УДК 629.4

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SIMULATION MODEL OF TRAIN MOVEMENT IN SMALL-RADIUS CURVES

Движение поездов по криволинейным участкам пути определено в виде поперечных колебаний системы «поезд – путь». Имитационная модель системы составлена на языке MATLAB. В кривых малого радиуса при движении с максимально разрешенными скоростями система работает в экстремальных условиях, вызывающих высокие напряжения как в экипаже, так и в железнодорожном пути. Кроме того, система при этом работает на пределе с точки зрения безопасности движения. Необходимость количественного определения износов железнодорожного пути и поездов, оценки безопасности движения и комфортабельности особенно актуальна в настоящее время в связи с введением в эксплуатацию поездов с наклоняемым кузовом, для которых поперечные колебания поезда весьма значительны. Имитационная модель также включает в себя возможность подготовки к измерениям и экспериментальным исследованиям, поскольку позволяет получить достаточно точные результаты, появления которых можно ожидать при проведении ходовых испытаний в нормальных или экстремальных условиях, что приводит к экономии времени и затрат.

Introduction

A new field in this work are the oscillating systems lateral direction to the train movement. The idea is to develop simulation models which will prove and quantify the existence of lateral vehicle-rail high frequencies oscillations, that may be a significant cause of the vehicle and rail wear, that could affect the comfort and safety of travelling and that could be the source of noise generated by the moving train. The problem will be specially emphasised once the tilting trains are introduced into traffic.

This work studies the oscillating vehicle-rail system in the lateral direction, as well as its behaviour in small-radius curves of the railway line. The attempt is made to define this system and to develop its simulation model in order to prove its existence and to obtain the tools for further research of the system's behaviour.

The same as in previous works, this one will be also based on our already tested approach which is to define the system and its physical model, to define the mathematical model of the system and to develop the simulation model, to record the movement values on the simulation model and to make available testing of the procedure and the simulation model, where possible, also using all the available data from other sources.

The final testing of the simulation model would be provided by the measurements on the actual vehicle and actual railway line.

This work will briefly describe the development of the simulation models of the oscillating system of the wheelset on a straight line, and then the simulation model of the lateral oscillating vehicle-rail system on the section of the railway line featuring small-radius curves.

Defining the oscillating system of the wheelset and its physical model

The first step is the defining of the oscillating system of the wheelset in the lateral direction on a straight railway line. After that we will add the car body to the system

The task is not so simple, since this oscillating system is not as noticeable as for instance the vertical oscillating system of the same wheelset, where one can nicely see the springs and shock-absorbers as standard elements of the oscillating systems. Can this oscillating system be defined and can its simulation model be successfully developed? What would be an acceptable proof of its existence? If this can be done, can the simulation model at least partly explain and quantify the past inexplicable occurrences, such as for example, the generation of wheel noise in movement along the lines, and other phenomena?

If the scheme of the wheelset laid on the tracks according to the Figure 1 is considered, some elements of the oscillating system can be seen, which is the mass of the wheelset and the conical loose wheel–rail contacts, which can certainly feature the changeable forces acting on the wheels, and cause lateral movements of the wheelset mass.

Any asymmetry in the position of the wheelset on the rails appears as a disturbance in the system and causes differences in the components of the active lateral forces, resulting in misbalance of forces and the resulting force acts on the mass, bringing it into dynamic condition. This immediately causes the forces of inertia, as well as the forces of friction between the wheels and the rails in the lateral direction.

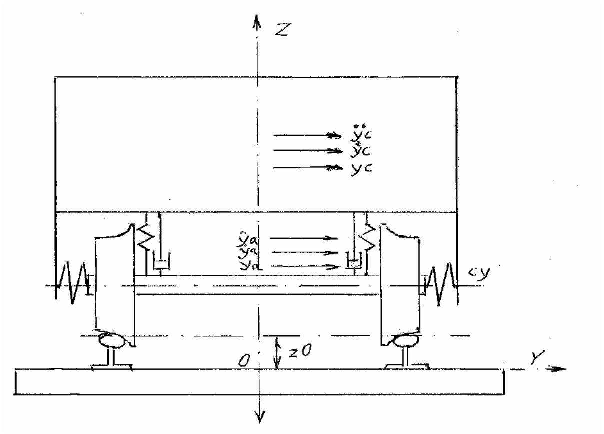

Fig. 1. Scheme draft of the wheelset

The conicity of the contact plane between the wheels and the rails is variable in the real system with the wheelset moving left – right within the allowed range of movement. During such movements, the conicity of contact of the left and right wheel differs a lot, also resulting in great differences both of the lateral active forces and of the friction forces, and all of these together introduce great disturbance into the system.

The Figure 1 shows also the main axes of the Y-Z coordinate system, in which the lateral movement as well as the displacement of this system with relation to the symmetrical axis of the wheelset will be analysed.

It is necessary to enter the shape of the wheel profile as input value into the model of the oscillating system of the wheelset in the lateral direction, in order to be able to calculate the current angles of the variable contact plane and all the trigonometric functions in the range within which the contact points are changing. These geometrical forms will be used to calculate the angles for the left and the right wheel profile, and then also their trigonometric functions tg, sin and cos.

