddot{u}_{t_n} + \gamma \cdot h\}] \cdot \gamma \cdot h, \quad (2)$$

$$\{u_{t_n} + \gamma \cdot h\} = \{u_{t_n}\} + \{\dot{u}_{t_n} \cdot \gamma \cdot h\} + [(1-2\alpha) \cdot \{\ddot{u}_{t_n}\} + \alpha \cdot \{\ddot{u}_{t_n} + \gamma \cdot h\}] \cdot \frac{(\gamma \cdot h)^2}{2}, \quad (3)$$

where α and β are Newmark parameters.

For the second sub-step (Euler) is considered

$$\{\dot{u}_n\} = c_1 \cdot u_n + c_2 \cdot u_{n+\gamma h} + c_3 \cdot u_{n+1}, \quad (4)$$

$$\{\ddot{u}_{n+1}\} = c_1 \cdot \dot{u}_n + c_2 \cdot \dot{u}_{n+\gamma h} + c_3 \cdot \dot{u}_{n+1}, \quad (5)$$

where:

$$c_1 = \frac{1-\gamma}{\gamma \cdot h}, \quad (6)$$

$$c_2 = \frac{-1}{(1-\gamma) \cdot \gamma \cdot h}, \quad (7)$$

$$c_3 = \frac{2-\gamma}{(1-\gamma) \cdot h} \quad [6]. \quad (8)$$

5 DESCRIPTION OF THE INTERACTION TATRA 815- PAVEMENT

For the numerical simulation of the interaction, two interaction models were used. The common component of the models is pavement and it is modelled using springs elements which are part of the Winkler elastic half-space. The material characteristics of the pavement are provided in chapter 3. The geometry of the vehicle was studied to supply the detailed model of the lorry Tatra 815. Supporting documents were obtained on the basis of previous research which was made at our department. They were obtained primarily by experimental measurements. We also used the spring elements, whose stiffness characteristics are presented in Chapter 2. Numerical model of the vehicle is identical for both models

The main and essential difference is in the modelling of the pavement. In the first simulation with offsets, we are considered unevenness. In the second simulation, the pavement was considered perfectly straight.

5.1 Simulation modelled with offsets

The first and essential step was to properly assemble the whole model geometry. In this model, a vehicle was composed of the 19 points and 17 lines.

The pavement was modelled as a 330 elements of the length 0.3 m, which simulate a lifted penetration of the contact tire-pavement. Offset values were based on the experimental measurements. Laser scanner LEICA SCANSTATION C10 was used for recording the pavement unevenness. Inputs and offset values are real and based on experimental measurements.

The whole interaction model of vehicle-pavement consists of 719 points and 782 lines. The lines were meshed in the pavement with material characteristics mentioned in Chapter 3. The relevant degree of freedom and boundary conditions were set in the model.

After start of the simulation, the vehicle moves on the pavement with constant speed of 40 km·h⁻¹. The simulation took 14 seconds. In the first 10 seconds, the gravity is activated and whole model is numerically stabilizing. In the last 4 seconds, the vehicle is moving along the pavement with constant speed. In this simulation, the time step was constant 0.001 s. The scheme of the model is shown in Fig. 3.

