TEKA Kom. Mot. i Energ. Roln. – OL PAN, 2011, 11A, 232-244

MODELLING OF A CONTROLLED TRACTIVE WHEELSET FOR A BOGIE OF A RAILWAY VEHICLE BASED ON NOISE SPECTRUM ANALYSIS

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Summary. This paper examines an intelligent railway vehicle system subjected to adjust and control a complex mechatronical system that includes controlled wheelsets. The dynamic and tractive characteristics of a railway vehicle are controlled based on noise spectrum analysis for the friction coefficient detection and railway wheel squeal. In this paper, we propose a combined control system with two stages of control strategies. The first control strategy is used for adhesion control and adjustment of railway vehicles based on an observer, which allows the determination of the maximum tractive torque based on the optimal adhesion force between the wheels of a railway vehicle and rails depending on weight load from a wheel to a rail, friction conditions in the contact zone, a lateral displacement of wheel set and wheel sleep. The second control strategy allows the adjustment of a wheel set's position on the track to be executed by means of actions from actuators to links of axle boxes depending on analysis of noise in the wheel-rail contact. The non-linear MBS software package called Simpack was used for the simulation model of the proposed mechanical system. The proposed control strategy was modeled in Matlab/Simulink. The Simpack model was linked with the control unit in Matlab/Simulink by means of a SIMAT-interface. The system was investigated using co-simulation.

Key words: dynamics of rail vehicles, mechatronic systems, fuzzy logic controller, bogie, adhesion model, actuator, stability control, guidance control, integrated control, rolling noise, microprocessor control system, simulation, locomotive model

INTRODUCTION

The realization of maximum adhesion forces for a rail vehicle in straight and curving parts of track is a very difficult process because it is connected with use of tractive efforts and depends on the contact characteristics in the zone between the wheels and rails.

Modern solutions in the field of the development of new control systems for mechatronic systems of running gears allows the possibility to improve the interaction between wheels and rails for different modes of the movement for rail vehicles. These systems can be tentatively divided into the following groups:

- traction control systems
- suspension control systems

- brake control systems
- combined control systems.

At the present time, there has been special research attention on the problem of reducing the wear of wheels and rails on the curving parts of a railway track. For this research, it is necessary to determine the exact parameters of the contact between a wheel and rail, and the displacement and position of a wheel set on straight and curving parts.

Usually for decreasing wear and the improvement of adhesion realization in the tractive mode, only two control systems are used from the above written classification. One of these systems is the adhesion control system; the second one is the active steering control system.

In our previous publications [Spiryagin M., Lee K.S., and Yoo, H.H., 2007, Spiryagin M., Lee K.S., and Yoo H.H., 2008] we presented control systems that allowed for the adjustment of traction efforts for different adhesion conditions. These systems were developed based on a method of steepest descent and fuzzy logic [Pupkov K.A., Egupov N.D., 2004].

Active steering control system of a rail vehicle is described in . [Spiryagin M., Lee K.S., Yoo, H.H., Spiryagin V., and Vivdenko Y., 2007]. That system was proposed for a two-axle bogie which uses constraints with radius links and one of the radius links of axlebox also functions as an actuator.

The systems described above have one common feature – information about contact characteristics for the system is obtained by means of noise analysis from the wheel-rail contact.

However, the system that allows doing combined control of characteristics of a wheelset's movement, is one of the most interesting examples to improve vehicle dynamics. This system [Perez J., Busturia J., Mei T.X., and Vinolas J., 2004] allows the control of traction efforts as well as the active steering control by means for mechatronic bogie vehicles with independently rotating wheels. From a practical point of view, mechanical components of this kind of systems need further improvement. The system has a good chance to find an application for new types of rail vehicles in the future.

At the present time, the modernization of existing electromechanical designs of running gears for rail vehicles is one of actual questions. In this article, we describe an improved mechatronic system that includes two subsystems. One of these subsystems is an adhesion control system (it is connected to the traction control). The second one is the active steering control system. The proposed decision was estimated by means of simulation. For the simulation, a complex model of a bogie of a rail vehicle, control system for traction motors and actuators were developed.

OBJECT AND PROBLEMS

Model Of Rail Vehicle

The evaluation of traction and dynamic characteristics of a rail vehicle requires an adequate representation of different modes of a vehicle's work and an interaction between running gear's elements and track [Masliev V.G., 2002, Iwnicki S. , 2006, Himmelstein, 2004]. The solution of this task is possible to reach if the friction process, which present in the contact between wheel and rail, is described in the correct way.