Thus, the basic input data is the form of the wheel profile. The standard form of this profile has been taken, for the left and the right wheel and is entered into the simulation model according to Table 1.

When the system is stationary, the central regular position of the contact points of the left and the right wheel is y0 = $\pm$0.750 m, and the form of the profile of the right wheel already is drawn in MATLAB from the data in the file whprofil.m presented in the Figure 2.

Table 1

y0=0.750

∑y	z	y
-y0-0.0650	0.1625	-0.8150
-y0-0.0322	0.1610	-0.7822
-y0-0.0000	0.1600	-0.7500
-y0+0.0050	0.1595	-0.7450
-y0+0.0100	0.1590	-0.7400
…	…	…
y0-0.0200	0.1578	0.7300
y0-0.0100	0.1590	0.7400
y0-0.0050	0.1595	0.7450
y0-0.0000	0.1600	0.7500
y0+0.0322	0.1610	0.7822
y0+0.0650	0.1625	0.8150

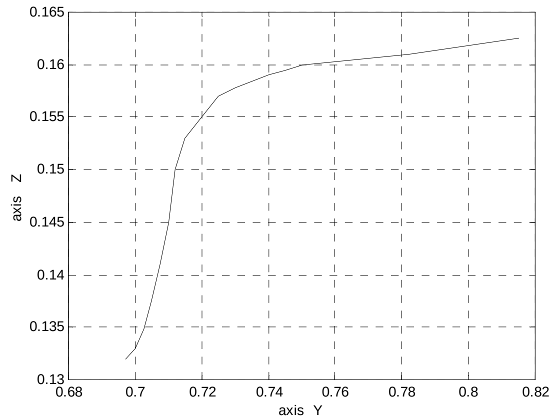

Fig. 2. Form of the wheel profile

Defining of the mathematical model of the system

If the form of the wheel profile has been given as a curve of the value pairs y and z according to Table 1, the derivation of the curve is easily calculated using MATLAB. With the known angles and their trigonometric functions, the lateral components of the active forces on the wheelset and the friction forces are defined according to the Figure 3.

The reactions of the rails are divided into two components: the component parallel to the current gradient (sin component) and the component perpendicular to the gradient (cos component). The component parallel with the gradient is the active force, and the perpendicular component multiplied by the coefficient of friction μ determines the friction forces which are, in the first version, multiplied by the function sign($-\dot{y}$). The value of the coefficient of friction μ is still quite undetermined. The left and the right wheel are firmly fixed and with the axle form the mass *maw*, and the force of inertia is $-maw.\ddot{y}$.

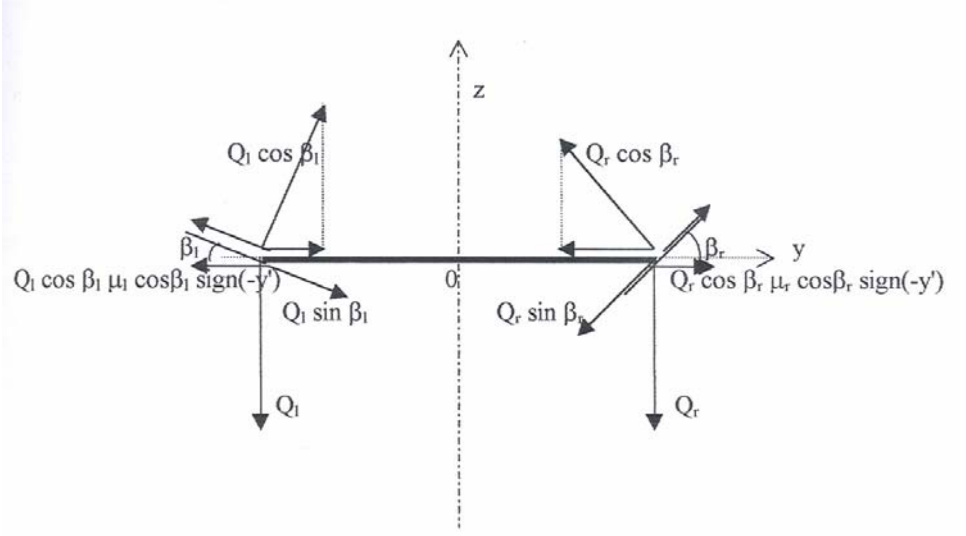

Fig. 3. Lateral forces on the wheel flange

The differential equation for the movement of the wheelset in the lateral plane are obtained according to

$$\Sigma Y = 0$$

$$\text{- maw} \cdot \ddot{y} - Q_l \cdot \sin \beta_l \cdot \cos \beta_l + Q_l \cdot \cos \beta_l \cdot \mu_l \cdot \text{sign}(-\dot{y}) \cdot \cos \beta_l - - Q_r \cdot \sin \beta_r \cdot \cos \beta_r + \cdot Q_r \cdot \cos \beta_r \cdot \mu_r \cdot \text{sign}(-\dot{y}) \cdot \cos \beta_r = 0$$