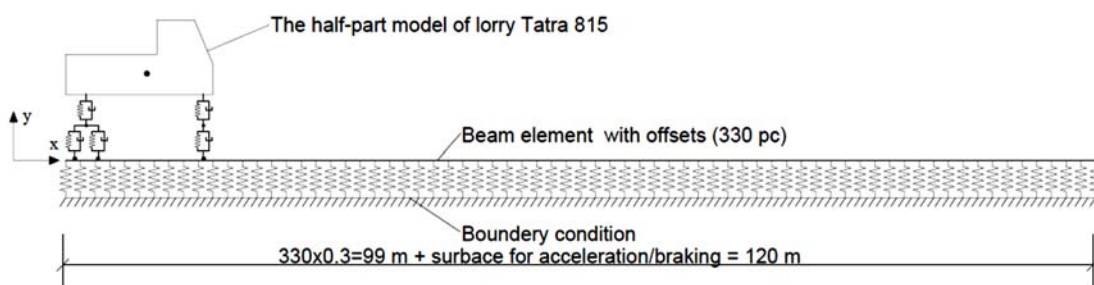


Fig. 3: Scheme of the computational model with offsets contacts

5.2 Simulation with Winkler elastic foundation

The pavement with smooth surface was modelled as a Winkler elastic foundation. The vehicle-pavement interaction model consists of 26 points. The material characteristics of the pavement and the subgrade are in the Chapter 3. Other parameters for the vehicle pass are the same as mentioned in the Chapter 5.1.

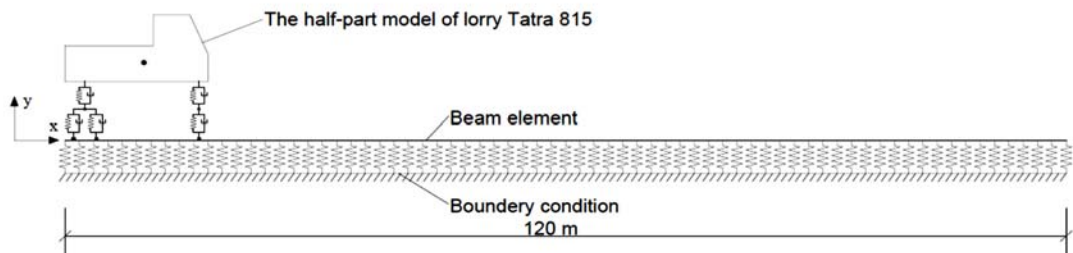


Fig. 4: Scheme of the computational model with Winkler Elastic half-space

6 RESULTS

Vertical displacement (z-direction) and vertical acceleration in selected points are presented in this chapter. Point nr.1 was selected in the front vehicle axle, nr.2 in the rear axle and nr.3 in the centre of gravity of the lorry Tatra 815. Results are presented for quantities in vertical axis and have been obtained in 2D simulations in XZ plane.

