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ACTIVE STEERING CONTROL SYSTEM OF A RAIL VEHICLE BASED ON FUZZY LOGIC AND THE ANALYSIS OF THE SOUND RADIATION

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Summary: The object of this investigation was to design, develop and simulate a fuzzy logic controller for an active steering control system of a rail vehicle. The active steering railway bogie is built upon the application of axle boxes with links and actuators inclined to the longitudinal axle of bogie in the horizontal plane. Actuator actions depend on analysis of noise in the wheel-rail contact. The simulation of the proposed system was performed using Matlab/Simulink and Simpack software products. The obtained results of simulations with a locomotive model running in a curve show the possibility of the application of the proposed design for new rail vehicles and locomotives produced earlier, which have running gear based on Alstom designed constraints.

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

INTRODUCTION

Dynamics of rail vehicles has been significantly improved during last years by means of implementation complex mechatronic systems. These systems are designed to improve the tractive forces and characteristics of adhesion between wheel and rail on straight and curved parts of track. The behavior of locomotive running in a curve is more complicated because the lateral forces are appeared between a flange of wheel and head of rail in the contact zone, and the values of wheel slip are higher than for straight parts of track. These two factors are the main reason of wheel wear. To solve this problem and to improve vehicle dynamics, the steering systems have found application.

According to research [1], steering ability provides improvements of the contact conditions, increases the contact area between a wheel and a rail, decreases lateral forces and reduces wear more than two times.

More effective steering strategy is based on active steering. Control methods, which allow for provision of steering, can be classified in different ways. For an example, a very good review and analysis in the field of active steering control systems for railway vehicles was made by R.M. Goodall and T.X. Mei. According with this review, the active steering system is divided into five groups [2]:

- Stability control - solid-axle wheel set,
- Stability control - independently rotating wheel set,
- Steering control – solid-axle wheel set,
- Guidance control - independently rotating wheel set,
- Integrated control design.

Searching for the best performance, some scientists propose different approaches, but it can be useful for the development of new units of railway vehicles. For an example, the paper [3] proposes a variant for steering high-speed provided steering and stability controls by means of two AC motors acting through gearboxes, from which steering linkage mechanisms transfer the control action to the wheelsets.

However, a large number of locomotives produced earlier still work for operation services. This paper describes proposals for the improvement of tractive and dynamics characteristics of such railway vehicles by means of modernization of their running gear and the application of active steering system, which is possible to develop by means of the last experimental and theoretical investigations of noise in the contact between a wheel and a rail.

The paper is based on theoretical and experimental investigation in this field and contains the necessary background for the creation of active control for the wheelset steering, which is included a fuzzy logic controller for getting a desired performance.

OBJECT AND PROBLEMS

Mechanical System

The mechanical system based on Alstom designed constraints, where the radius links are positioned on different levels in an anti-parallelogram, which has found world-wide application [2], is used for our investigation.

The theoretical and experimental investigation described in [4] shows that more effective results can be reached in case of the use of inclined links to the longitudinal axle of bogie in the horizontal plane. The effectiveness of this installation of the radius links was confirmed with an experiment on a real locomotive [1]. The obtained results shows the possibility to attain a reduction of the angle of attack for wheelset in curved parts from 8 to 15 percent for the angle of installation of radius links equaling 8 degrees. The locomotive shows stable character of movement for the entire velocity range.

However, to enhance the steering ability of a railway vehicle, it is better to install dual direction actuators on a bogie, because if the angle of steering is not enough then actuators could transfer additional displacements to axle boxes in two directions.

Based upon the above, we proposed a decision for the active steering of wheelsets on curved track, which is shown in Fig.1 and Fig.2. Several design ideas are being explored to a development of a bogie with the better performance. One of the similar design constructions was applied for the three axle bogie [5].