$$\ddot{y} = \frac{1}{\text{maw}} \begin{Bmatrix} \left(- Q_l \cdot \sin \beta_l \,.\, \cos \beta_l + Q_l \cdot \cos \beta_l \cdot \mu_l \cdot \text{sign}(-\dot{y}) \cdot \cos \beta_l \right) + \\ + \left(- Q_r \cdot \sin \beta_r \cdot \cos \beta_r + Q_r \cdot \cos \beta_r \cdot \mu_r \cdot \text{sign}(-\dot{y}) \cdot \cos \beta_r \right) \end{Bmatrix}$$

$$\ddot{y} = \frac{1}{\text{maw}} \left(Y_{la} + Y_{lf} + Y_{ra} + Y_{rf} \right)$$

The obtained differential equation is the most important part of the mathematical model of the oscillating system in the lateral direction.

This mathematical model has been developed to observe the behaviour of the lateral oscillating system of the wheelset. For the moment the possible rotational (roll) or other movements of the wheelset around the longitudinal vehicle axis, etc. are not taken into consideration.

Development of the simulation model

The simulation model of the lateral oscillating system of the wheelset consists of three files

– control file sidirp.m;
– wheel profile file whprofil.m i;
– simulation file sidir.mdl.

Control file sidirp.m

This file has the usual functions, which are setting the initial values and parameters, calling the file whprofil.m, calculating of the coefficients for the simulation model, calling of the simulation file sidir.mdl and plotting instructions of the oscillating system values.

Wheel profile file whprofil.m

The form of the wheel profile is given in the form of a matrix according to Table 1. A sufficient number of y-z pairs is taken in order to obtain a smooth curve. An even better measure of the smoothness of the curve are the later values of derivation and trigonometric functions sin and cos, and therefore, subsequently new y-z pairs were added. A number of other instructions follow in this file until the necessary vectors are obtained.

Simulation file sidir.mdl

The simulation diagram consists of the common part and blocks Left wheel's lateral movement and Right wheel's lateral movement according to the preview Figure 4.

The Figure 4 shows the common part and the blocks for the left and the right wheel (and also the car body). The most important part of the simulation diagram is in the blocks Left wheel's lateral movement and Right wheel's lateral movement, but there is not enough room here for their description.

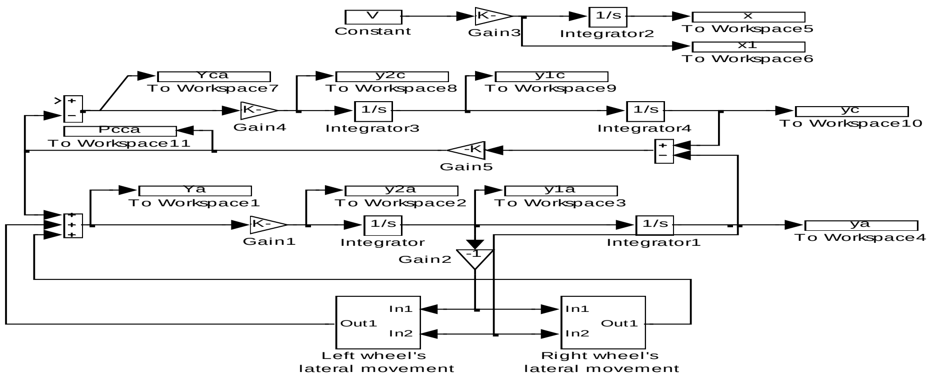

Fig. 4. Simulation diagram

Only the part of the differential equation for the left wheel using MATLAB syntax will be shown.

Yl = Yla + Ylf =
(sinbetal*cosbetal*(-1))*Qil + . . .
(sign*(-mil)*cosbeta*cosbeta)*Qil.

This relation (in the first version) has been realised on the simulation model by blocks Product1, Gain3, Product3, Sign, Gain2, Product2, Product6, Product4 and Sum.

It is equal for the right wheel, with the only difference in the indices which are r (right).

Dynamic values in the simulation model

The described simulation model of the lateral oscillating system of the wheelset (and the car body) in straight movement of the vehicle has started to work after quite a long period of development.

The past studies of the simulation model have tested its logic behaviour, the logic behaviour of the lateral oscillating system of the wheelset as well as the relation of the values from the oscillating system.

All the tests should have proven the existence of the lateral high frequency oscillating system of the wheelset also during ride of the vehicle along a straight railway line.

Satisfactory results have been achieved with a variable calculating step and the choice ode45(Dormand-Prince) in the solver and will be presented in this study.

For the presentation of the operation of the simulation model and for the presentation of the behaviour of the lateral oscillating system, comprehensive research was carried out, such as e.g. the system in the stationary status, small disturbance due to the displacement of the wheel-rail contact point and disturbance due to the middle displacement of the contact point.

This work will present only some of the testing results.

