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ON SIMULATION OF OPERATION CONDITIONS OF RUNNING GEARS IN THE PERIOD OF DESIGN[1]

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Abstract

When designing new vehicles, the reliable prediction of the future operation conditions of running gears based on quantitative statistics is very important both for the strength dimensioning and for ensuring the required riding comfort. This study introduces the analysis of the vertical dynamics of a vehicle under design, based on real-time simulation using the data of the traction and trailer units of the train and those of the railway line in question, especially the spectral density function of the vertical track irregularities. The combined numerical treatment of the train operation process and the vertical vehicle vibrations, as well as the predicted load statistics are illustrated for the running gear and suspension system of a four-axle bogie vehicle in suburban traffic.

Keywords: railway vehicle system dynamics, stochastic vibrations, load statistics.

1. Introduction

The loading conditions of a complete railway vehicle and its running gear are typically of stochastic character, if the regular operation process of the vehicle is considered in a long time interval [1]. The mentioned stochasticity is caused by the random length of the sequential speed-timing cycles, by the random effects due to driver's activity in the tractive and braking force exertion determining the train motion, as well as by the changing and in stochastic sequentionality realizing track-resistance forces. On the other hand, railway vehicles and also the trains are complicated vibratory systems, so in the operation of running gears one should reckon with dynamical excess loads caused by stochastic vibration processes excited by the irregularities in the track [2,3,4]. In this study the application of the general real-time loading-state simulation method developed at the Department of Railway Vehicles of the Technical University of Budapest will be introduced to determine the future vertical load statistics of a vehicle *being designed for operation under given train track and time schedule conditions.* When

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applying the simulation method, the train should be led along the specified railway line(s), by giving appropriate controls from the computer keyboard. In the course of the train motion simulation the time functions of the vertical track irregularities belonging to each wheelset are determined, based on the known spectral density function(s) of the irregularities. The mentioned time functions are used as excitation functions of the vertical in-plane dynamical model of the vehicle considered. The set of equations of the model is solved numerically and the statistics of the motion and force processes realizing in the connection elements of the model are determined. The load statistics ensure exact predictions for the operational and strength dimensioning of the running and suspension gear components.

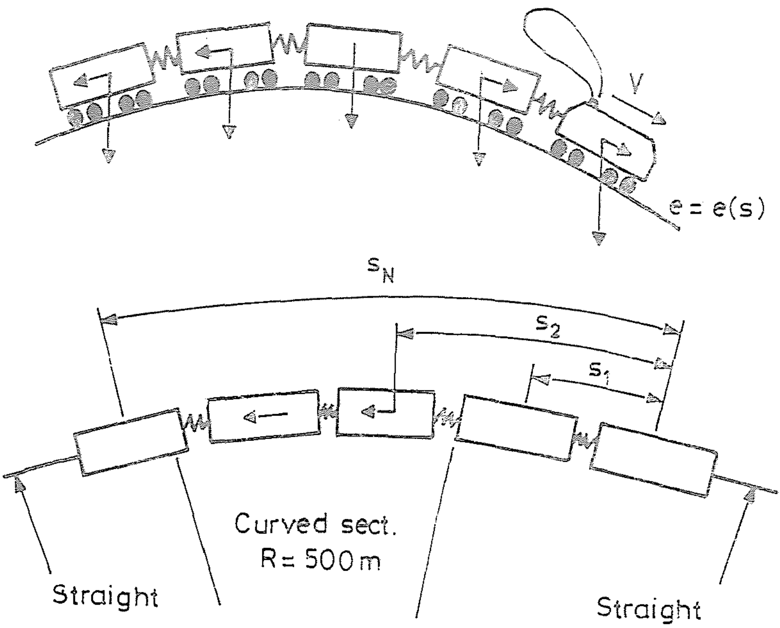


Fig. 1. Side and top views of the lumped parameter train model on the track

2. Real Time Simulation of the Train Motion

For the simulation of the train motion the complex longitudinal dynamical model and the program system described in [4] were used. This longitudinal dynamical model takes into consideration one loco at the front end of the train and maximum 30 cars. In the train model the vehicles are represented by lumped masses as it is indicated for a train in *Fig. 1*.

To specify the model, the geometrical and vertical characteristics of the vehicles, as well as the longitudinal stiffness and damping values of the intervehicle connections should be fixed, see *Fig. 2*.