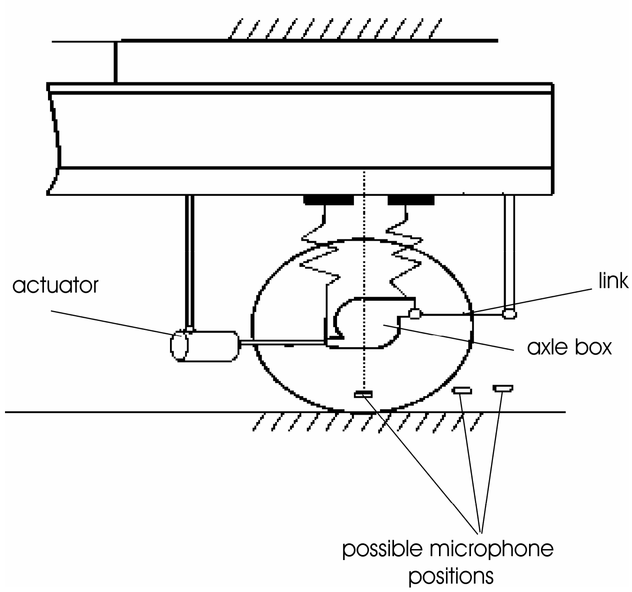

Fig. 1. Side view of the part of the bogie with an actuator

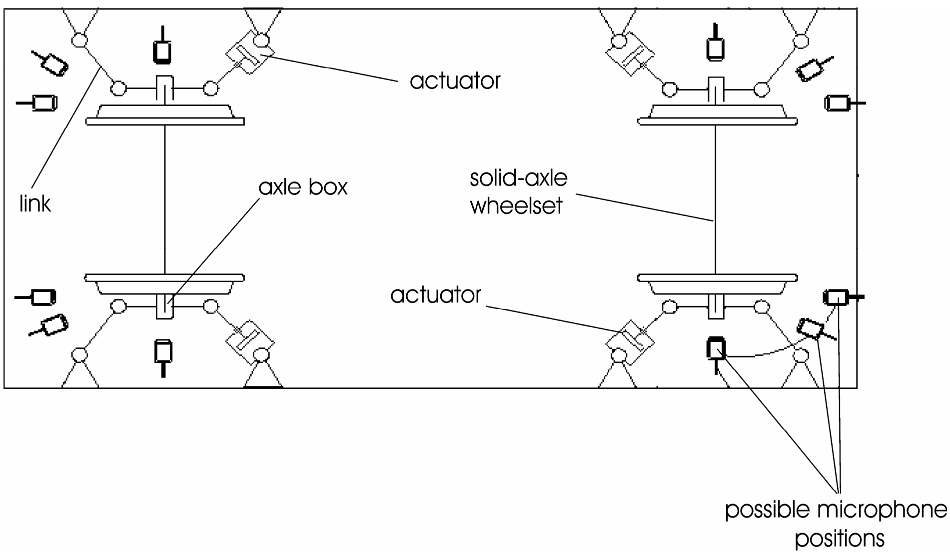

Fig. 2. View from above of the bogie with actuators for active steering

Wheel- Rail Noise

A large number of research works are being done for the detection and simulation of noise for railway transport at the present time.

Wheel-rail noise can be divided into four groups [6]:

- Rolling noise,
- Impact noise,
- Squeal noise (noise depends on the lateral displacement of the wheel relative to the rail),
- Flange noise (noise is present when the wheel flange has a contact with the rail head).

The application of noise analysis provides a good possibility for the creation of complex mechatronic systems. For example, the analysis of rolling noise between wheel and rail can be used for adhesion control system [7] and the flange noise for the application of a lubrication control system [6].

In our case, the situation with noise analysis for vehicle's movement on the curved part of track is more complicated. Recently, the papers in this research area were published. The publication [8] describes theoretical and experimental investigation for developing a complete, validated model of curve squeal noise generation accounting for friction characteristics, excitation due to unstable forces between the wheel and rail and vehicle dynamic behavior. This investigation was performed with the twin disc rig. The analysis confirms that noise levels are different and depend on yaw angle for different adhesion coefficients. On the basis of the analysis of the power spectral density of the lateral acceleration of the rollers and the sound pressure level, authors of that investigation made classification of the sound radiation as follows:

- Wheel and rail rollers are stable, no squealing: less 80 dB(A);
- Wheel and rail roller vibration increased, rail response is larger than wheel, the rail mode at 1490 Hz is predominant in the sound radiation, ringing: 80~90 dB(A);
- Wheel roller is unstable and response is much larger than that of the rail roller, the wheel mode at 1090 Hz is predominant in the sound radiation, squealing: 90~110 dB(A).

Also, the obtained results of experimental investigation in publication [9], show that squeal sound pressure amplitudes emitted by undamped wheels increase in direct proportion to rolling speed and to angle of attack, and curve squeal disappears when the wheel flange is in contact with the rail. The dependences between sound pressure level and the angle of attack, obtained in this investigation, is plotted in Fig. 3.