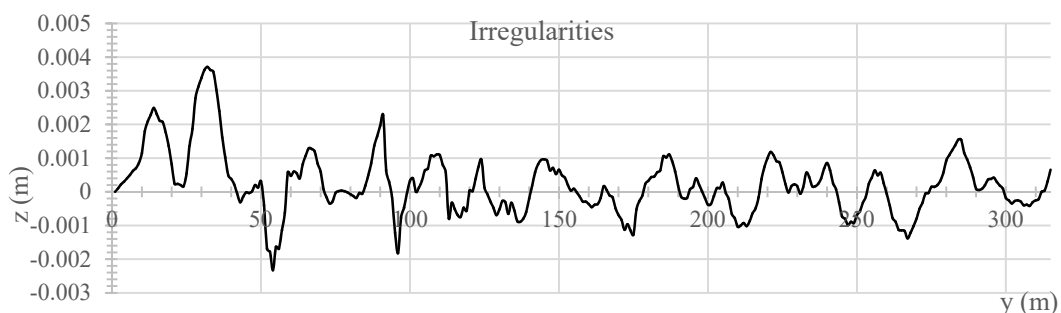


Fig. 5: Road profile obtained by the laser scanning

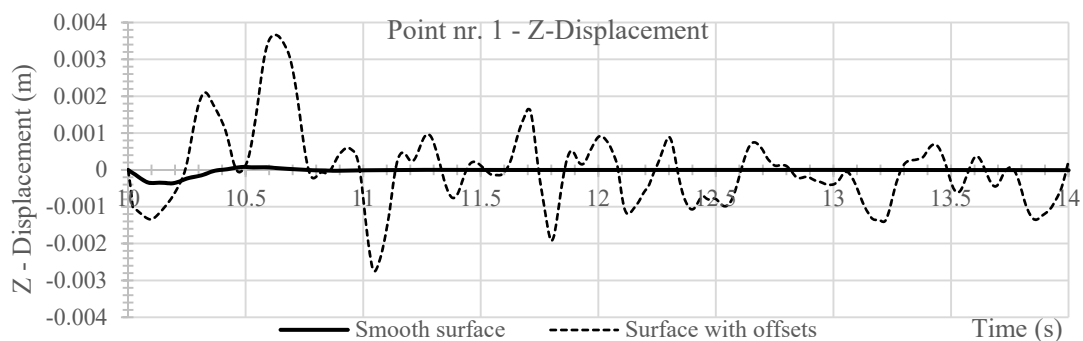


Fig. 6: Time history of displacement point nr. 1 - front axle

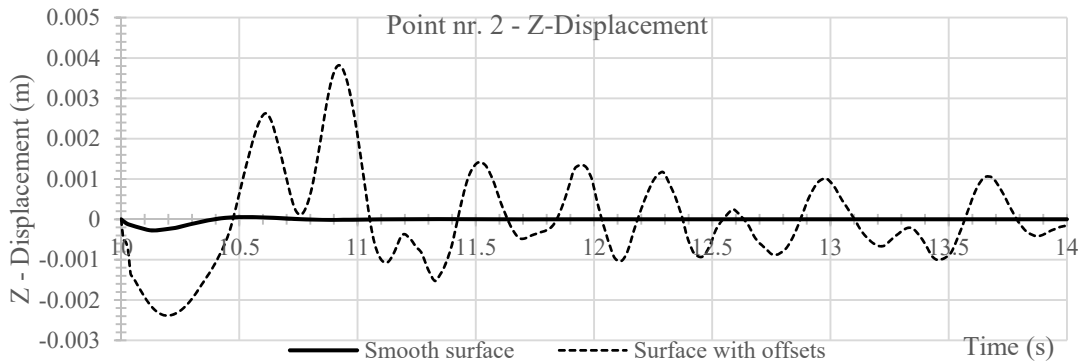


Fig. 7: Time history of displacement point nr. 2 - rear axle

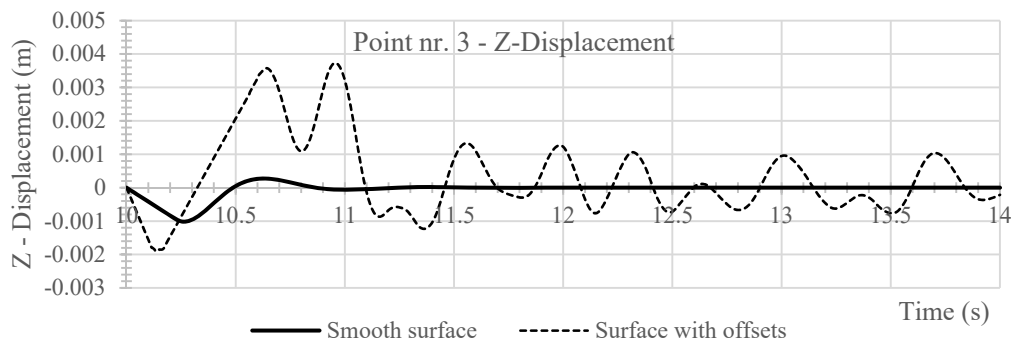


Fig. 8: Time history of displacement point nr. 3 - centre of gravity

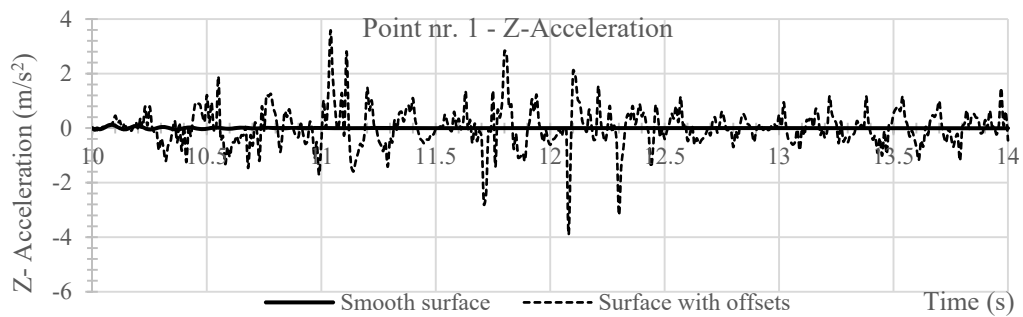


Fig. 9: Time history of acceleration point nr. 1 - front axle

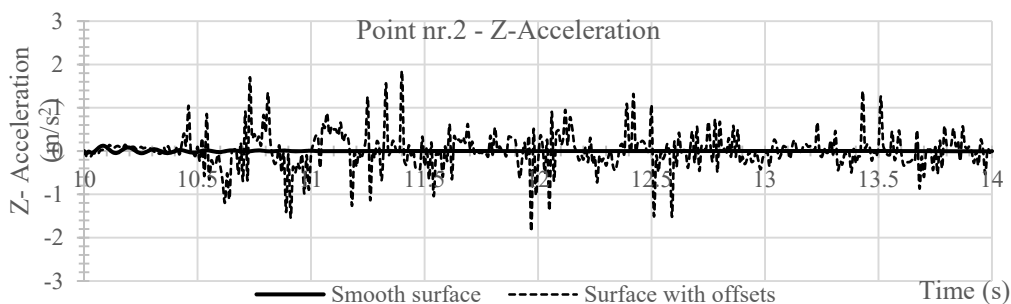


Fig. 10: Time history of acceleration point nr. 2 - rear axle

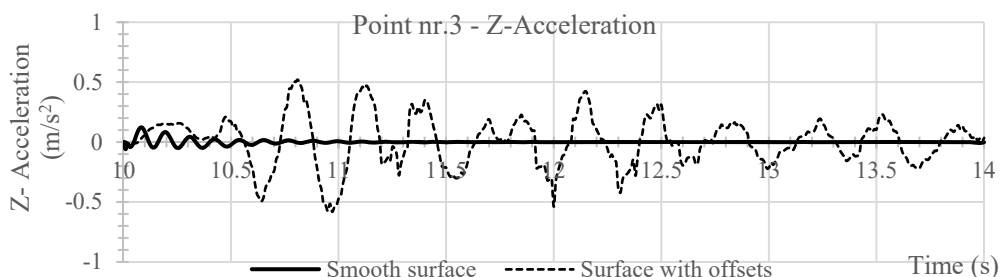


Fig. 11: Time history of acceleration point nr. 3 - centre of gravity

7 CONCLUSION

Using of FEM methods can give useful results of modelling of the phenomenon of the vehicle-pavement interaction. Presented results from numerical simulation were obtained for road pavement with unevenness (offsets) and for the smooth pavement surface. For the smooth surface, there is a leading wave caused by the acceleration for whole model. In time 10 seconds, the vehicle is moved from velocity $0 \text{ km} \cdot \text{h}^{-1}$ to $40 \text{ km} \cdot \text{h}^{-1}$, and this effect causes the leading wave. After stabilization of the model, the ride is absolutely smooth.

The model with offsets also has the same wave with amplitude in the same direction. Subsequently, the curve shows the displacements, which were activated by the unevenness. Accelerations of front axle, rear axles and centre of gravity of the vehicle are shown in Fig. 9, 10 and 11. The leading waves are also observed as in the model with smooth pavement surface. The propagation of the accelerations in the model with measured offsets, obtained by the laser scanning, shows the course of the accelerations of the vehicle masses.

The unevenness of the pavement has influence on the response of the vehicle-pavement system. This influence is mutual and the calculations with consideration of this pavement unevenness give more realistic (stochastic) results conditioned by the stochastic nature of the measured pavement surface profile.

The validation of the calculated results by the experimental measurements will be the effort of the further investigation.

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