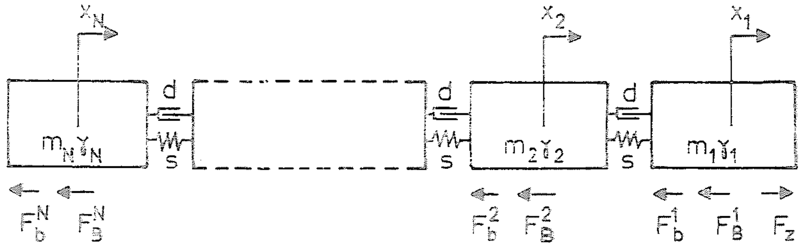


Fig. 2. The train as a longitudinal vibratory system

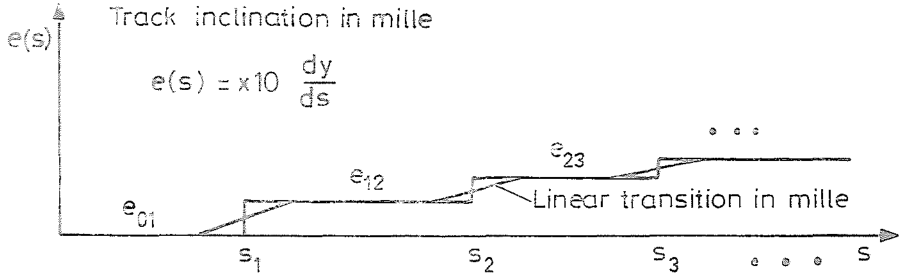


Fig. 3. Track inclination function vs. track arc length

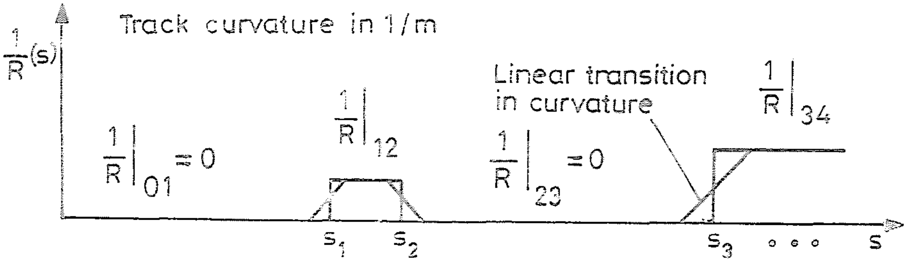


Fig. 4. Track curvature function vs. track arc length

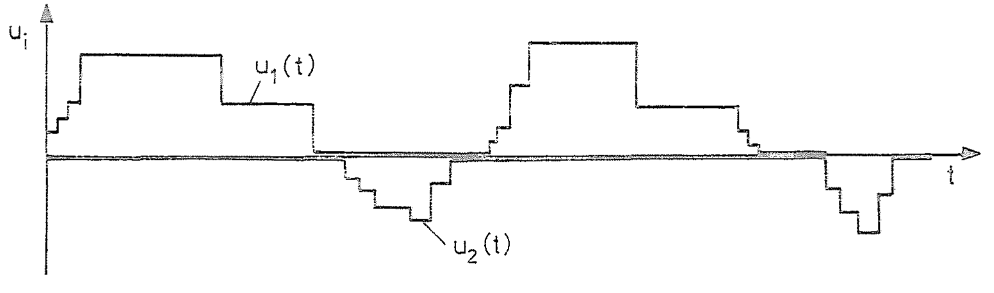


Fig. 5. Drive and brake control functions vs. time

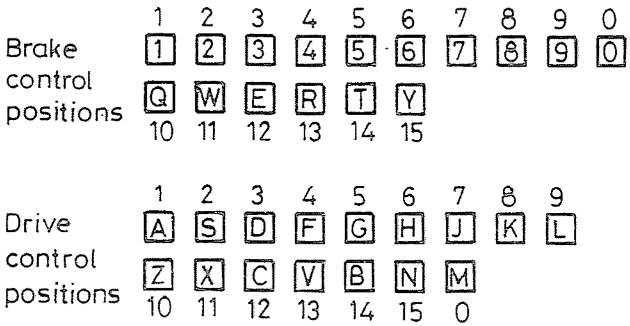


Fig. 6. Partition of the keyboard positions

Also the coefficients of the specific basic traction resistances, the brake cylinder diameters, the mechanical advantages of the brake rigging, as well as the velocity and brake-block pressure dependent friction coefficients of the friction wheel brake should be specified for each vehicle in the train. The adhesion limit is considered as a velocity independent constant. The tractive-effort performance curves of the traction unit should be specified as a bivariate function of the velocity and the drive control. The maximum number of the tractive-effort control positions is 15, and the same is the number of the loco driver's brake valve handle positions. The railway track is specified by two track arc-length dependent piecewise linear functions, namely by the *inclination conditions and the curvature conditions*. The track inclination conditions are characterized by the mille values. In case of constant inclination angles the mille values are also constants, while in case of the vertical rounding circles the variation of the mille values is approximated by a linear law (see *Fig. 3*).

The *curvature conditions* are characterized by the numerical values of the track curvatures, see *Fig. 4*.

In straight sections the curvature takes zero values, in circular sections it takes constant values, while in transition curves it is a linear function of the arc length, reflecting the *clotoid geometry*.

By using appropriate integer valued $u_1(t) \leq 0$ drive, and $u_2(t) \leq 0$ brake controls given from the computer keyboard and the real-time numerical solution of the equations of motion of the train model, the train can be led along the railway line (or lines) specified by the customer railway company. A typical control function pair is shown in *Fig. 5*.

The partition of the set of keyboard positions for initiation the required brake and drive control integers is shown in *Fig. 6*.

Thus, the speed – timing diagram $v = f(t)$, or the speed – distance covered diagram $v = f(x)$ can be determined using an integration time step of length 0.01 s for each vehicle in the train. For example a set of time-dependent diagrams appearing on the computer screen is visualized in *Fig. 7*.