However, the authors of experimental investigation [10], where the set of real measurements of squeal noises in curves was taken from railway vehicles, made a conclusion that the same noise can be identified only for the same models with specified design characteristics.

Based upon what is written above, it is possible to develop an active steering control system that allows accounting for the adhesion contact characteristics depending on noise analysis in the rail-wheel contact.

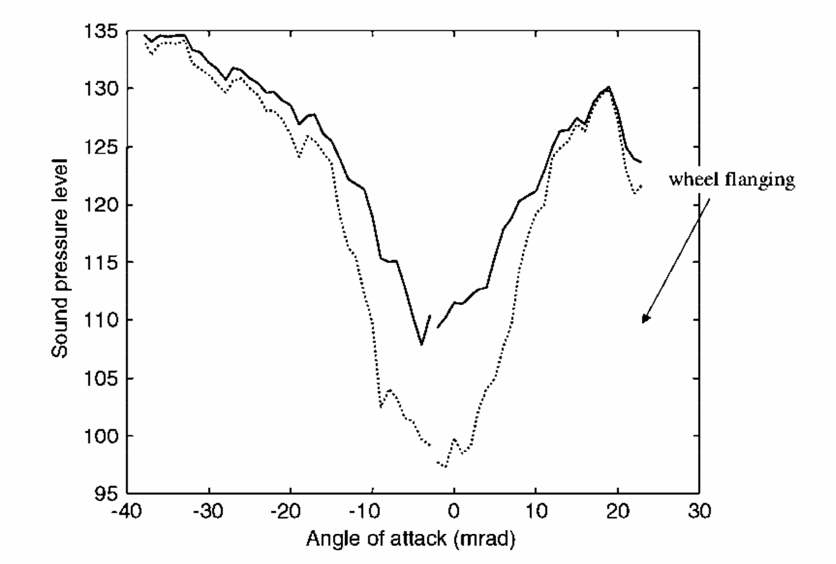

Fig. 3. Sound pressure level versus angle of attack for rolling speed 20km/h
(— overall level 0–10Hz; --- overall level 1.6–1.8Hz) [9]

Control System

The proposed design of the axle box with the link and the link-actuator allows for automatic setup of the wheelset with some initial angle. This initial steering angle depends on many factors, but most important is a centrifugal force. Here, it is necessary to say that the obtained steering angle is still not an optimal solution, because in this stage only the passive mechanical steering works. Therefore, it is possible to apply a variant for control systems, which will adjust the steering angle to the optimal steering angle for the current track curvature by means of actuators.

According with the publication [2], for an ideal active steering it is required to achieve equal longitudinal creep between the wheels on the same axle (or zero force if no traction/braking) and equal creep forces in the lateral direction between all wheelsets of a vehicle. It can be readily shown that the perfect steering can be achieved if the angle of attack for two wheelsets (in addition to the radial angular position) can be controlled to be equal and the bogie to be in line with the track on curves. It is possible to do, if make a control of the position of each actuator, such that the wheelset forms an appropriate steering angle with respect to the bogie.

However, as one can see in Fig. 4, in the real work conditions, it is almost impossible to reach the required equality only by means of an appropriate steering angle with respect to the bogie. According with publication [1], the angle of attack is a one of main parameters, which has a big influence on wear process. Therefore, authors propose an improved control system, compared with a previous one published in [11]. The proposed variant is based upon noise spectrum analysis in the wheel-rail contact and using GPRS and GPS technologies.

