The reduction in force interaction of wheel with the rail in the curves by means of the automatic control over the locomotive wheel pair position

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S u m m a r y . The paper deals with the question of reduction in force interaction of wheel with the rail in the curves by means of the automatic control system (ACS) over the locomotive wheel pair position, using an acoustic method for determining the attack angle and the navigation systems of the motion direction.

Acoustic method of control over the wheel attack angle on the rail has been chosen and investigated.

The locomotive bogie design has been improved and the simulation model of the locomotive motion with the improved bogie design with regulated axlebox with the axial formula 3o-3o has been further developed, taking into account the automatic control system dynamics with the position of wheel pair in a horizontal plane.

Automatic control system over the wheel pair position in the straight and curve sections of the track has been developed.

The theoretical research and the comparison with the experimental data of dynamic processes, occurring in the mechanical part of the serial locomotive and the improved locomotive bogie design when moving in the curve sections of the track have been done.

K e y w o r d s . locomotive, attack angle, automatic control system, acoustic emission, force interaction.

INTRODUCTION

In terms of modern exploitation of the existing rolling stock there is a problem of intensive wheel flange wear of the wheel pair band related to the force interaction of a wheel with a rail [29, 11, 15, 18]. That's why a task related to the estimation of bogie design influence on the quality of motion that supposes: diminishing of the force effecting on the railway, wear of wheels and rails, environmental influence, increase of safety and stability of motion, comfort.

It has theoretically and experimentally been established that 80 % reasons of wheel pair band damage takes place because of rolling stock design imperfection and about 20 % – on reasons depending on the condition of a railway [25, 12, 4].

The solution of the given problem is connected with the creation of a basically new carriage design. The reduction in force interaction, the improvement of dynamic indicators in the curve and the diminishing of intensity of locomotive band flange and rails wear is possible by means of improving the control system of a position of wheel pair in rail track [11, 16, 9].

RESEARCH ANALYSIS

In spite of a large amount of the theoretical and experimental work on research

of a motion of locomotive in the curve, the definition of the wheel attack angle on a rail is not enough studied, and the main difficulties in research of wheel attack angle on a rail lies in the absence of information about actual wheel attack angle on a rail [19, 8, 13].

The main requirements presented to the new locomotives are the increasing of motion safety and the diminishing of the level of the dynamic influence on a railway. The main influence a locomotive is on the railway when passing a curve, that is accompanied by the increased degree of wheels and rails wear [26, 1].

The perspective direction of decrease in the intensity of wear in the system a "wheel-rail" is the application of rational designs of the carriage part of the locomotives, supplemented by the system of active control of a wheel pair turn when moving at curve [18, 2, 21].

To determine the method of control of a wheel pair position in the track, it is necessary to know the characteristics of the controlled object and disturbances entering the controlling device.

A great attention is devoted to the theoretical and experimental research due to the complexity of the processes taking place in the curve [3].

RESEARCH OBJECT

The research object is the radial setting of the locomotive wheel pair when moving.

The research subject is the automatic control system of the radial setting of the wheel pair when moving in the curve sections of the track.

The main objective: a decrease of force interaction of a wheel with a rail when moving the locomotive at curve through the automatic control system of the position of a wheel pair on the basis of acoustic method for determining the angle of wheel-rail attack and the navigation system of determining the curve direction for this section of the track.

The objective mentioned above has proved the necessity to solve the followings scientific tasks:

1. The choice of the method of control over the position of the wheel pair in the rail track.

2. The choice and the research of the control method of the wheel pair angle attack on the rail.

3. The improvement of locomotive carriage design and the development of mathematical model of locomotive motion with the axial formula 3o-3o with an active control system over the position of the wheel pair in a horizontal plane on the straight and curve sections of the track.

4. Theoretical research of the dynamic processes occurring in the mechanical part of the locomotive and in the "wheel – rail" contact when moving in the curve sections of the track.

5. The development of the automatic control system of the wheel pair position in the straight and curve sections of the track.

On the basis of scientific and technical information analysis it is determined that the dynamic properties of the carriage in the horizontal plane and lateral band flange wear of the wheel and head of the rail depend on the wheel attack angle on the rail, state of the carriage part of the locomotive, on which it is possible to influence effectively by means of the rational choice of the locomotive carriage design. Carriages with the passive setting of the wheel pair tend to increase undulation in the straight sections of the track and it does not allow the radial setting of the wheel pair when moving on the curve sections of the track [7].

A turning device with the unrevolved axis has got a great distribution on the railway transport, which does not provide control on the curve sections of the track and has no control of the wheel pair turn in a horizontal plane.

One of the methods to reduce the horizontal transversal effect on the railway carriage on the curve sections of the track is the controlled wheel pair motion [15].