Lateral forces from the conical wheel flange on the left and the right wheel of the stationary system are equal regarding the value but opposite according their action, so that they cancel each other out (Figure 5)

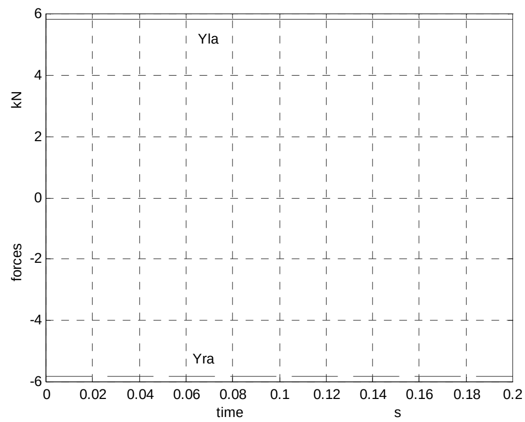

Fig. 5. Lateral forces in the stationary condition

Small disturbance due to the displacement of the wheel-rail contact point (ya0 = yc0 = 0.00001 m) is most frequently the status of the lateral oscillating system of the wheelset in the direction of the railway line. Due to any disturbance the wheelset moves in the lateral direction and starts lateral movement in order to return to its stationary position. Is it, then the oscillations in the system occur and how is this seen on the simulation model? Which part of the characteristic noise in passing of the vehicle results precisely from the lateral oscillations of the wheelset?

The model was used to carry out research of the behaviour of almost all the values from the system depending on time or depending one on the other, which is mainly set by the control file sidirp.m.

Figure 6 presents a diagram of the lateral acceleration of the wheelset. This value is oscillating, which was to be expected.

The values of oscillation amplitudes are within the range in which they can be measured.

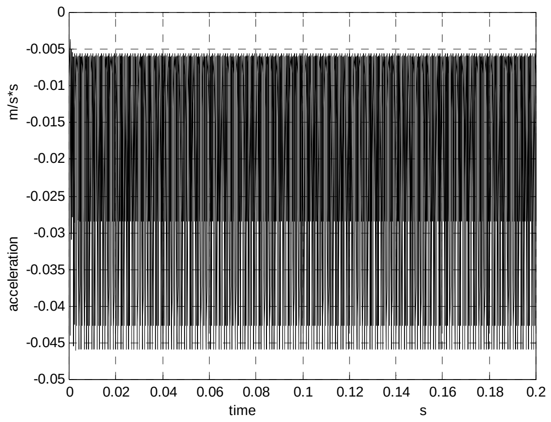

Fig. 6. Lateral oscillations of the wheelset

Since the variable step of integration is used, because the system is very stiff, the usual files for the frequent analysis cannot be used.

In the Figure 7 there is the lateral acceleration of the car body.

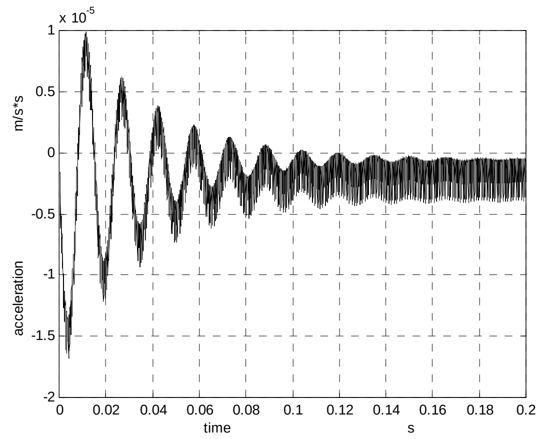

Fig. 7. Lateral oscillations of the car body

The lateral system of the wheelset is an oscillating system!

Finally, only the diagram of the longitudinal vehicle movement is given, in order to see the length of the railway line along which the process occurs (Figure 8)

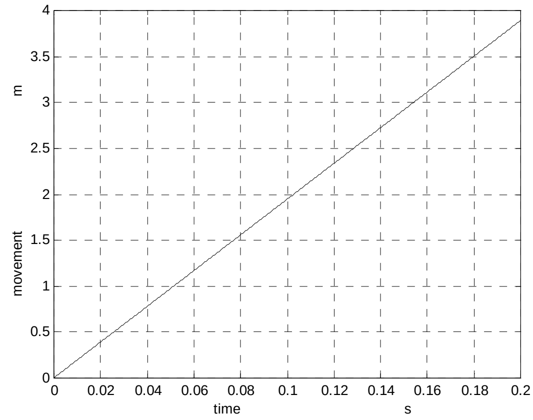

Fig. 8. Vehicle longitudinal movement

Disturbance due to the middle displacement of contact point

Due to limited space here, only the possibilities of studying this phenomenon on this simulation model will be shown.

The initial middle displacement of the wheelset is 10 mm and the variable-step integration step is taken. The duration of integration can be short, in order to see what we are interested in. The lateral displacement, speed and acceleration are oscillating values. In the Figure 10 the form and the values of the curve of the lateral wheelset and car body speed can be seen.