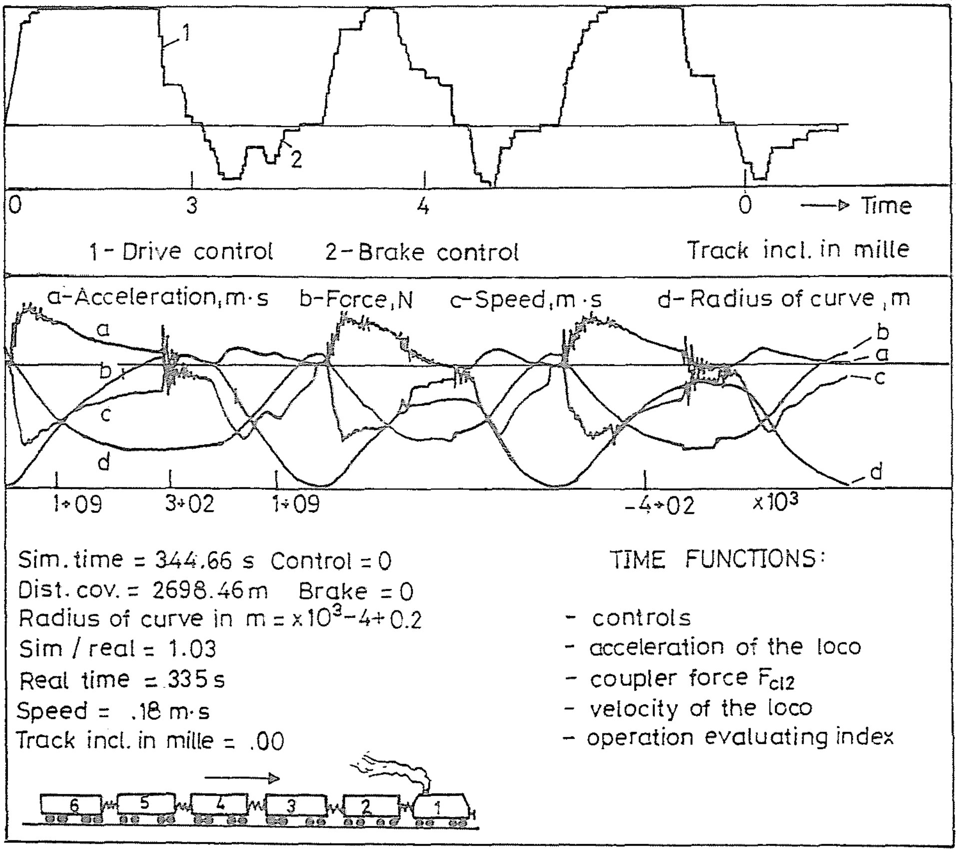


Fig. 7. Graphical and numerical information appearing on the screen

Similarly, the distances covered by the gravity points of the wheelsets become known for any vehicle in the train, also on a time sequence of pace 0.01 s.

3. Generation of Track Irregularities

The vertical irregularities of the railway track are approximated by the realization of a track length parameter weakly stationary stochastic process. It can be assumed that the spectral density function globally characterizing the vertical irregularities of the railway line has been specified by the customer railway company. It is known [1,2,3], that the realization function of a weakly stationary track irregularity process $u(x)$ having spectral density function $S(\Omega)$ can be obtained in the following form:

$$u(x) = c_0 + \sum_k 2c_k \cos(\Omega_x x + \psi_k) .$$

In the formula, $\Omega_0, \Omega_1, \ldots, \Omega_N$ stand for the given spatial angular frequency points, at which spectral density ordinates $S(\Omega_0), S(\Omega_1), \ldots, S(\Omega_N)$ are specified. Sequence $c_0, c_1, \ldots, c_N$, consists of *normally distributed independent random variables of zero expectation and prescribed variances*:

$$\sigma^2(c_k) = S(\Omega_k)\Delta\Omega, \quad k = 0, 1, 2, \ldots, N$$

Here $\Delta\Omega$ stands for the distance between the midpoints of the partition intervals generated by points Ω_k. Sequence $\{\psi_k\}$ consists of *independent random phase-angles, uniformly distributed over* $[-\pi, \pi]$. In the simulation procedure the required random variables are represented by properly generated pseudo-random numbers.

