REAL POSSIBILITIES OF NUMERICAL MODELLING OF VEHICLE RESPONSES

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Abstract. *The presented article is devoted to the assessment of real possibilities of numerical modelling of interaction phenomena in the vehicle - road system. It analyses the observed phenomena in the time and frequency domain. Describes the possibilities of numerical modelling of road irregularities as a source of vehicle kinematic excitation. It presents a computational model of the vehicle and a method of numerical solution of its response. Describes the performed experiment and the used measuring technique. Numerically obtained results are evaluated based on the results of the in situ experiment. Makes conclusions for applications in engineering practice.*

Keywords

Vehicle, roadway, stochastic, numerical modelling.

1. Introduction

The development of computer technology also resulted in the development of numerical methods, the creation of numerical computational models and their application in various areas of engineering practice. The results of numerical simulations do not always have to fully correspond to reality. Therefore, in certain cases, it is necessary to verify the results of numerical simulations based on a laboratory or in situ experiment. Alternatively, to calibrate the numerical model with the help of model updating and only then proceed to the numerical simulation of the observed phenomena. The presented article tries to numerically model the response of a truck when driving on the road in the time and frequency domain and to verify the quality and usability of the numerically obtained results by means of an experiment. The vehicle-road system consists of two separate subsystems, the road and the vehicle. Road irregularities are the source of the truck kinematic excitation. During numerical modelling, the longitudinal road profile in the individual vehicle tracks must first be generated numerically. Only then is it possible to numerically model the response of the truck. At the workplace of the authors, numerical and experimental analysis of the vehicles movement along the transport structures is given long-term attention. This is evidenced by a number of publications [1-5].

2. Road Profile

The experiment with the vehicle was performed at Hričov Airport near Žilina. The airport road is a classic asphalt road. For the needs of numerical simulation of the vehicle response, it is necessary to know the road unevenness. For this purpose, two longitudinal profiles 500 m long with a distance of 2 m from each other were laid out. Road irregularities were mapped in two ways: accurate levelling and spatial scanning. Information on comparing the accuracy of two methods is given in [6]. In both longitudinal profiles, they were measured by accurate leveling the road surface height with a length step of 0.25 m. According to ISO 8608 [7], the quality of the road surface is assessed by means of power spectral densities (PSD) of unevenness. PSDs are displayed in log-log scale. The smoothed PSD can be approximated by function

$$\log S_u(\Omega) = \log S_u(\Omega_0) - k \cdot (\log\Omega - \log\Omega_0), \quad (1)$$

or also

$$S_u(\Omega) = S_u(\Omega_0) \cdot \left(\frac{\Omega}{\Omega_0}\right)^{-k}. \quad (2)$$

Spectrum of unevenness can be expressed as a function of various autonomous variables, e.g. angular spatial frequency Ω [rad/m], angular frequency ω [rad/s], time frequency f [Hz], wavelength L in [m], or wavenumber $\lambda = 1/L$ [1/m]. The mutual relation is in (3), where the v is a velocity of the vehicle in [m/s].

$$\omega = \Omega \cdot v = \frac{2\pi}{L} \cdot v = 2\pi \cdot \lambda \cdot v = 2\pi \cdot f. \quad (3)$$

International standard [7] divides the pavements into 8 categories marked from A to H depending on their surface quality. The coefficient k is introduced as $k = 2$. The values of constant $S_u(\Omega_0)$ for reference path angular frequency Ω_0 = 1.0 [rad/m] are given in [7] in tabular form. In numerical simulations, the opposite procedure is applied. Based on the known PSD, a random road surface profile $u(x)$ is generated [3]. The following relation can be used

$$u(x) = \sum_{i=1}^{N} \sqrt{2 \cdot S(\Omega_i) \cdot \Delta\Omega} \cdot \cos(\Omega_i \cdot x + \varphi_i). \quad (4)$$

In the reverse process, the phase characteristic is missing. The phase angle φ_i is generated according to a uniform distribution as randomly distributed over the interval (0; 2π). An example of the generated profile of the road surface of B category at stationing from 280 m to 420 m is in Fig. 1 and its PSD in Fig. 2.