The traction bogie of a rail vehicle DEL-02 manufactured by JSC “Holding company “Luganskteplovoz”, was taken to conduct the simulation experiments. The bogie is shown in fig. 1 and has a two-stage spring suspension. This bogie and non-motor bogie of the same vehicle has unified parts such as the frame, brake, mounting-returning device. The traction bogie has two AC traction motors with supported-frame suspension and two torque gears. The traction from the wheel to the pivot is transmitted through the resilient axle box radius links, bogie frame and resilient traction rods.

We make an assumption that the bogie is equipped with wheels, which have a profile as shown in fig. 2, and the wheels move on the track with a rail profile plotted in fig. 3.

The value of the adhesion force is separately calculated for each wheel and depends on a rail vehicle’s velocity, a slip velocity of contact bodies, wheel and rail profiles, a weight load from a wheel to a rail, friction condition in the contact zone and a position of a wheel relative to a rail.

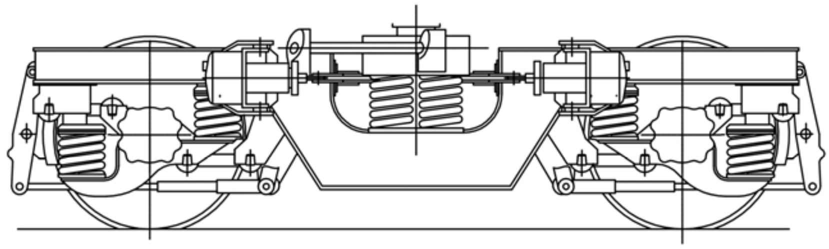

Fig. 1. Side view of front traction bogie of the rail vehicle DEL-02

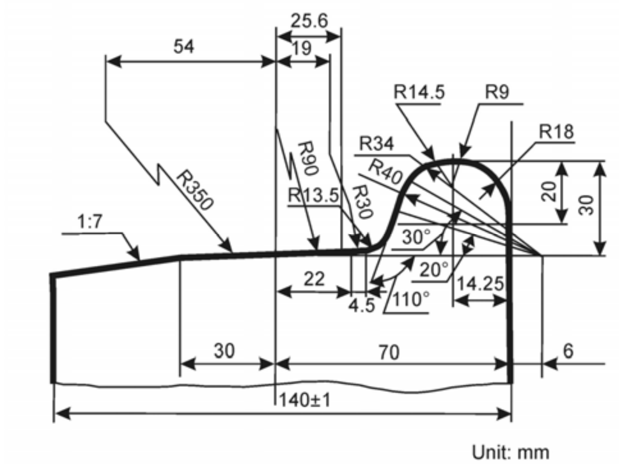

Fig. 2. Wear wheel profile, which is obtained by means of wear analysis for locomotives’ wheels [Carev 1982]

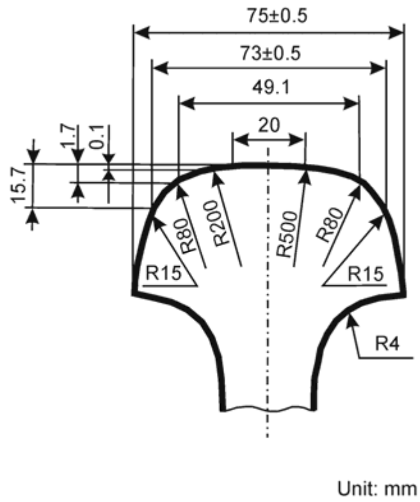

Fig. 3. New rail profile

For the simulation of adhesion process in the contact zone, the adhesion model [Spiryagin V., 2004, Spiryagin, M., Lee, K.S., Yoo, H.H., Kashura, O., and Kostjukevich, O., 2007] was applied. The adhesion force can be defined as

$$\vec{F}_a = N\frac{\vec{S}}{|\vec{S}|} / \left(A_1 / \exp(\varepsilon \cdot B) + A_2 \ln(\varepsilon \cdot B) + A_3 / (\varepsilon \cdot B) + A_4(\varepsilon \cdot B) + A_5 \right) T_2 T_4 T_9 / T_7 T_8 \quad (1)$$