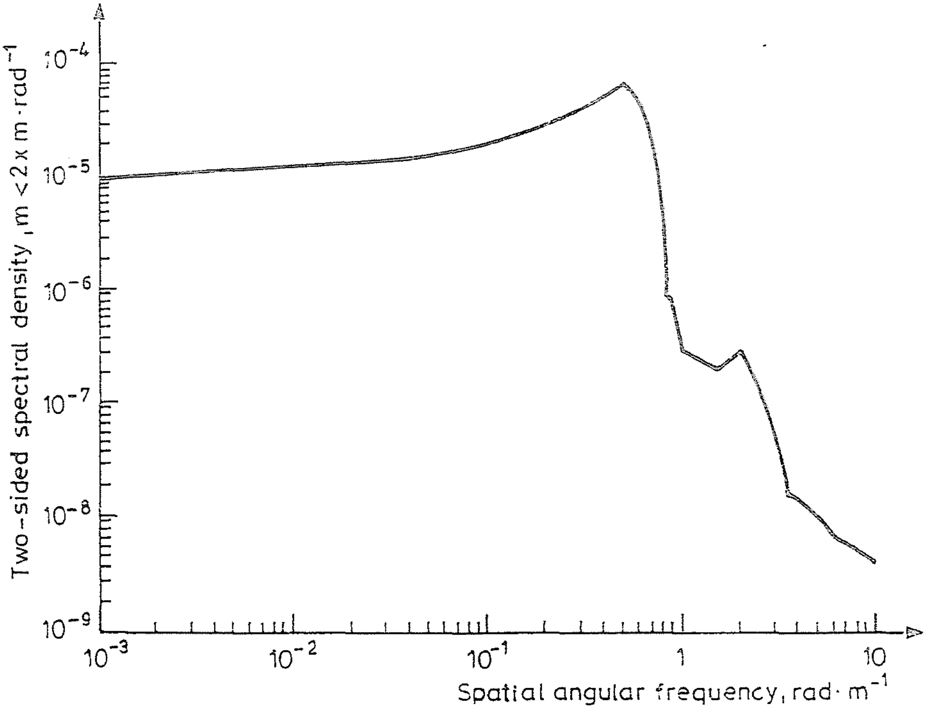


Fig. 8. Two-sided spectral density function of the vertical track irregularities

In *Fig. 8* the spectral density function of a weakly maintained track is shown, while in *Fig. 9* the realization function generated on the basis of the spectral density introduced is visualized.

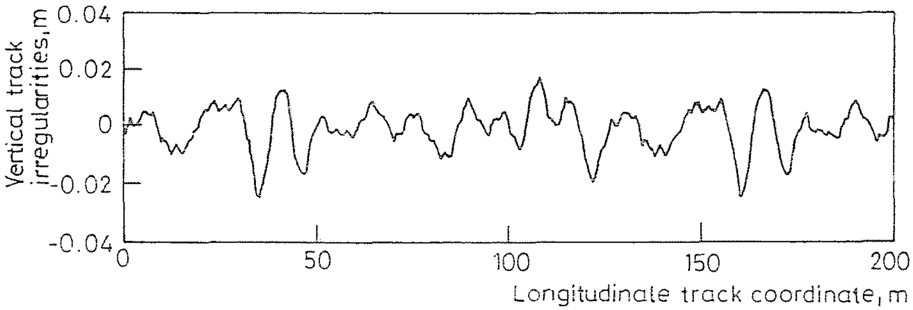
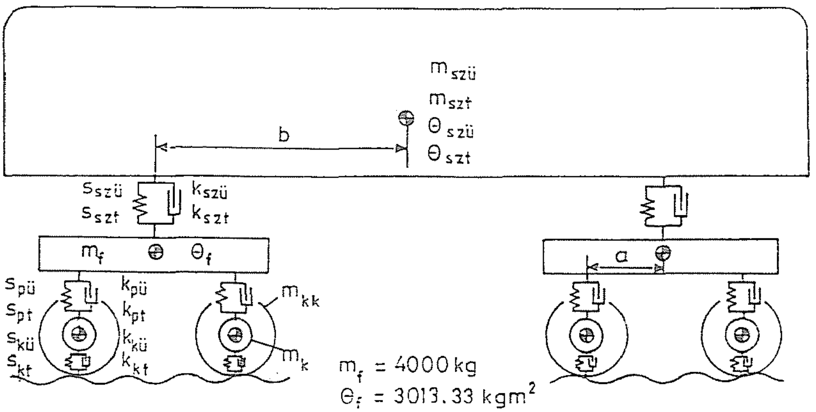


Fig. 9. Realization function of vertical track irregularities generated from spectral density function shown in *Fig. 8*



$m_{szü}$ = 19262 kg	$s_{szü}$ = 0.546 kN·mm^{-1}	m_k = 1200 kg	$s_{pü}$ = 2.16 kN·mm^{-1}
m_{szt} = 32282 kg	s_{szt} = 0.903 kN·mm^{-1}	m_{kk} = 429.21 kg	s_{pt} = 2.48 kN·mm^{-1}
$\Theta_{szü}$ = 583413.88 kgm^2	$k_{szü}$ = 100.0 kNs·m^{-1}	$s_{kü}$ = 80 kN·mm^{-1}	$k_{pü}$ = 3.95 kNs·m^{-1}
Θ_{szt} = 977767.98 kgm^2	k_{szt} = 100.0 kNs·m^{-1}	s_{kt} = 80 kN·mm^{-1}	k_{pt} = 4.23 kNs·m^{-1}
a = 1.05 m	b = 6.3 m	$k_{kü}$ = 18.6 kNs·m^{-1}	k_{kt} = 18.6 kNs·m^{-1}

Fig. 10. Lumped parameter vertical in-plane dynamical model of the vehicle

In this way the track irregularities under each wheelset of the vehicle can be computed for each time step of pace 0.01 s when the train passes through