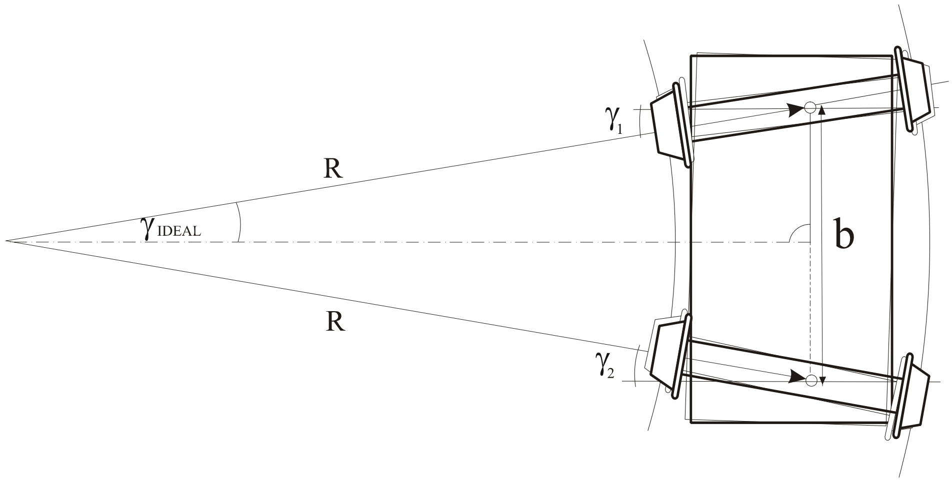

Fig. 4. Bogie on the curving part of track

The block scheme of the proposed microprocessor control system for a railway vehicle is shown in Fig. 5.

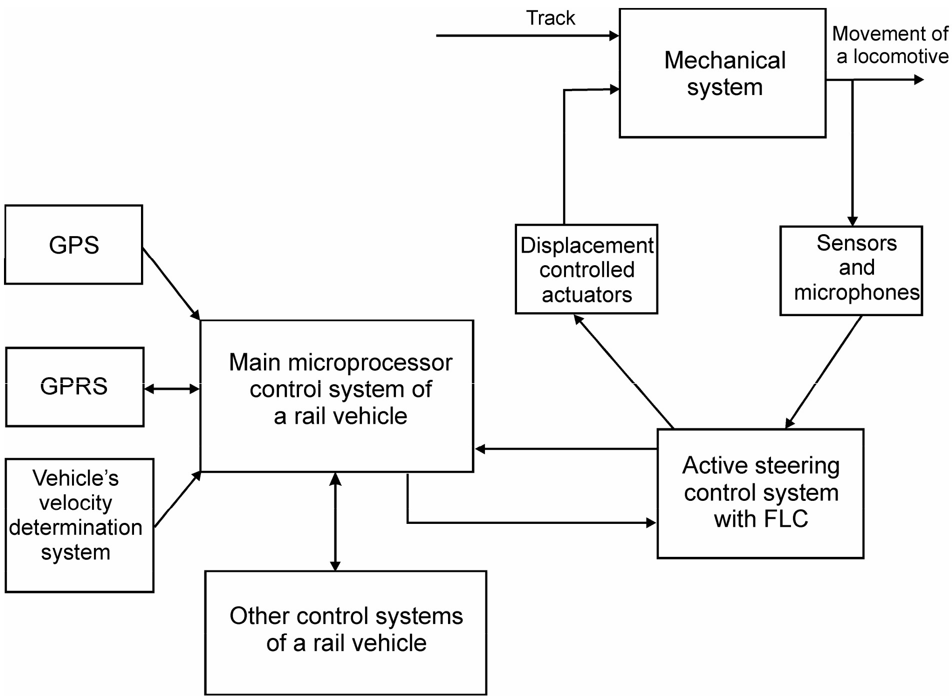

Fig. 5. Microprocessor control system of a rail vehicle

The detection of the angle of attack is based upon noise spectrum analysis in the wheel-rail contact and using GPRS and GPS technologies. GPS satellite system is used for obtaining a 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 proposed active steering control system is presented in Fig. 6. As one can see, the control system consists of the controller and the observer. Observer collects all information from sensors and microphones, and processes it and gives the optimal and the estimated steering angles as outputs. After that, the values of angles are received by the feedback controller.

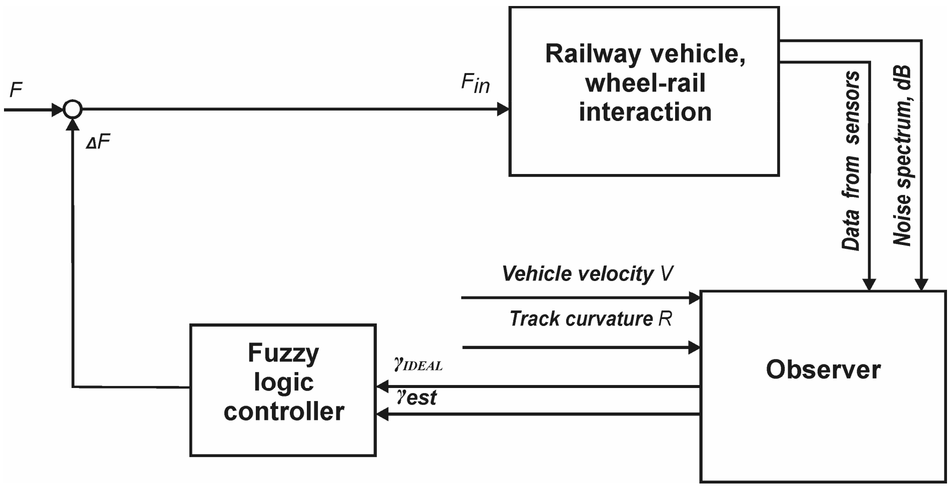

Fig. 6. Block diagram of the active steering control system.