Here: N – weight load from a wheel to a rail;
A1, A2, A3, A4, A5 – coefficients of relation;
$\vec{S}$ - vector of wheel slip;
ε - relative slip, [%];
B=T1T3T5T6;
T1, T2 – coefficients, which depends on friction conditions in rail-wheel contact;
T3, T4 – weight load coefficients;
T5 – velocity coefficient dependent on the velocity V of the locomotive;
T6, T7 – coefficients, which are dependent on cross motion y of a wheel relative to the rail;
T8 – coefficient of angle of attack of the wheel;
T9 – coefficients, which depends on traction of braking mode of a rail vehicle's movement.

Coefficient T9 should provide a safety in the braking mode. Furthermore, the process, which has a place in a suspension and is called a suspension lock, has a big influence on vehicle dynamics. In this case, the dynamics start worsening and, as a result, the adhesion coefficient between the wheel and rail decreases. Based on this, the coefficient T9 can be equal to 1 in the traction mode and equal to 0.5 in the braking mode.

The values of coefficients for equation (1) for the wheel and rail profiles, shown in fig. 2 and fig. 3, are listed in Table 1. Furthermore, in this table, μ is the maximum friction coefficient of concrete friction condition for two contact bodies.

In the next section, the possibility of obtaining information about friction contact characteristics such as the maximum friction coefficient and the angle of attack by means of noise analysis will be discussed.

Noise In Wheel-Rail Contact

A review of investigations on the possibility of detecting friction conditions in the contact zone with the help of the method of using of noise analysis was published by [Spiryagin M., Lee K.S., and Yoo H.H., 2008]. It allows making a preliminary conclusion that the detection of the maximum adhesion coefficient is possible by means of noise analysis.

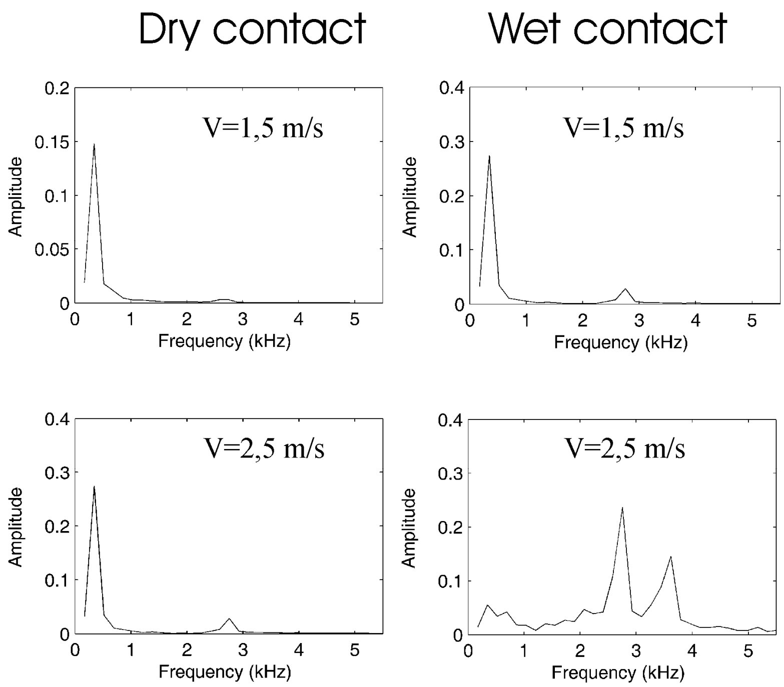

Fig. 4. Results of noise analysis in the contact with the permanent slip and the angle of attack ψ=0

The problem of the dependence of the angle of attack on noise characteristics has been studied in works published by [Hsu, S.S., Huang, Z., Iwnicki, S., Thompson, D.J., Jones, C.J.C., Xie, G., and Allen, P. D., 2007, and Koch, M., Hentschel, F., Himmelstein, G., and Krouzilek, R., 2003]. The obtained results for the measurements, made on special test rigs, show the possibility of getting information about the angle of attack based on an analysis of the power spectral density and the sound pressure level. Fig. 5 shows the investigation results obtained by [Hsu, S.S., Huang, Z., Iwnicki, S., Thompson, D.J., Jones, C.J.C., Xie, G., and Allen, P. D., 2007].