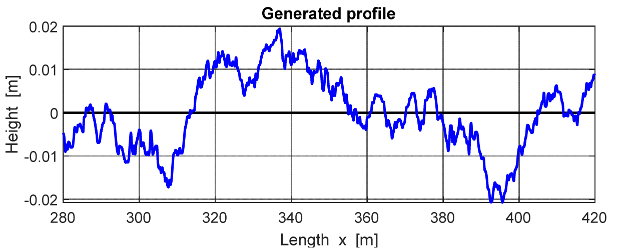

Fig. 1: Generated road profile of B category.

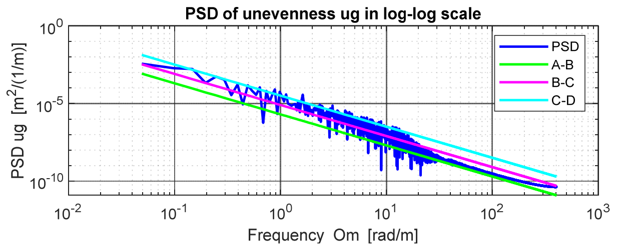

Fig. 2: PSD of generated road profile in log-log scale.

The road surface profile has a random character. We cannot expect an absolute identity between the measured profile and the profile generated according to (4), even if both profiles have the same frequency composition given by the PSD. In addition, each time we generate a random road profile, we get a different profile. A comparison of the randomly generated profile according to equation (4) and the profile obtained by levelling is shown in Fig. 3.

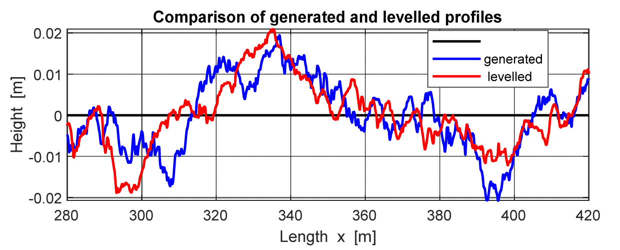

Fig. 3: Comparison of generated and levelled road profile.

3. Vehicle Model

The subject of numerical modelling is a Tatra truck. A multi-body computational model with 15 degrees of freedom was created for the vehicle, Fig. 4. Tangible degrees of freedom (in number 9) correspond to movements of the mass points of the model and intangible degrees of freedom (in number 6) correspond to movements of the contact points with the road. The displacement components of the individual points of the vehicle model (vector $\{\mathbf{r}(t)\}$) are numbered 1 - 15 (positive orientation is indicated by an arrow). The joining elements are numbered from 1 to 10 by numbers in rings.

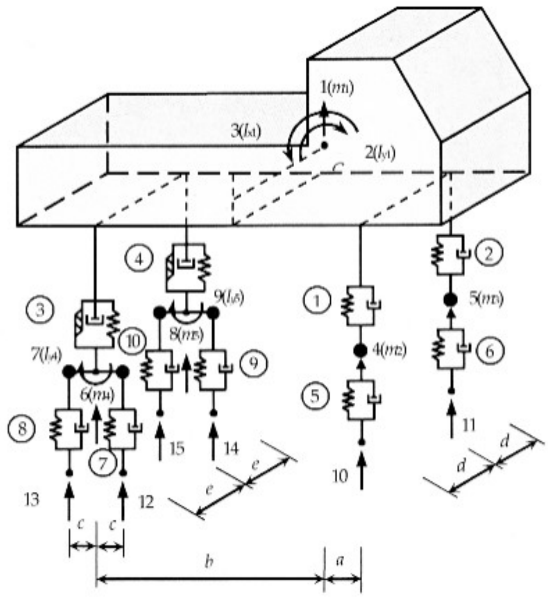

Fig. 4: Vehicle computational model.

The model is described in detail in [3], so only the most necessary information is given here. Due to the used method of solution, the equations of motion are given in the form

$$[\mathbf{m}]\{\ddot{\mathbf{r}}(t)\} = \{\mathbf{F_R}(t)\}, \quad (5)$$

where $[\mathbf{m}]$ is mass matrix of the model and vector of resulting forces

$$\{\mathbf{F_R}(t)\} = \{\mathbf{F_{DF}}(t)\} + \{\mathbf{F_G}\} + \{\mathbf{F_{RS}}(t)\}. \quad (6)$$