The radius of the track curvature R is known now by means of using GPS/GPRS technologies and the ideal steering angle γ_{IDEAL} (Fig. 4) for the wheel set can be calculated with the following equation:

$$\gamma_{IDEAL} = \arcsin\left(\frac{b}{2R}\right), \tag{1}$$

where: b is the distance between the leading ant trailing axles.

The noise in the contact zone are picked up by using a microphones provided near each wheels of bogies. The obtained noises are processed by a special algorithm to obtain a sound pressure level of a certain frequency band. By looking up a special database data, received from experimental and theoretical research, the dependence between the sound pressure level, vehicle velocity V, relative slip, the lateral displacement and the angle of attack ψ can be obtained.

The estimated steering angle γ_{est} (in our case, γ_1 and γ_2 for each wheelset) can be calculated by means of the equation obtained from [12]:

$$\gamma_{est} = \psi - \frac{y_1 - y_2}{b} + i * \cdot \frac{b}{2R}, \tag{2}$$

where: y_1, y_2 are the lateral displacements of wheel sets; $i^* = 2i - 3$ (for the leading wheel set i=1 and for the trailing one i=2).

The control law is based on a simple feed-back control and can be represented as the following equitation:

$$F_{in} = F + \Delta F, \tag{3}$$

where F is the initial control force given to the wheel set from the actuator. The value of the initial control force F at the starting moment of locomotive movement on a curved part of track can be obtained by looking up a special database data, received from theoretical research. In this case, one has the dependence between the track curvature R, vehicle velocity V and initial control force F. After that, we suppose that next values of *F(t)* should be equal to *Fin(t-1).*

The corrective actuator force ΔF can be obtained by means of fuzzy logic controller. Therefore, in the following section, we will provide more detailed information to illustrate the development of the fuzzy controller, including the necessary data for the membership functions.

RESULT OF EXPERIMENTAL RESEARCH

I. Active Fuzzy Logic Controller

The approach that we propose to use for a development of a fuzzy logic controller based on appropriate input and output variables, which were decided upon. Using the analysis of our mechanical systems and numerical simulation techniques, we found that the optimum choice for state variables is the difference between optimal and estimated steering angles of wheelset. The output of the controller is the corrective force of the actuator ΔF.

We chose triangle and trapezium shapes for membership functions in our controller because they are very basic and widely applied. The group of linguistics variables was used for the both input and output variables. This group includes N and P stand for negative and positive values, S, M and B means small, medium and large values, and ZE means zero. The membership functions used for the controller are illustrated in Figs. 7 and 8. The range of values for difference of angles for these membership functions were obtained from analysis of mechanical design constraints. The fuzzy rules are shown in Table 1.

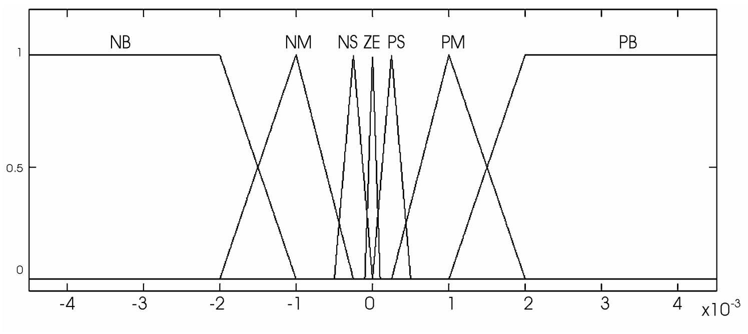

Fig. 7. Initial input membership function of the difference between estimated and optimal steering angle