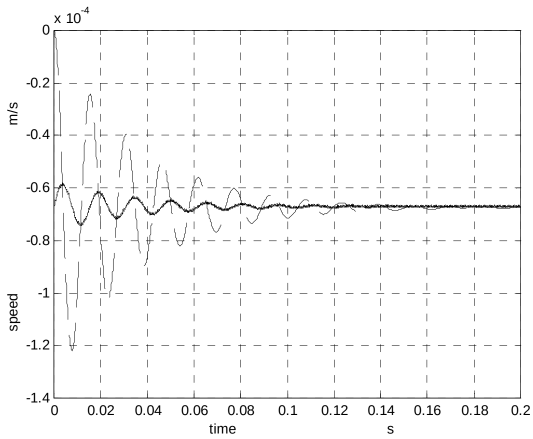

Fig. 10. Lateral speeds in the line curve

Other values can also be seen from the oscillating lateral system of the wheelset, since their vectors are also within the Workspace of the computer.

All further research of the lateral oscillating system of the wheelset should be combined with the physical measurements.

Finally, it may be said that.

The assumption that in the lateral direction of the vehicle movement, the wheelset, car body and the track form a lateral high frequency oscillating system has been proven by means of a simulation model of this system. For the moment this assumption is only a hypothesis which needs to be proven by measurements.

Maybe the polished surface of the rail is argument of the existence of lateral oscillations of the wheelset of high frequencies? The rail is equally polished by empty cars as well as by loaded cars?

Up to now, these high frequencies of the lateral oscillating system could not be found through measurements, since the measuring instruments have filters to eliminate frequency ranges, but also the frequency of taking samples of the measuring values is not high (every 1 – 200 ms).

If these oscillations exist, then the acceleration and the forces are also of high frequencies, and the issue of unknown stresses is in the closed wheelset–rails chain.

Lateral oscillating system of the wheelset could be the most important source of noise generated by the moving vehicle.

SIMULATION OF LATERAL OSCILLATING VEHICLE-RAIL SYSTEM IN SMALL RADIUS CURVES

Introduction

How the lateral oscillating vehicle-rail system behaves in the railway line curves and how a simulation model of this system can be developed – this will be dealt with further in the text.

It is known in advance that new lateral forces and accelerations occur in the railway line curves, and they have to be included in the mathematical and simulation model as addition to the previous model.

The oscillating system of the wheelset in the lateral direction of the line is supplemented in defining the system, in physical, mathematical and simulation model. These additions are not minor, but are discussed here very briefly.

Supplementing the system and its physical model

The previous schematic figure of the vehicle on a straight line according to Figure 1 is inclined compared to the horizontal, and thus represents an inclined picture of the previous work, but with substantial additions. The body is separated from the wheelset by an elastic bond of very big constant of the spring *cy*. The mass *m* is now the total mass per axle, whereas m_{aw} is the mass of the axle and the wheels. New lateral force in the line curve Y_c acts as disturbance force in the lateral oscillating system. This force acts on the body mass and is transmitted on the wheelset and the rail causing dynamic conditions of the system. It may cause oscillations in the system.

When this lateral force occurs, the vehicle moves until the flange of the outer wheel in the curve comes into contact with the lateral side of the rail, and returns when the lateral force disappears. Apart from the high frequencies oscillation of the lateral oscillating system known from the previous work, low frequency oscillations occur both of the wheelset and of the car body.

The lateral force in the curves depends on the parameters of track geometry (elevation, curve radius, transition gradients, and transition radii), of vehicle (mass per axle, mass of axle and wheel, height of the centre of gravity, drive axles or car axles), of travelling speed and allowed lateral acceleration. The mathematical model will take the influences of all these parameters into consideration according to the data for the real railway line (section Zagreb – Rijeka) and a real vehicle (tilting train Pendolino - tilting system is off).

All the previous data for the oscillating system of the wheelset in the lateral direction such as shape of the wheel profile, calculation of the current angles of the variable contact plane and all the trigonometric functions in the field of changing the point of contact, calculation of current lateral components of the active forces and friction forces remain in the mathematical and simulation model.

In the model the connection between the body and the wheelset is, according to experience in the operation of the model, elastic bond of high stiffness (c_y = 2000000 kN/m), in order to obtain their independent oscillating.

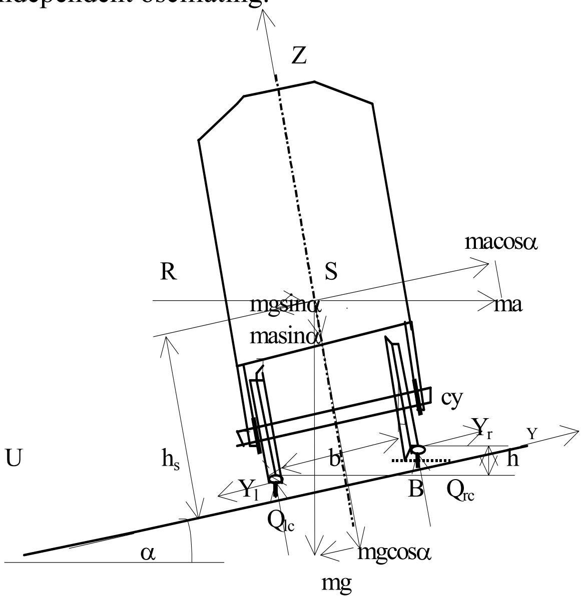

Fig. 11. Scheme of the lateral oscillating system vehicle-rail in the railway line curve

Defining the mathematical model of the system

The mathematical model is developed based on the scheme presented in the Figure 11.