Vector $\{\mathbf{F_G}\}$ represents the gravity forces and vector $\{\mathbf{F_{RS}}(t)\}$ reactions in supports. The static equivalents corresponding to individual degrees of freedom $\{\mathbf{F_{DF}}(t)\}$ are calculated as

$$\{\mathbf{F_{DF}}(t)\} = [\mathbf{A}]\ \{\mathbf{F_{JE}}(t)\}, \quad (7)$$

where $[\mathbf{A}]$ is so-called static matrix and $\{\mathbf{F_{JE}}(t)\}$ represents the forces in joining elements

$$\{\mathbf{F_{JE}}(t)\} = -\{\mathbf{F_{re}}(t)\} - \{\mathbf{F_d}(t)\} - \{\mathbf{F_f}(t)\}. \quad (8)$$

The vectors on the right side of equation (8) represent elastic forces, damping forces and friction forces in joining elements.

Numerical simulation of the vehicle movement along the road was carried out in MATLAB [8]. The ode45 procedure was used to solve the system of differential equations. Relative error tolerance RelTol = 1e-3, absolute error tolerance AbsTol = 1e-6. The output of the numerical integration was realized in steps of 0.0005 s, which corresponds to a sampling frequency of 2000 Hz. At the beginning of the simulation, at time $t = 0$, the vehicle is at a rest in the state of static equilibrium and in contact with the road. The rear axle is at the beginning of the monitored 140 m long road section. At the end of the simulation, the front axle is at the end of the monitored section. The vehicle moves at a constant speed throughout the section. The total weight of the vehicle is 21500 kg. The damping in the vehicle tires is neglected in the simulation.

4. Experimental Test

The experiment was performed with the vehicle Tatra T815. During the test, vertical accelerations were monitored at three points on the right side of the vehicle. At the centre of gravity (CG) of the vehicle's sprung mass - sensor A1. On the right front axle (FA) - sensor A2. On the right rear axle (RA) - sensor A3. Acceleration sensors Brüel & Kjær type BK4508B were used to monitor the response. The measuring system is composed of these components: sensor, amplifier with a band-pass filter, analog-digital interface, computer. The signal from the sensor was routed through a coaxial cable. The measuring string was located in the vehicle. The sampling frequency was 2000 Hz.

The length of the monitored section of the road was 100 m. On this section of road, the average vehicle speed was measured. Steel strips and accelerometers D2 and D3 were placed on the road in the transverse direction at a distance of 100 m. The average speed was calculated from the known distance and travel time. The passage of the wheel through the steel strip is manifested as a sharp impulse in the accelerometer record. By comparing the records of accelerometers D2 and D3, it is possible to determine the travel time. The time record from the sensors on the road was synchronized with the time record from the sensors on the vehicle. A total of 12 vehicle runs were performed in the experiment at different speeds, from 15.18 km/h to 52.95 km/h.

5. Experiment versus Numerical Solution

From the records of vehicle response obtained by the experiment and by numerical simulation, sections corresponding to the vehicle movement along the selected section of road in the length of 100 m were selected. These selected sections were subject to mutual comparison. Runs at the lowest speed $V = 15.18$ km/h and at the highest speed $V = 52.95$ km/h were chosen for comparison. As an example, this article presents the response records (values of the vertical accelerations) at the centre of gravity of the vehicle (CG), sensor A1.

At vehicle speed $V = 15.18$ km/h time records last 23.71 s and contain 47 421 samples. Fig. 5 shows a visual comparison of the vertical accelerations at the CG of the sprung mass of the vehicle obtained experimentally and numerically. A comparison of the distribution functions for this case is shown in Fig. 6.

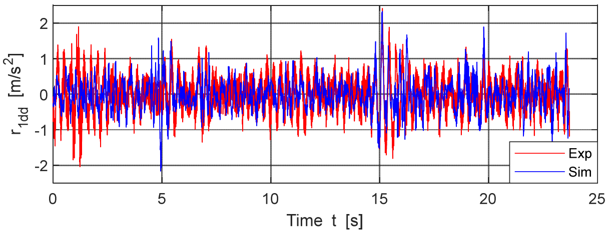

Fig. 5: Acceleration in the CG of vehicle sprung mass, $V = 15.18$ km/h.