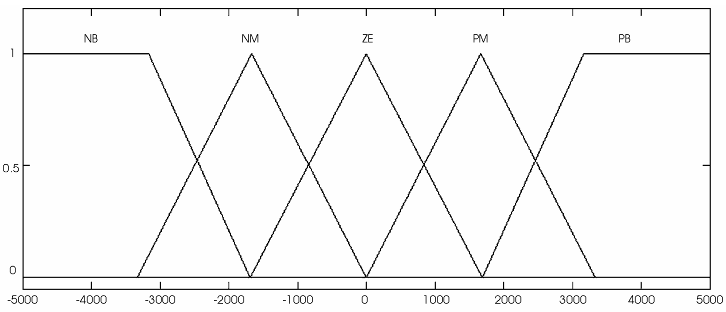

Fig. 8. Output corrective force membership function

Table 1. **The Set of Rules for the Controller**

	$\gamma_{IDEAL} - \gamma_{est}$						
	NB	NM	NS	ZE	PS	PM	PB
ΔF	NB	NB	NM	ZE	PM	PB	PB

II. Simulations

Advances in technology and modeling in specialized software products for the rail transport industry make possible highly accurate simulation of a rail vehicle. Therefore, the test of the proposed active steering control system was completed by means of a simulation on a tractive unit of a rail vehicle DEL-01. This vehicle is produced by Holding Company “Luganskteplovoz” in Ukraine. The tractive bogie of DEL-01 was modernized according to the proposed design in Section 2.

For the generation of the simulation model the non-linear MBS software package called Simpack has been used. The proposed control strategy was modeled in Matlab/Simulink.

The Simpack model of the vehicle 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.

In our implementation of the simulation process, we chose to apply the blocks allowed simulating a real environment and sensors. For example, the values for the angle of attack ψ depending on noise in Equation 2 for the contact zone were taken from the Simpack model. Also the GPS/GPRS technology was used the method described in [13]. Based on that method, the curvature radius was obtained from the following equation:

$$\frac{1}{R} = \frac{\Omega}{V}, \tag{4}$$

where: Ω is yaw rate of the bogie in the track, the measurement of the yaw rate is smoothed by means of low-pass filter.

The estimated rail curvature is plotted on Fig. 9.

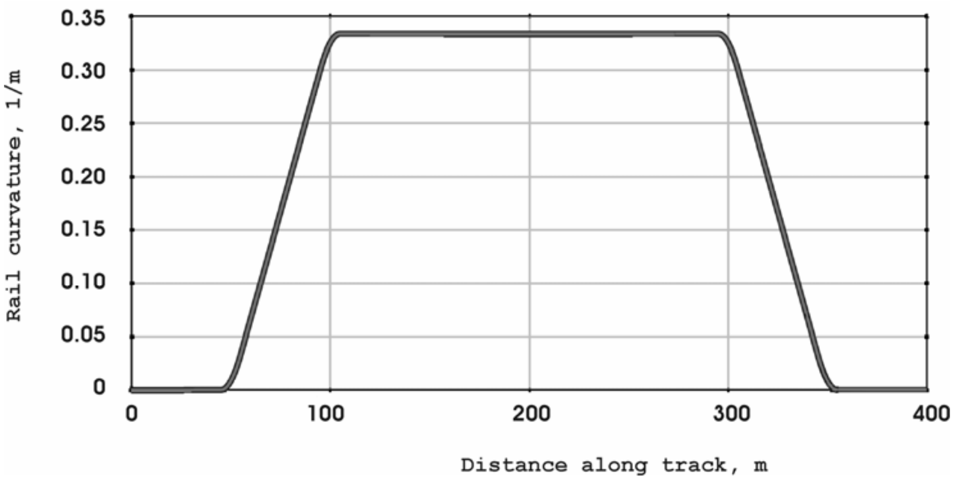

Fig. 9. Estimated rail curvature

The simulations were made for two types of design for the diesel-train DEL-01. Fig. 10 shows the obtained results of angles of attack and lateral displacements for the leading and trailing wheelsets as a function of the distance for the uncontrolled mechanical system and the controlled mechatronic system.

As we can see, the angles of attack for leading and trailing wheelsets are almost equal, and it confirms that the proposed control strategy can provide the satisfactory work.