For the moment the interest is on the component of the centrifugal force parallel with the running surface of the rail, since this force will be appointed as the disturbance force in the already developed simulation model of the lateral oscillating system of the wheelset. This total lateral force is to be distributed on both wheels according to the lateral displacements of the wheel flange. This force is

$$\Sigma Y_c = Y_l + Y_r = -m \cdot g \cdot \sin\alpha + m \cdot a \cdot \cos\alpha$$

Normal forces between the wheels and the rails will also be variable in passing through the railway line curves, and their expressions are:

$$Q_{lc} = (m \cdot g \cdot \cos\alpha \cdot \frac{b}{2} + m \cdot g \cdot \sin\alpha \cdot h_S - m \cdot a \cdot \cos\alpha \cdot h_S + m \cdot a \cdot \sin\alpha \cdot \frac{b}{2}) \cdot \frac{1}{b} \quad \text{(kN)}$$

$$Q_{rc} = m \cdot g \cdot \cos\alpha + m \cdot a \cdot \sin\alpha - Q_{lc} \quad \text{(kN)}$$

These equations are only one part of the mathematical model, and other parts cannot be presented due to limited space, besides the fact that it also contains the part that has already been mentioned for the lateral oscillating model of the wheelset.

Development of a simulation model

The simulation model of the lateral vehicle-rail oscillating system consists of four files:

– control file sicup.m;
– track parameters file cudata.m;
– wheel profile file whprofil.m;
– simulation file sicu.mdl.

The control file has the usual functions which include setting of the initial values and parameters, calling the file cudata.m, calling the whprofil.m file, calculating of the coefficients for the simulation model, calling the simulation file sicu.mdl and instruction for plotting the values of the lateral oscillating system. Here is a part of the file:

```
    %   SICUP.m
    %   SIMULACIJU SILA NA VLAK PRI
    %    GIBANJU U KRIVINI
    %   1.    Pocetne vrijednosti:
    V=70; x10=V/3.6;
    %
    %   2.    Parametri:
mi0=0.3; mir=0.3; mil=0.3;   p=0.03;
m=12000; maw=800; g=9.81; k=0.02;
cy=2000000; b=1.5; hs=1.5;
    keyboard
    .  .  .   .
    cudata;
%   4.    Koeficijenti:
%    Gain8
k08=1/3.6;
%    Gain9
k09=1;
 .  .  .  .  .
%    Simulacija uz pomoc menija
     sicu;
     keyboard
plot(t,h,'k-',t,sinalfa,'k--'),grid
keyboard
plot(t,R,'k-'),grid
      .   .   .
```

The data for the rail parameters have been taken for the section of the real railway line Zagreb - Rijeka in the distance from km 542,860 to km 543,860 according to the longitudinal profile of the railway line, highest allowable travelling speed from the timetable diagram and the superelevation table from the Regulations 314, all of which can be seen in the copy of a part of this file:

```
%    CUDATA.M
%   Matrica podataka za dio pruge Zagreb – Rijeka
%
%    km     Put   Nagib Radius  Nadvišenje
%   položaj                                     brzina
%    (km)    (m)   (%)     (m)       (m)        (km/h
%
RMAX=20000;
DM =[ 542.860  0    0    RMAX       0      70
      542.970  110  0    RMAX       0      70
      542.975  115  0    3564     0.009    70
      542.985  125  0    1188     0.027    70
      543.000  140  0     594     0.055    70
      543.015  155  0     396     0.082    70
      543.030  170  0     297     0.110    70
        . .   .  .  .   .  .  .   .  .  .   .
      543.710  850  0    -2080    -0.014   70
      543.715  855  0    -4160    -0.007   70
      543.720  860  0    -RMAX      0      70
      543.720  861  0     RMAX      0      70
      543.860  1000 0     RMAX      0      70];
          .   .   .
```

Individual vectors per columns are easily extracted from the data matrix, major diagrams of these values are plotted, and subsequently these are automatically used as input data for the rail parameters in the simulation model in the blocks Look Up Table. These parameters are obtained at the end also as output values of the simulation process as function of time, as follows:

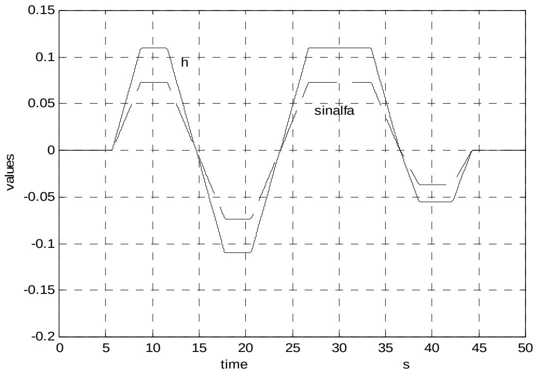

Fig. 12. Superelevation and sinalfa

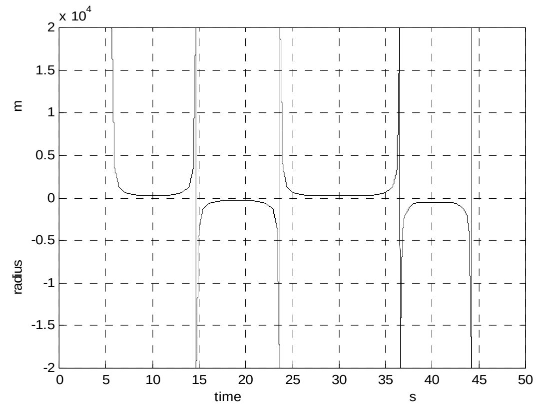

Fig. 13. Railway line radius curve

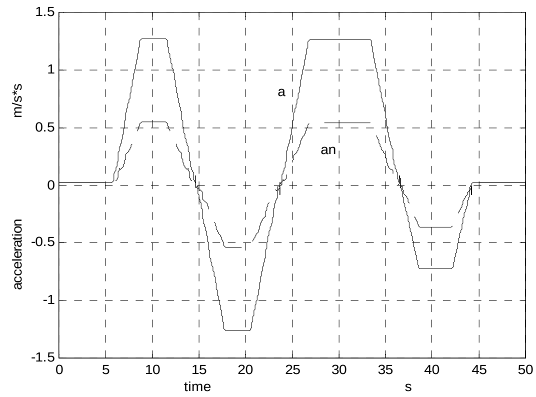

Fig. 14. Total and non-compensated lateral acceleration

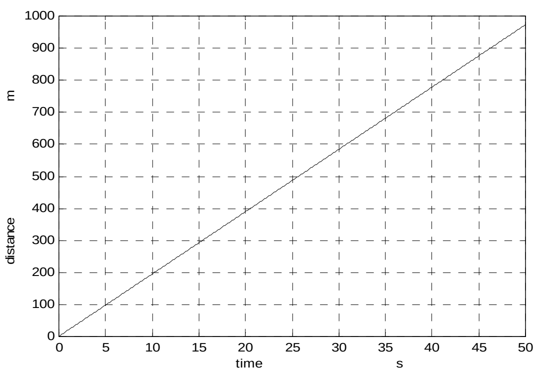

Fig. 15. Vehicle pass distance

Wheel profile file whprofil.m

The wheel profile file is the same as the one in the previous work. In this simulation model it is automatically called and executed as before.

Simulation file sicu.mdl

The simulation diagram consists of a common part and blocks Left wheel's lateral movement, Right wheel's lateral movement, and has also a new block Train and track, but there is not enough space for its description.

The simulation model of the lateral oscillating system vehicle-rail in the railway line curve has been set and tested on a computer and operates successfully.

The problems occur in the selection of the integration step. With a very small integration step and the used computer, only a small section of the line could be included and that would be a poor solution. The compromise was accepted to make the step such (0.001 s), as to make it possible to follow the selected railway line section with well knowing elimination of the possibility of seeing the high frequencies oscillations of the system.

As the travelling speed, the upper allowed travelling speed for that line was taken and that is V = 70 km/h.

Dynamic values in the simulation model

From the computer which performed the simulation model and all the analyses of its behaviour, the maximum has been obtained. A longer rail section was taken into consideration (about 1000 m) with "S" curves and with calculation step 0.001 s.

For the presentation of the simulation model functioning and for the presentation of the lateral oscillating system behaviour in the railway line curve, the instructions in the control file are given. We are interested in the displacement of the wheelset mass and the body mass in lateral direction on the considered curved section of the line (Figure 16.)

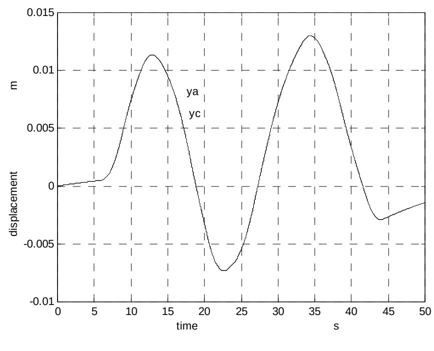

Fig. 16. Lateral displacement of wheelset and car body

The "elastic" connection between the car body and the wheelset is such that they actually move together in the lateral direction.

Normal forces Qr and Ql can be seen according to the programmed instructions in the Figure 17 but their difference is of greater interest here, and therefore is given in the Figure 18.