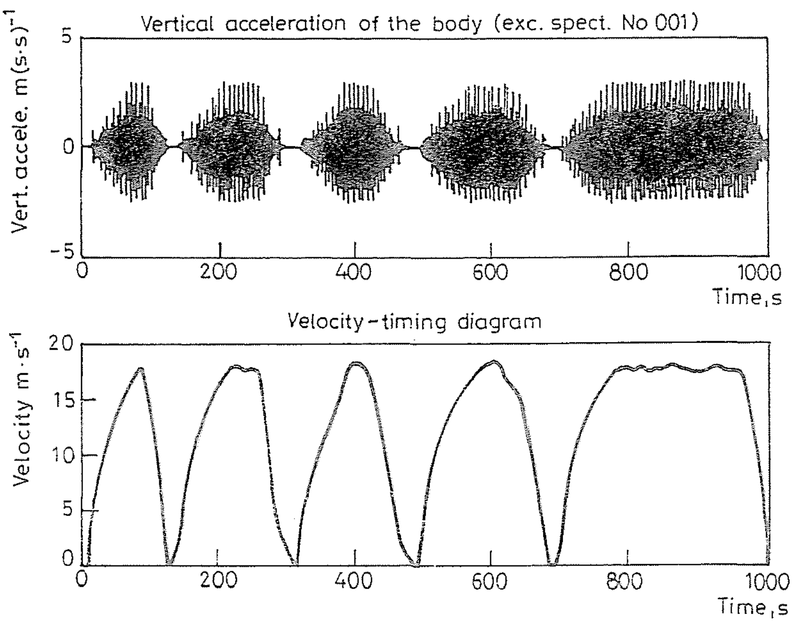


Fig. 11. Time history of the carbody acceleration belonging to the velocity – timing diagram shown in the lower part

a line section. The continuous vertical track irregularity excitation function $u_1(t), u_2(t), \ldots, u_4(t)$ can be obtained for the analysis of the vertical dynamics of the vehicle by using C_2 spline interpolation on the discrete (sampled) track irregularity values obtained from the simulation of the train motion.

4. Simulation of the Forced Vertical Vibrations of the Railway Vehicle

For the simplified analysis of the excited stochastic vertical vibrations of traditional four-axle railway vehicles a dynamical model of 10 degrees of freedom was constructed. As free coordinates the vertical displacement of the vehicle body, the bogies and the wheelsets, as well as the pitching angular displacements of the vehicle body and bogies were selected (see *Fig. 10*).

The time-dependent excitation effect of the vertical track irregularities is represented by vertical displacement excitations $u_1(t), u_2(t), \cdot u_3(t), u_4(t)$ prescribed for the wheel treads. The set of motion equations describing the vertical and pitching vibrations are treated in the framework of the state-space method. The resulted first order set of differential equations is solved numerically in the time domain. In *Fig. 11* the vertical acceleration function

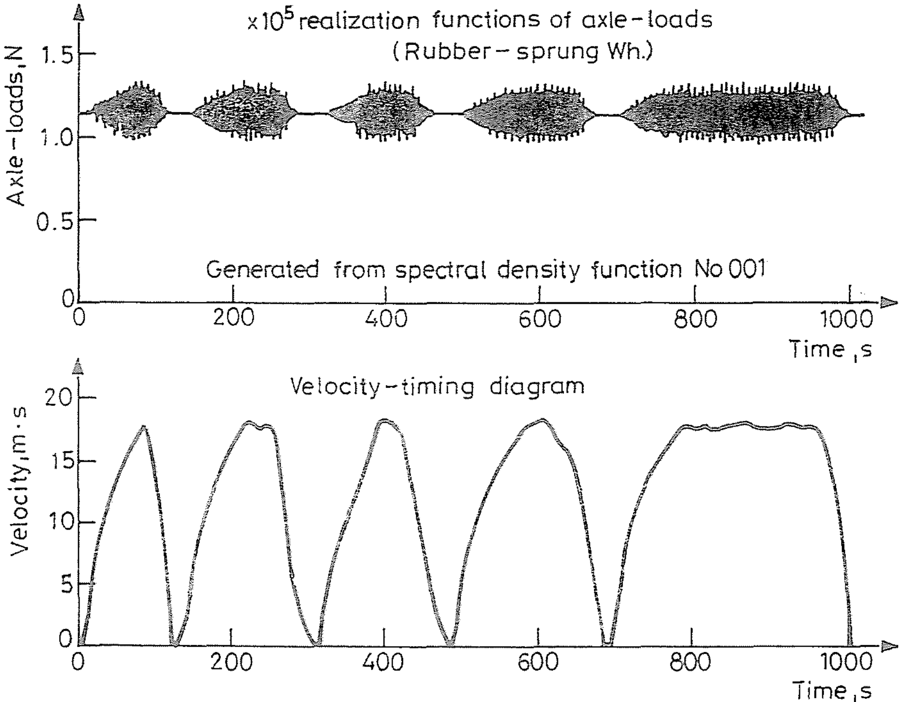


Fig. 12. Time history of the dynamic axle loads in the rubber sprung wheelsets

of the carbody gravity point is shown belonging to the irregularity function in *Fig. 9*, together with the speed – timing diagram characterizing the actual train motion considered.

The solution functions received for the velocities and displacements of the bodies in the model are substituted into formulae determining the connection forces arising in the linkages in the running gear and the suspension system. The time history of the vertical forces arising in the rubber-sprung wheelsets between the hubs and the sprung rings of the wheels is represented in *Fig. 12*.

