Assessment of dynamic properties of a carriage using multibody simulation considering rigid and flexible tracks

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Abstract. Recently, we cannot imagine investigation and analysing mechanical properties of railway vehicles without using state-of-art tools. They are implemented in whole process of design, analysing, verification, testing and optimising of railway vehicles. Such an approach saves time for development, production costs and finds application across whole spectrum of produced types of railway vehicles. In order that the approach based on simulation computations can reliably simulate the reality, a virtual model of a railway vehicle has to take into account as many factors as important. When we investigate behaviour of a railway vehicle in terms of dynamics, we used the multibody approach for creating its computational model. The goal of this article is evaluation of output quantities of a passenger car from the dynamics point of view. The main objective is assessment of selected values for rigid and flexible models of a track. There are evaluated quantities, which belong to main assessed outputs for investigation of dynamic properties of a passenger car. There are values of vertical forces in the wheel/rail contact as the indicator of dynamic load of a railway track as well as the bodies of a railway vehicle.

1. Introduction
Nowadays, passenger cars design has to meet the quite strict requirements before commissioning for regular operation. Phases of production and operation of passenger cars closely associated with economic factors. Modern approaches of computational simulations significantly help determine mechanical properties of passenger cars and verify they dynamical behaviour [1], [2]. Correct dynamical analyses require setting-up a representative multibody model of a passenger car, which correspond to actual operational conditions [3]. There are several commercial software working based on multibody system principle and inbuilt functionalities allow to create such a virtual model of a railway vehicle/railway track multibody model, which simulate actual running conditions [4], [5].

When we set-up a multibody model, we usually consider just a rigid track model. But, such an approach to the process of modelling does not always correspond to the real conditions, which are reached in a railway vehicle/a track couple reached [6], [7]. Therefore, in many studies the flexibility of a track is defined in the multibody model in order to evaluate the dynamic response of the entire mechanical system of a passenger car/a track [8-10].

2. Multibody model of the railway vehicle/railway track interface
This contribution introduces a study of influence of flexible track on dynamic response, i.e. selected output quantities. The multibody models of a passenger car and a track have been created in Simpack program package. There is a commercial program, which enables to an user building up many kind of virtual models, which can be quite simple subsystem of any transport mean, e.g. individual parts of
suspension system, partial systems of a drive mechanism, such as an engine, gearbox, etc. [11-14], or there can be a bogie of a railway vehicle, even an entire train sets [15-17].

In our work we have submitted a passenger car to simulation computations. Its model created in the Simpack software package (figure 1).

![Figure 1. A virtual model of the analysed passenger car created in Simpack software package.](image)

There is a standard model passenger car, which consists of two bogies and one body of a wagon. Individual elements of the passenger car are represented by rigid bodies. Mechanical system of a passenger car composes of rigid bodies (15 totally), which are connected by so-called force elements of various types. There are force elements of “spring-damper” type as steel coil springs of primary and secondary suspension and as hydraulic dampers installed also in primary and secondary suspension system. Depending on positioning of hydraulic dampers they serve as dampers of oscillations of bogie or body of wagon on bogies in vertical direction, lateral direction and as anti-yaw dampers.

Each wheelset is guided in an axlebox, which functions as a swinging arm. As usually, the analysed passenger car uses primary as well as secondary suspension system. The primary suspension system connects unsprung masses of wheelset and axleboxes with a bogie frame and the secondary suspension system ensures desired conform level by joining the body of the passenger car to a bogie. Mass and inertia parameters of the analysed passenger car rigid bodies are listed in table 1.

![Table 1. Parameters of the analysed railway vehicle rigid bodies.](image)

Among other specific elements, which arise in a railway vehicle model, the wheel/rail contact represents one of the most important element, which significantly influences credibility, reliability as well as time-consuming of simulation calculation [18], [19]. We have defined the FASTSIM model of the wheel/rail contact in our multibody model. Its use is most widely defined in case of simulation of a railway vehicle dynamic analyses, because it is robust enough, calculation time is acceptable and it calculates all required quantities in the contact patch (namely values of tangential forces) with a sufficient accuracy [6], [20], [21].