For the further confirmation of the proposed method, a series of experiments on a specially developed test bench were made by [Spiryagin M.I., Spiryagin V.I., Klyuev A.S., Klyuev S.A., Ulshin V.A., 2008, Spiryagin M., Lee K.S., Yoo H.H., Spiryagin V., and Vivdenko Y., 2008]. The obtained results show that the detection of the contact characteristics only by noise sound pressure analysis is not possible. However, the study on acoustical signal allows the possibility to get this information. The example of analysis is shown in fig. 4. However, a more detailed investigation in this field is still required.

Table 1. **Coefficients for equation (1) for the definition of the value of adhesion force in the wheel-rail contact**

A_1	1
A_2	-0.1419381
A_3	0.026201
A_4	4.3642
A_5	2.0729
T_1	$0.026+2.38\mu$
T_2	$\mu/0.40907$
T_3	0.00635+0.0000368N, N[kN]
T_4	$0.9713+0.0003454N-0.0000005674N^2$, N[kN]
T_5	$(0.10108v-0.108)^{0,5}$, v[m/s]
T_6	$1.0002+0.1026y+0.002419y^2-0.000728y^3$, y[m]
T_7	$0.99976+0.0059684y-0.00006288y^2+ +0.0000577856y^3$, y[m]
T_8	$1-0.0056\vert\psi\vert(0.1057+0.087y+0.01156y^2)$, ψ [rad]

Based on these results, it is possible to make a conclusion that the use of noise analysis to get the friction characteristics in the contact zone as well as the angle of attack is a possible variant. However, it is necessary to remember that for each concrete case of interaction between wheels and rails, the same noise can be identified only for the same models of rail vehicles with specified design characteristics, such as wheel and rail profiles, suspension systems and etc.

Proposed Control System

For our proposed system, we need to use the algorithms for control systems described in works published by [Spiryagin M., Lee K.S., and Yoo H.H., 2008, Spiryagin M., Lee K.S., Yoo, H.H., Spiryagin V., and Vivdenko Y., 2007]. In this paper, we investigate combined work of control subsystems for the complex control of wheelset's dynamics. Fig. 6 shows the proposed microprocessor systems for one wheelset.

For the correct work of adhesion control subsystem, it is necessary to make a comparison of optimal and estimated adhesion forces.

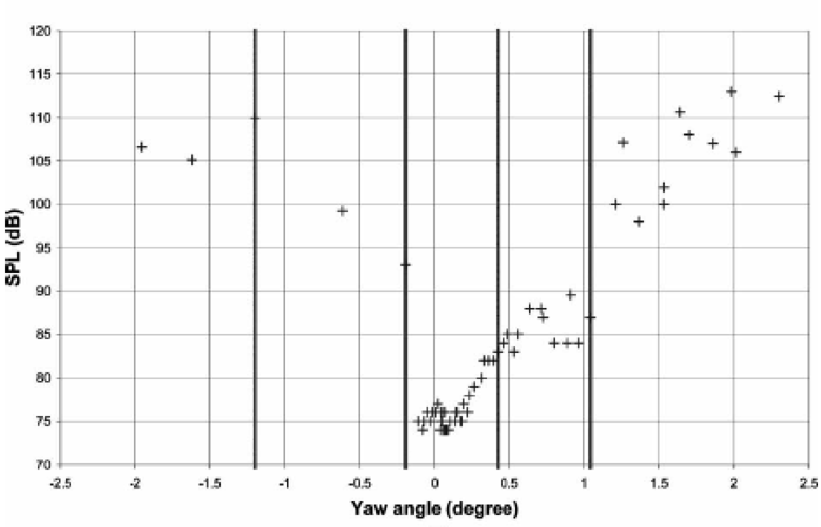

Fig. 5. Dependence between sound pressure level of the dominant frequency and yaw angle for rail-wheel contact [Hsu, S.S., Huang, Z., Iwnicki, S., Thompson, D.J., Jones, C.J.C., Xie, G., and Allen, P. D., 2007]

Optimal adhesion force can be computed according to Equation (1). In this case, the slip value should approximately be equal to 3 percents because this slip provides a stable work in the wheel-rail contact [Engel B., Beck H.-P., Alders J., 1998].