In *Fig. 14* the time history of the vertical forces transmitted by the secondary suspension system is shown.

In *Fig. 13* the time history of the vertical forces transmitted by the primary pension system is visualized.

Based on the latter force – time functions the predicted load statistics of the running gear and the suspension system can be determined.

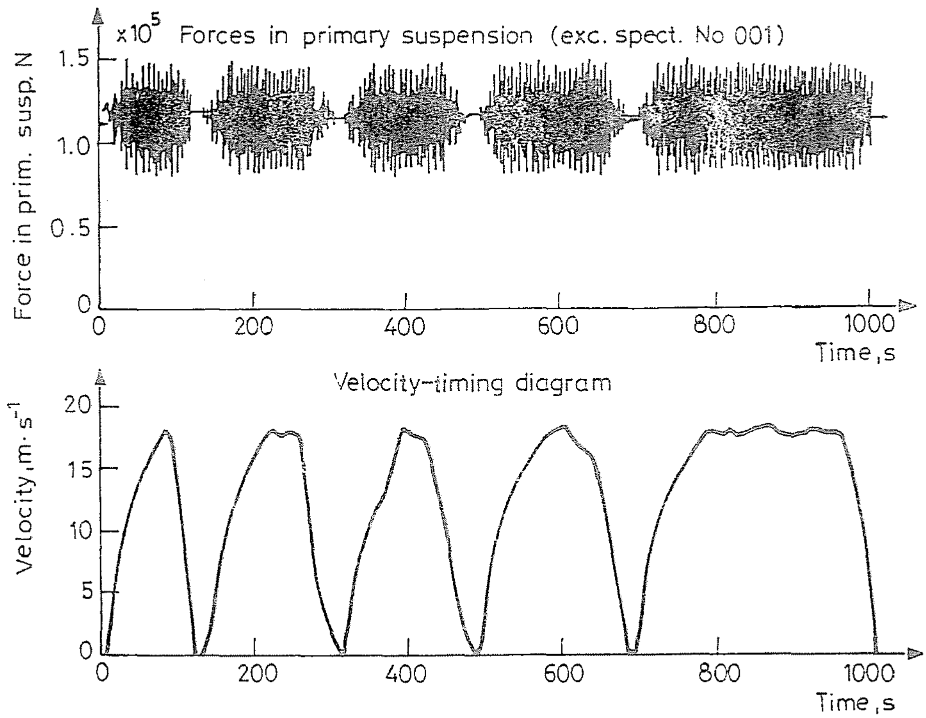


Fig. 13. Time history of vertical forces transmitted by the primary suspension system

5. Load Statistics

The operation-loading conditions are characterized by means of probability distribution approximating relative frequency histograms evaluated from the time history functions mentioned. The software elaborated for the automatic evaluation makes it possible either to illustrate on the screen, or to make printed documents. Also the mean values and empirical standard deviations are determined ensuring a proper description of the predicted future motion and loading conditions. The Gaussian probability density functions generated on the basis of the arithmetical mean and the empirical standard deviation computed from the time histories are included in the diagrams to ensure a preliminary (visual) normality test.

In *Fig. 5* the relative frequency density histogram belonging to the computer-generated track irregularities plotted in *Fig. 8* is shown.

In *Fig. 16* the relative frequency density histograms of the vertical accelerations of the carbody over the front and rear king-pin linkages are plotted. The two diagrams are constructed by taking into consideration the

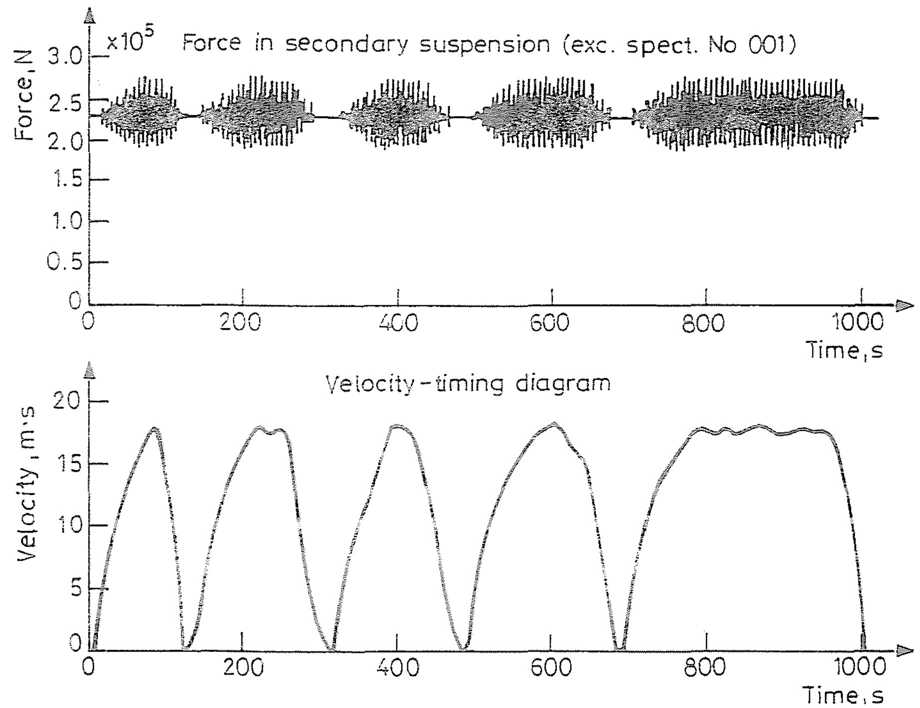


Fig. 14. Time history of vertical forces transmitted by the secondary suspension system