If we consider flexible track foundation, a track model is no longer modelled by its layout in a space (the position coordinates \(x, y, z\) in respect of considered coordinate system and the orientation angles \(\phi, \psi, \theta\) representing roll, pitch and yaw angles), but, there is necessary to add into a model additional bodies representing track sleepers, ballast etc. [22], [23]. It means, the entire multibody model becomes more complicated (figure 2).
In the used software package, a user can set-up such a complex multibody model system consisting of a railway vehicle and a flexible track, what can be achieved more detailed model and there is possible to assume, that even more detailed results of simulation computations.

![Multibody system diagram](image)

**Figure 2.** A dynamical model of a passenger car and a flexible track foundation.

In our research, we have defined the flexibility of a track by two manners. Dynamic response of the passenger car was evaluated for track flexibility, when coefficients of stiffness and damping were set-up on the constant value and for other set of simulations, coefficients of stiffness and damping were prescribed by the sinusoidal function. In the case of the sinusoidal function, the parameters of stiffness and damping are no longer constant during calculation, but they vary according to formulation (1) in certain bounds, which represents different stiffness-damping parameters of a track in compliance with sleepers’ layout. Hence, for sinusoidal stiffness-damping coefficients the following formulation is considered:

$$c_i(s) = c_{i0} + c_{i1} \cdot \sin \left\{ F_i \cdot (s(t) - s_0) \right\}$$  \hspace{1cm} (1)

where $c_{i0}$ is constant stiffness (or damping), $c_{i1}$ is amplitude of the track stiffness (or damping), $F_i$ is the nominal force resulting from the gravity of the passenger car, $s(t)$ is moved distance, which depending on the integration time and $s_0$ represents an offset of the start position. As there is obvious from eq. (1), in simulation calculation the stiffness-damping coefficients vary depending on the moved distance (not depending on time).

For purposes of dynamical analyses, we have performed relatively large number simulation computations for various running speeds, and several track foundation. In case of the flexible track foundation, we have chosen two levels of values of stiffness-damping coefficients. In order to differentiate them to each other we have marked them as “soft” flexibility for lower values of stiffness and damping coefficients and “stiff” for their higher values. Thus, in following section contains results of simulation computations for four different track flexibility foundation, namely “constant soft”, “constant stiff”, “sinusoidal soft” and “sinusoidal stiff”.

In our multibody model we have defined the straight track model, because we have wanted to eliminate influence of centrifugal forces or other additional dynamic effects resulting from the running in curves and we have aimed mainly at evaluation of the dynamic response due track flexibility. In the track model, track irregularities were defined in discrete form.
3. Results from simulation computations

In this section, results from numerical calculations of the passenger car running on a track with various track flexibility foundation are presented. They are introduced in the form of graphs.

As there was mentioned above, from the large number of simulation for various running speeds, we have selected only several speeds, which can concrete show influence of different running speed on waveforms of output quantities. We have decided that the representative examples of results are waveforms for 60 km/h, 100 km/h and 140 km/h.

In our research we have focused on dynamic response of a passenger car running on a track represented by the dominant forces, which act in the railway wheel and railway track during operation of a railway vehicle, namely the vertical wheel force. This force affects significantly the dynamic loads of a track as well as dynamic loads of main structural units of a railway vehicle [18], [20], [23].

Figure 1 contains waveforms of vertical wheel force for “constant soft” and “sinusoidal soft” track foundation. We can see, when constant values of stiffness-damping coefficients are defined in the track model, dynamic vertical force is for every evaluated running speed almost the same and it varies only negligible.

The different situation can be observed, when the “sinusoidal soft” track foundation is defined in the track model. As we can see in figure 3 (lower), in this case the track flexibility foundation influences dynamic response of the passenger car during its running on the track. Here we can observe that a value of the vertical wheel force oscillates regularly with the noticeable amplitude and frequency. Further we see, the amplitude of the vertical wheel force is maximal for lower running speed, namely for 60 km/h and with increasing running speed the amplitude of this force is being changed indirectly, i.e. the dynamic response of the vertical force is being decreased 100 km/h (green) and 140 km/h (red).

Figure 3. Dynamic vertical force for “constant soft” and “sinusoidal soft” track flexibility.