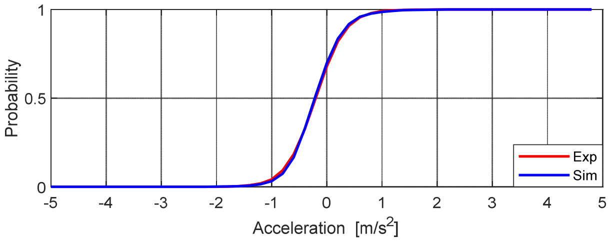

Fig. 6: Distribution function, acceleration in vehicle CG.

In the next step, the PSDs were also compared. The $2^{15} = 32768$ samples from the beginning of acceleration records were selected for the analysis, Fig. 7.

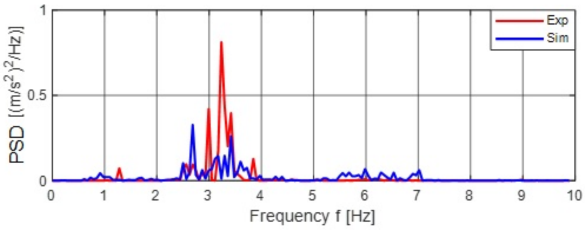

Fig. 7: PSD of vertical accelerations in vehicle CG.

At vehicle speed $V = 52.95$ km/h time records last 6.7985 s and contain 13 598 samples. Fig. 8 shows a visual comparison of the vertical accelerations at the CG and Fig. 9 compares distribution functions.

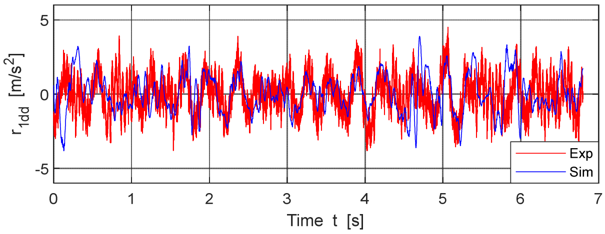

Fig. 8: Acceleration in the CG of vehicle sprung mass, $V = 52.95$ km/h.

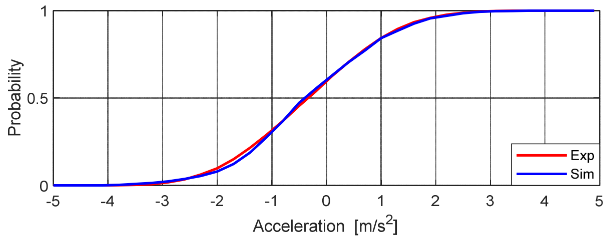

Fig. 9: Distribution function, acceleration in vehicle CG.

In the 2nd step, the PSDs were compared with each other using the FFT. The 2^{14} = 16384 samples were selected for the analysis, 2786 samples were filled with zeros, Fig. 10.

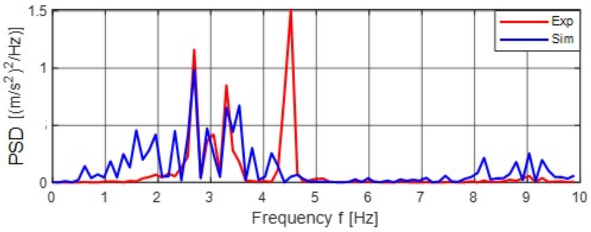

Fig. 10: PSD of vertical accelerations in vehicle CG.

More detailed information can be found in [9].

6. Conclusion

Although the current computational technologies are at a high level and the methods of numerical simulation have made considerable progress, it is not always possible to numerically simulate everything as we would like. Therefore, in many cases it is necessary to confront the results of numerical analyses with the results of the experiment, as the experiment represents the only way to verify the numerically obtained results. In solving the problem of vehicle-road interaction, the confrontation takes place on two levels. It applies to the road as well as the vehicle. From the comparison of the results of numerical simulations with the results of the experiment, it is possible to state the following facts. In connection with road inequalities, the longitudinal road profile cannot be modelled in real values. Only the trend of changes in a given road category given by the belonging PSD can be modelled. In connection with the response of the vehicle (for example, the acceleration at characteristic points), due to the randomness of the process, it does not make sense to compare the time courses of the individual signals. It makes sense to compare the statistical characteristics of individual signals (distribution functions or distribution histograms). In this respect, the agreement is very good. There is no good agreement in the frequency domain. Although similar frequency clusters appear in the frequency spectra, their powers are completely different. So we have to be careful when using the results of numerical simulation in the frequency domain.

Acknowledgements

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