The detection of the adhesion coefficient, which is also used in Eq. (1), is possible by means of noise spectrum analysis in the wheel-rail contact and using GPRS and GPS technologies. A GPS satellite system is used for obtaining the position of a railway vehicle at a specific moment of time. After receiving the current position on the curve, the track characteristics for the current position can be obtained by means of the GPRS from the station computer. The obtained noises are processed by a special algorithm to obtain the noise characteristics for certain frequency bands. By looking up a special database data, received from experimental and theoretical research, the dependence of the adhesion coefficient on noise and track characteristics, vehicle velocity, relative slip, the lateral displacement and the angle of attack can be obtained.

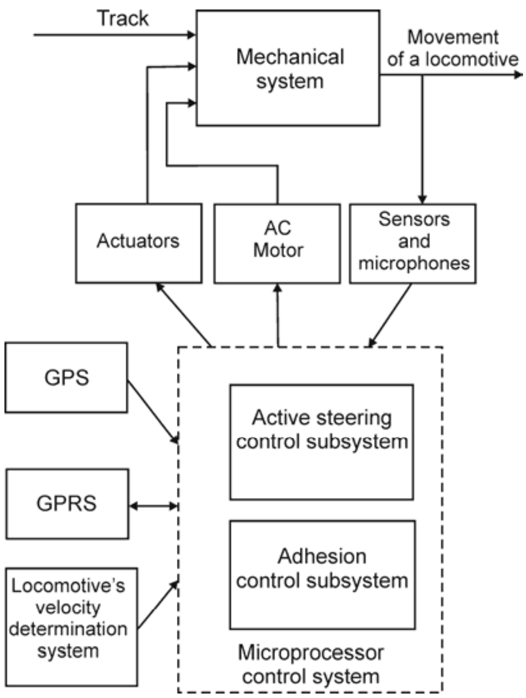

Fig. 6. Microprocessor control system

The estimated adhesion force can be defined based on Laplace transformation and adapt primary order low-pass filter by the following equation

$$F_{est} = \frac{T_{wheels}}{r} - \frac{J}{r^2}\frac{1}{\tau_0}(1 - \frac{1}{\tau_0 s + 1}) \cdot V(s) \tag{2}$$

Here: T_{wheels} is the tractive torque applied to a wheelset, r is a radius of wheel, J is an inertia of wheelset, τ_0 is a time constant of the observer, and V is the locomotive velocity.

Based on a comparison of the obtained results of the values of the optimal and estimated adhesion forces, the adjustment of the required torque of the AC traction motor for a wheelset is provided by means of a controller, which has been developed with the use of fuzzy logic. More detailed information on this controller used for our proposed system can be found in [Spiryagin M., Lee K.S., Yoo, H.H., Spiryagin V., and Vivdenko Y., 2007].

For the second subsystem for active steering of the wheelset, it is necessary to change one of radius links of axlebox by a link-actuator in the mechanical system. This decision does not require any change in the bogie's design. The algorithm is based on a comparison of values for optimal and estimated steering angles (the steering angle is a yaw angle of wheelset relative to a bogie's frame).

The optimal angle can be obtained with the following equation:

$$\gamma_{opt} = \arcsin\left(b / 2R\right) \tag{3}$$

Here: b is the distance between the leading ant trailing axles of bogie, R is the track curvature, which can be defined by means of using GPS/GPRS technologies.

The estimated steering angle γ_{est} can be defined as

$$\gamma_{est} = \psi - (y_1 - y_2) / b + i^* \cdot (b / 2R) \tag{4}$$

Where: ψ is the angle of attack (this angle can be obtained from noise analysis as described in Sec. 3), y_1 and y_2 are the lateral displacements of wheelsets; i* = 2i – 3 (for the leading wheelset i=1 and for the trailing one i=2).

The controller for the active steering control system, based on the simple proportional control law, is described by [Spiryagin M., Lee K.S., Yoo, H.H., Spiryagin V., and Vivdenko Y., 2007].

Design And Simulation Model

The evolution of the proposed system was performed by means of a simulation on a traction bogie of a railway vehicle DEL-02. The weight of a half carbody was connected unmoveable as weight forces to the supports. For the development of the simulation model, the non-linear MBS software package called Simpack was used. The proposed control strategy was modelled in Matlab/Simulink. The Simpack model of the bogie was linked with the control unit in Matlab/Simulink by means of the SIMAT-interface. Based on the software packages described above the system was investigated by using co-simulation.