Figure 4. Dynamic vertical force for “rigid” track flexibility.
Figure 4 contains waveform of the observed quantity for “rigid” track foundation, i.e. without any stiffness or damping coefficients defined between rails and a ground. As we can see, waveform of forces are in this case similar to those, which can be observed for “constant soft” track foundation (figure 3 upper).

Figure 5. Dynamic vertical force for “constant stiff” and “sinusoidal stiff” track flexibility.

Waveforms of dynamic vertical wheel forces for higher values of stiffness-damping coefficients are shown in figure 5. Upper part of this figure contains results for constant stiffness-damping values and lower part for sinusoidal values. From reached results we can see, that in case of definition of track flexibility foundation using constant stiffness-damping coefficients, the vertical wheel forces do not vary such significantly as in comparison with sinusoidal stiffness-damping coefficients. Among other findings we can include, that higher values of stiffness and damping coefficients of the sinusoidal track foundation reduce amplitude of the observed result vertical wheel forces.

Following figures (figures 6, 7 and 8) show waveform of vertical wheel for individual running speed depending on various track flexibility foundation.

Figure 6. Waveform of the dynamic vertical force for various track flexibility foundation, 60 km/h.
These figures confirm the fact, that resulting dynamic response of a passenger car running on significantly depends on values of stiffness-damping coefficient. Lower values lead to higher amplitudes of resulting vertical wheel forces and as we would expect, also higher running speed results to higher amplitudes of the vertical wheel forces. The greatest amplitudes of vertical wheel forces were reached for “sinusoidal soft” track flexibility foundation. The “sinusoidal stiff” track foundation have led to greater increasing amplitudes of the vertical wheel forces in case of running at the speed of 140 km/h (figure 8). In other observed cases the waveform of vertical wheel forces oscillate about so-called quasi-static value of the vertical wheel forces and peaks corresponds to the dynamic effects related with the fact, that track irregularities are defined in the track model and they excite the mechanical system of the passenger car. The quasi-static value of the vertical wheel force corresponds to the part of the gravitational force of the passenger car, which accrues to the observed wheel.

Finally, based on observed results of our research we can formulate some findings.

When one wants to analyse dynamic properties of a railway vehicle using multibody simulation, complexity of a multibody model depends on available parameters. The flexible track foundation is
closer to the reality, but it requires the credibility of the stiffness-damping parameters of the track foundation. As we have found out from our results, various values quite strongly influence accuracy of the results and it can lead to relatively mendacious output values. In our work we have decided to evaluate the dynamic vertical wheel force. Based on results we have observed that the credibility of the input data of the track will affect results of simulation computations. The evaluated vertical wheel force is the indicator of the track loading and also loads the mechanical system of a railway vehicle.

Results have shown that the track is the most loaded, when the track substructure is soft and the increasing running speed leads to worse loading of the track.

The part of the future research in this field, other simulation computations will be performed, at which the track model will be improved by definition of layout in the space. In such a manner we will assess change of dynamic response when a passenger car will run in curve, evaluate the safety for various track flexibility foundation and also other dynamic parameters, such accelerations in different location of the passenger car body. Based on values of acceleration we can evaluate comfort for passenger [24], [25] under variable loading conditions and also other vibration properties of structural units of a railway vehicle (e. g. vibration of wheelsets, axleboxes, frames etc.) If one wants to investigate only phenomenon related to wagon body, e. g. ride properties for passengers, there would be sufficient to use the rigid track foundation. As ride comfort for passengers is evaluated based on accelerations [22], [24], [25] resultant ride comfort indices would not be very different. But, if it would be necessary to assess affects a rail vehicle running on a track, even in case of any wheel untruenesses formed on a wheel tread surface, then definition of track flexibility influences results more markedly. Therefore, future research in this field will be focused on investigation in more detail, how flexibility formulation in a multibody model effects more outputs parameters.

4. Conclusion
The article brought knowledge about the problem of modelling the flexible track in multibody system of a railway vehicle. There were compared results of simulation computations for the chosen stiffness-damping parameters of a track in the straight section. The analysed passenger car has run on the track at various speeds, from which the most interesting have been chosen for presentation. Based on reached results we have found out that the dynamic response of the passenger car, which indicate the track loading as well as the railway vehicle loading depends on the credibility of input data for track flexibility foundation.

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