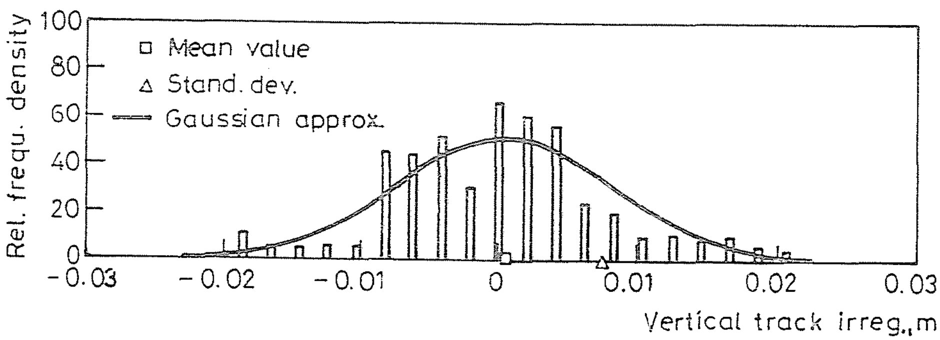


Fig. 15. Relative frequency density histogram of the vertical track irregularities

time history of the vertical acceleration of the carbody's gravity point and also the angular acceleration of the pitching vibrations of the carbody.

In *Fig. 17* the four relative frequency density histograms of the vertical axle loads transmitted through the rubber springs (and the parallely connected viscous dampers representing the internal energy dissipation in

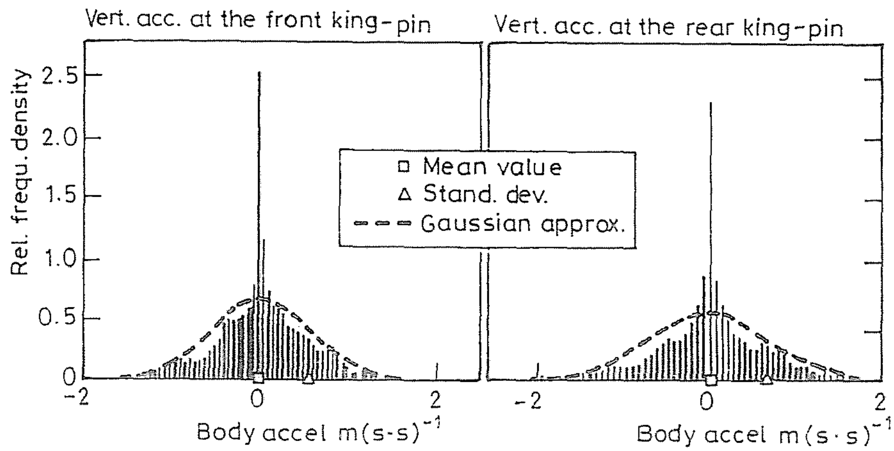


Fig. 16. Vertical accelerations on the carbody

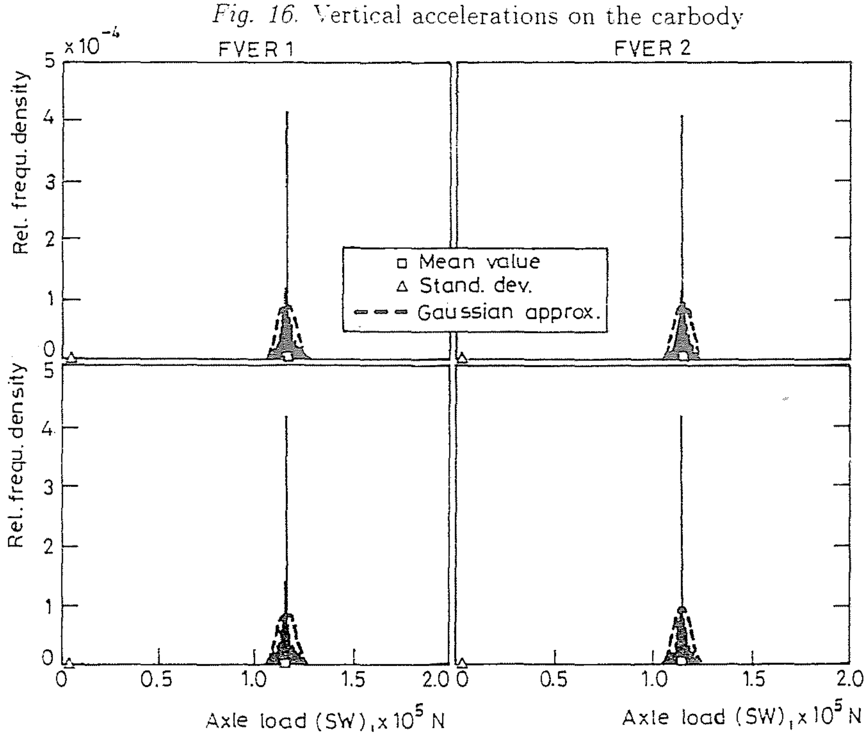


Fig. 17. Relative frequency density histograms of the vertical axle loads transmitted through the rubber springs

the rubber springs) built into the wheelsets are shown.