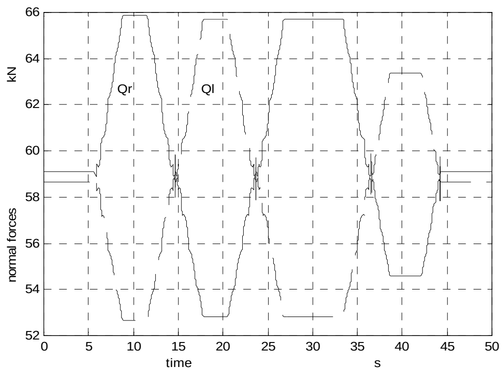

Fig. 17. Normal forces

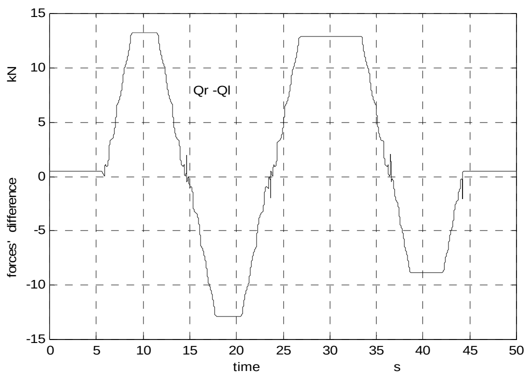

Fig. 18. Difference of normal forces

The difference of normal forces will be used in the simulation model for the study of the occurrence of rail corrugation in the line curves. This difference will probably lead to the disturbance in the condition of drive axles and thus also to the increased torsion oscillations of drive axles. The minimum of either left or right normal force limits both the traction force of the drive axles and the braking force of all the axles.

The displacement of the wheel flange along the rail in curves results in the change of the current rotation radius, which has also been included in the model and can be seen in the Figure 19 for the right and for the left wheel.

The most important and beautiful figure (special in the colour) is Figure 20. There are dynamic values for the right wheel during the vehicle moving along the line: active force according the geometry, friction and whole force in comparison with the displacement speed of this wheel.

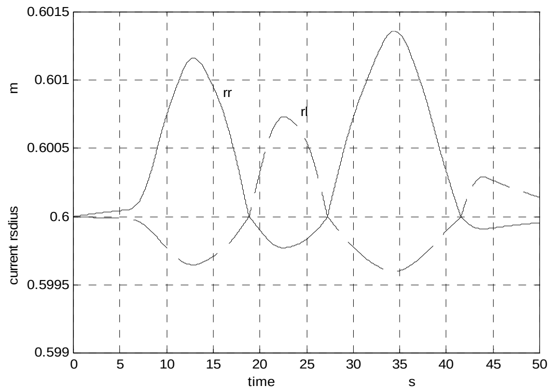

Fig. 19. Change of rotation radius

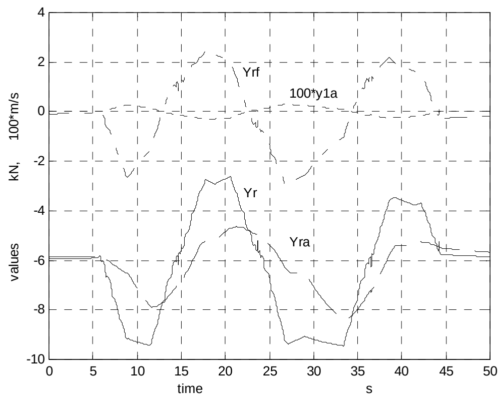

Fig. 20. Dynamic values for the right wheel

Other values from the lateral oscillating system vehicle-rail in the railway line curve can be also seen, since their vectors are also in the computer Workspace.

All further research of lateral oscillating system should be combined with the actual measurements on the vehicle and the railway line.

Conclusions

The model of lateral oscillating vehicle-rail system in the line curves was developed for the real railway line and vehicle. Some possibilities of study and analysis of the complex relations of the movement values and parameters in the movement of the rail vehicles through curves have been presented. The mathematical and simulation models are open models and can be upgraded by the new requirements according to the interests and the needs of the researchers and users.

Oscillating forces between the wheels and the rails certainly have great influence on all the parts of the system such as bearings wheels and connection of wheels and rails, rails (rail polishing), fastening equipment and sleepers.

Lateral oscillations can be measured on axles. It can be seen from literature that the measurements have discovered oscillating values of axial acceleration on the wheel flanges.

Lateral high frequencies oscillations of the system represent the source of noise generated by the riding vehicle.

The lateral oscillating system is a very stiff oscillating system and has difficulties in functioning of the simulation model, especially on a less powerful and slower computer, which was used to develop the model.

Nevertheless, in order to obtain all frequencies which occur in the oscillating system of the wheelset, only a short section of the path with variable integration step was studied and high frequencies were found in the system.

The results obtained by the study of the vehicle movement through curves show that the difference in the normal forces of the left and right rail are of very variable and high value, and can effect in the occurrence of torsion oscillations of the drive axles, and thus also of the rail corrugation. It is further important to determine that the minimum of either the left or the right normal force is the value which restricts both the traction force of the drive axles as well as the braking force of all axles.

The work on improving and upgrading the simulation model of lateral oscillating vehicle-rail system should be continued, as well as the measurements verification on the vehicle and the railway line, in order to develop the simulation model for multiple research. This will be especially required for the research of lateral oscillations of tilting trains.

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