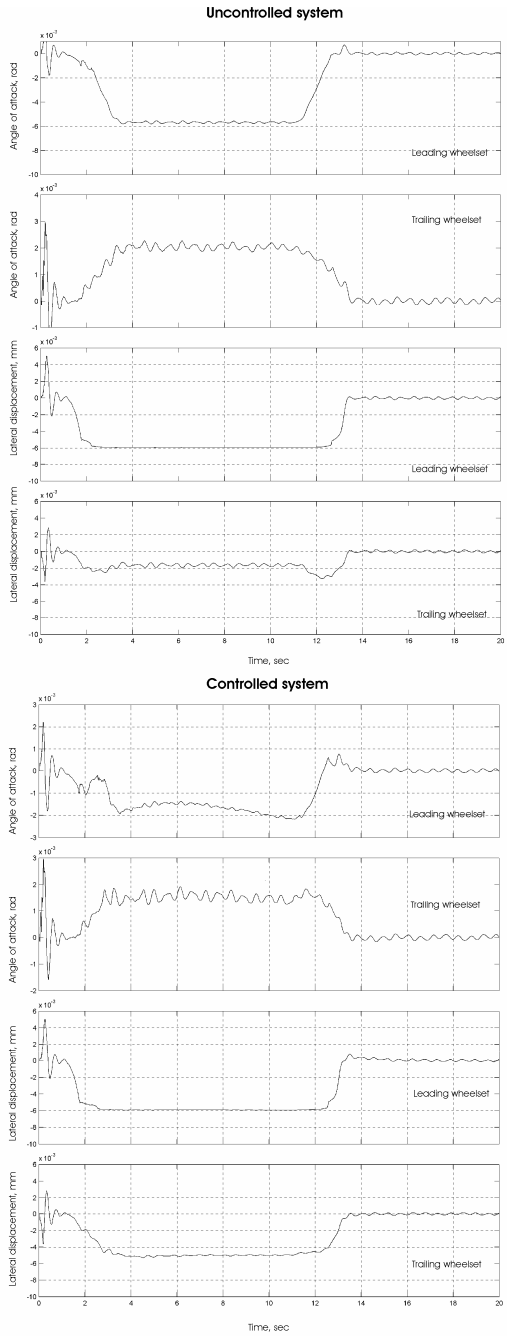

Fig. 10. DEL-01 vehicle simulation results (R=300 m, V=90 km/h)

CONCLUSION

In this paper, we outlined an approach to the development of an active steering control system for a bogie of a rail vehicle. As a result, we got the mechatronic system with two control strategies. First one is the passive mechanical steering control system, which allows for the automatic setup of the wheel set with some started steering angle, which is dependant on the centrifugal force. The second one is based on the application of actuators and makes possible to adjust the steering angle to the optimal value. In this case, the active steering control system works depends on data obtained from noise analysis.

We have implemented these concepts for a rail vehicle DEL-01. The system evaluation of the proposed system with the fuzzy logic controller has been performed by means of co-simulation in Simpack and Matlab/Simulink software. Results of the simulation include data of angles of attack and lateral displacements for both wheelsets of a traction bogie, and show a possibility of the use of the proposed control system for running gear of existing and new locomotives.

The ideas described in this paper can be further pursued to improve rail vehicle dynamics. It should be noted that a more detailed study and theoretical and experimental investigation on the dependence of the angle of attack from noise in rail-wheel contact for different service and friction conditions are needed for the correct working of the system in real conditions.

Finally, we should say that our proposed system of a locomotive has a room for further improvements.

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АКТИВНАЯ СИСТЕМА РАДИАЛЬНОЙ УСТАНОВКИ КОЛЁСНЫХ ПАР РЕЛЬСОВОГО ТРАНСПОРТНОГО СРЕДСТВА, ОСНОВАННОЕ НА НЕЧЕТКОЙ ЛОГИКЕ И АНАЛИЗЕ ЗВУКА

Спирягин М.И., Спирягин В.И., Ульшин В.А.

Аннотация. Объектом исследования является проектирование, совершенствование и моделирование работы устройства нечеткой логики для управления системой принудительной установки колесных пар тележек рельсового транспортного средства. Мехатронная тележка использует буксовые узлы с наклонными поводками и актуаторами, которые горизонтально наклонены к продольной оси. Моделирование предложенной системы выполнялось с использованием программных продуктов Matlab/Simulink и Simpack. Полученные результаты моделирований движения локомотива в кривой показывают возможность применения предложенного решения как для новых рельсовых транспортных средств, так и для локомотивов, которые производились ранее и спроектированы на основе решения компании Alstom для буксового узла.

Ключевые слова: динамика рельсового транспортного средства, мехатронная система, контроллер нечеткой логики, тележка, привод актуатора, контроль устойчивости, контроль установки, объединенное управление, шум качения, звуковое давление, моделирование, модель локомотива.