In *Fig. 18* the four relative frequency density histograms of the vertical

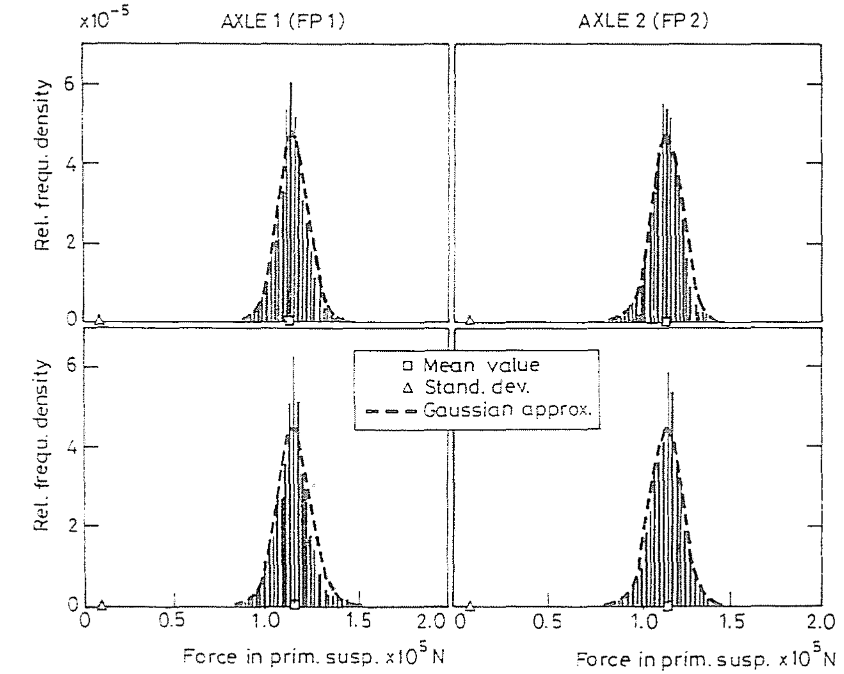


Fig. 18. Relative frequency density histograms of the vertical forces transmitted through the primary suspension system

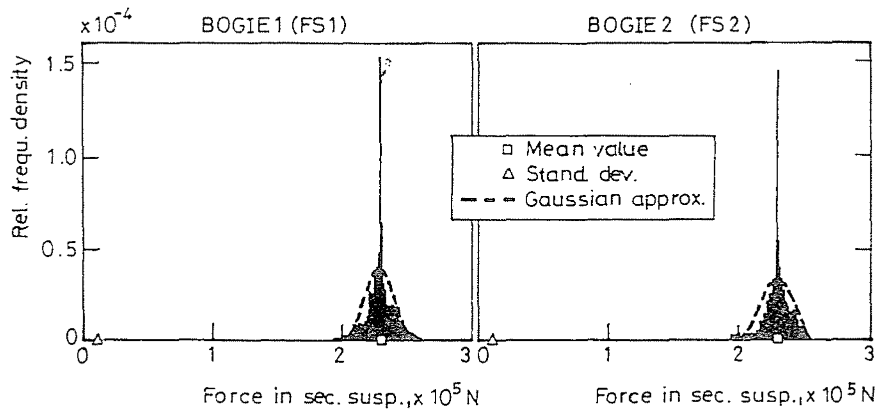


Fig. 19. Relative frequency density histograms of the vertical forces transmitted through the secondary suspension systems

forces transmitted through the primary suspension elements are plotted.

In *Fig. 19* the two relative frequency density histograms of the vertical forces transmitted through the secondary suspension elements are shown.

Of course, further statistical characteristics, such as correlation functions, spectral densities, etc. of the load process can be determined.

6. Conclusions

- The elaborated simulation method makes it possible to analyze the dynamic loading conditions realizing in the components of the running and suspension gears of a railway vehicle planned for a specified railway line (railway network) *already in the period of designing.*
- The basic condition of the application of the method is to have accurate data about the inclination and curvature conditions of the railway line considered, and about the lengths of the transition curves and the radii of the circulabr arcs interconnecting the adjacent inclined sections in the vertical plane.
- It is also necessary to know the *spectral density function* globally characterizing the stochastic irregularities of the railway track in the framework of a weakly stationary model or the spectral density functions belonging to the individual sections of the track.
- The computation procedure gives the *elastic and dissipative forces arising in the structural connections of the running and suspension gears* ensuring a solid basis for the exact stress dimensioning by taking into account the expected loading conditions on the railway line or network considered.
- The elaborated computation method makes it possible *to optimize the system parameters of a vehicle* planned for operation on a given railway line or network by maximizing the objective functions formulated for the running comfort and safety under appropriate constraint conditions.

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