Fig. 7 presents the dependence between the maximum adhesion coefficient and the distance along the track. This allows the simulation of different adhesion conditions between wheels and rails.

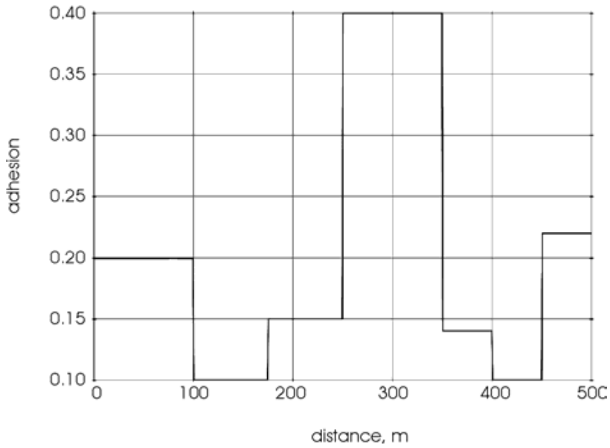

Fig. 7. Dependence of the maximum adhesion coefficient on distance along the track inputted in Simpack

The estimated rail curvature is plotted on fig. 8. For this simulation, the curvature radius was obtained from the following equation [Koch, M., Hentschel, F., Himmelstein, G., and Krouzilek, R., 2003]

$$1/R = \Omega / V \tag{5}$$

fig. 9 shows the calculated results as a function of the time. The obtained results confirm the satisfactory work of the proposed system.

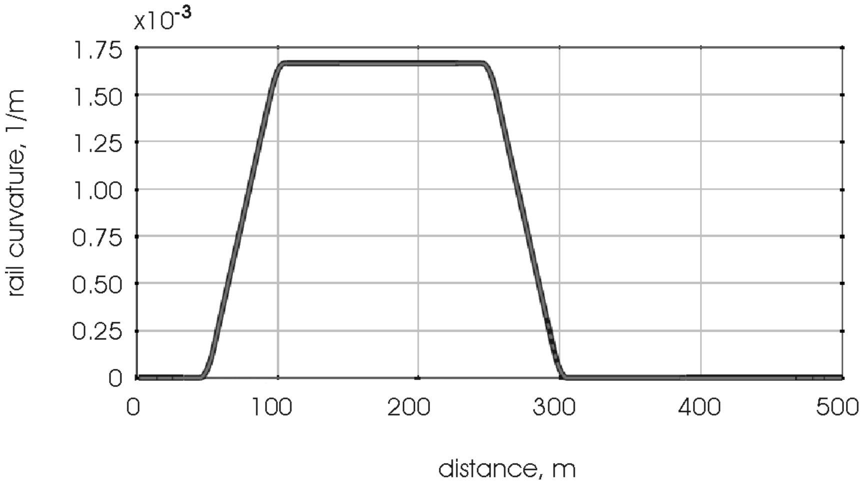

Fig. 8. Estimated rail curvature

CONCLUSIONS

This paper presents the design of a mechatronic wheelset for a bogie of a railway vehicle. Co-work of the adhesion control system and the active steering control system were used to improve vehicle dynamics in curved parts of track. The work of the proposed control subsystems is based on noise analysis.

The system performance was checked with co-simulation in Simpack and Matlab/Simulink software. As a result, we achieved a satisfactory control system.

In conclusion, for the correct work of the system in real conditions more detailed theoretical and experimental investigation needs to be performed on the dependence of the adhesion coefficient and the angle of attack from noise in rail-wheel contact for different working and friction conditions.

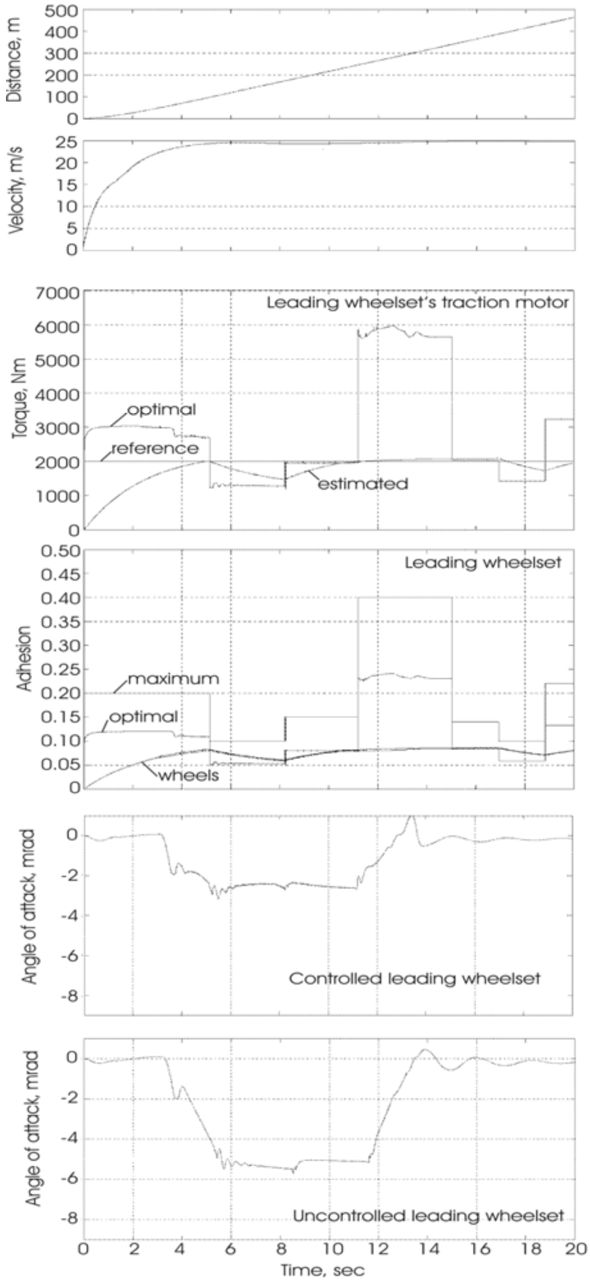

Fig. 9. The results obtained for a railway vehicle under different adhesion conditions from Simpack and MATLAB/Simulink co-simulation

ACKNOWLEDGMENT

The authors wish to acknowledge our debt to all people who have contributed their guidance and expertise in preparing this paper. The support of colleagues and supervisors from East Ukrainian National University named after Volodymyr Dal is also gratefully appreciated.

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МОДЕЛИРОВАНИЕ УПРАВЛЯЕМОГО КОЛЕСНО-МОТОРНОГО БЛОКА ДЛЯ ТЕЛЕЖКИ РЕЛЬСОВОГО ТРАНСПОРТНОГО СРЕДСТВА, ОСНОВАННОГО НА СПЕКТРАЛЬНОМ АНАЛИЗЕ ШУМА

Максим Спирягин, Валентин Спирягин, Ирина Костенко

Аннотация. В этой работе исследуется система управления железнодорожного транспортного средства объектом регулирования и управления являестя комплекс мехатронных систем управляющих колесномоторным блоком.Управление динамическими и тяговыми характеристики железнодорожного транспортного средства основываются на анализе спектра шумовом контакта колеса и рельса для содействующего фрикционнгого состояния. В статье, мы предлагаем комбинируемую управляющую систему с двумя стратегиями управления. Первая стратегия управления использует контроль и управление сцеплением колеса и рельса, позволяет определить максимальный тяговый вращающий момент, основанная на оптимальной силе сцепления между колесами железнодорожного транспортного средства и рельсами в зависимости от вертикальной нагрузки передаваемой от колеса к рельсу,фрикционных условий в контактной зоне, боковое смещения колеса относительно рельса и скорости скольжения. Вторая стратегия управления позволяет регулировать положение колесной пары относительно пути, посредством действий актуаторов установленных в буксовой ступени подвешивания в зависимости от анализа шума в контакте колеса и рельса. Для имитационной модели предложенной механической системы был использован пакет программ нелинейного моделирования Simpack . Предложенная стратегия управления моделировалась в Matlab/Simulink. Модель Simpack связывлась с устройством управления в Matlab/Simulink посредством SIMAT-interface. В результате чего иследовалась совместная работа двух стратегий управления транспорнтным средством.

Ключевые слова: Динамика рельсового транспортного средства, мехатронная система, конроллер нечеткой логики, тележка, модель силы сцепления, актуатор, устойчивость, система упраления направлением движения, интегральный контроллер, шум качения, микропроцессорная управляющая система, моделирование, модель локомотива