It has been theoretically and experimentally proved that traditional solutions and passive methods have been exhausted, and the further solution of the task to reduce the force interaction can be carried out by means of the application of active methods of control. The algorithm of work of such a control system consists in that when moving on the curve an executive device turns the wheel pair in a horizontal plane in the rail

track to minimize the wheel attack angle on the rail [6].

To solve the task of reducing the resistance motion, wear of wheels and rails is possible due to the further improvement of the existing design of the locomotive carriage part with supplementing it with the active control system of the position of the wheel pair in the rail track. The controlling influence on the carriage on the curve sections of the track opens new quality possibilities of improvement of the curve dynamics, provides the reduction in the dynamic influence on the track. The existing control systems of radial setting of the wheel pair do not provide the control of the wheel attack angle on the rail, because of complex measurements and the absence of the adequacy of the obtained measurements of this parameter [15].

The lack of the existing systems of the wheel pair turn in a horizontal plane is absence of the automatic control system of the wheel pair position in the rail track.

It is reasonable to create the fast-acting system of active control over the position of the wheel pair in the rail track in the curve section of the track not from the side of the operative parameters of the motion, but taking into account the control over the wheel attack angle on the rail and the direction of moving.

The duration of the transitional process must not exceed the time of the transitional curve passing by. According to the norms of the speeds allowed on the passenger transport, the minimum time of passing transitional curve (at $a_H = 0,7$ m/s^2) is 0,36 seconds [28].

The automatic control system (ACS) of the position of the wheel pair in the rail track must guarantee:

- stabilization of the wheel pair motion in the rail track when it's moving on the straight sections of the track,

- controllability and uniqueness.

A functional block of the control system over the wheel pair position in the rail track has been shown on Fig. 1.

The automatic control system over the position of the wheel pair contains a controlled object, measurement block, computing device and executive block.
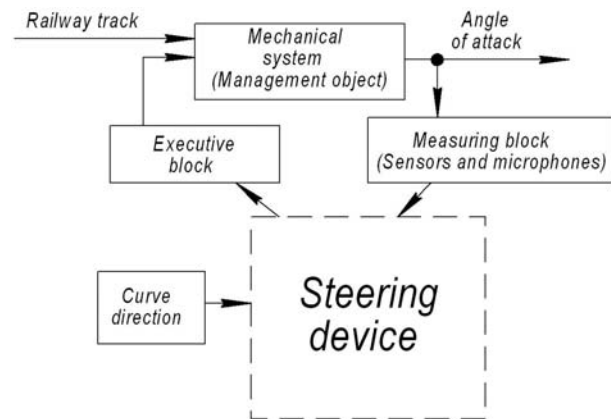

Fig. 1. A functional block of the guided motion of the wheel pair in the rail track

A measuring block contains the sensors of the wheel attack angle on the rail.

The functions of the controlling device are data processing received from sensors, formation of the controlling effect on the regulator fed to the executive mechanism.

A controlling device forms a controlling effect for the wheel pair turn in a horizontal plane in the rail track on the angle at which the reduction in the force interaction of band flange of wheel with the head of the rail is provided, which is done due to the minimization of the wheel attack angle on the rail.

A regulator must provide the required values of the transitional process time (t ≤ 0,36 seconds) without overcorrection [28].

One of the difficult problems when designing the ACS is how to get information about wheel pair attack angle on the rail.

The existing methods of determination the wheel attack angle on the rail without setting a stationary sensor on the groundwork use the indirect measurements to calculate the attack angle and do not allow to measure the wheel attack angle on the rail automatically.

The investigation of the mechanism of the acoustic emission generation in a contact wheel-rail has been executed when moving the locomotive with the purpose to ground the possibility of using the acoustic emission from a contact wheel-rail to determine the wheel attack angle attack on the rail.

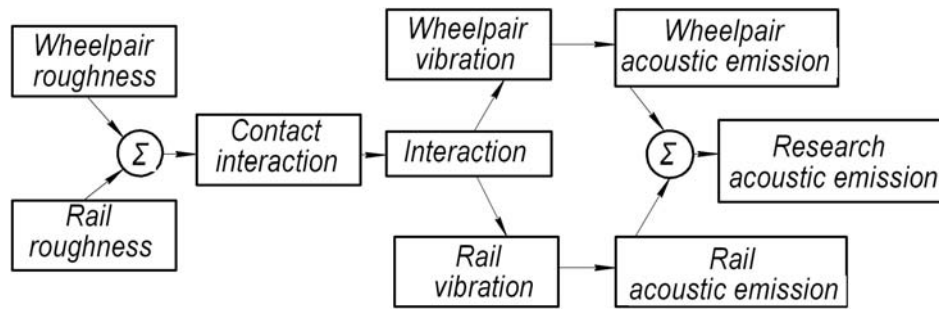The scheme of acoustic emission formation has been shown on Fig. 2.

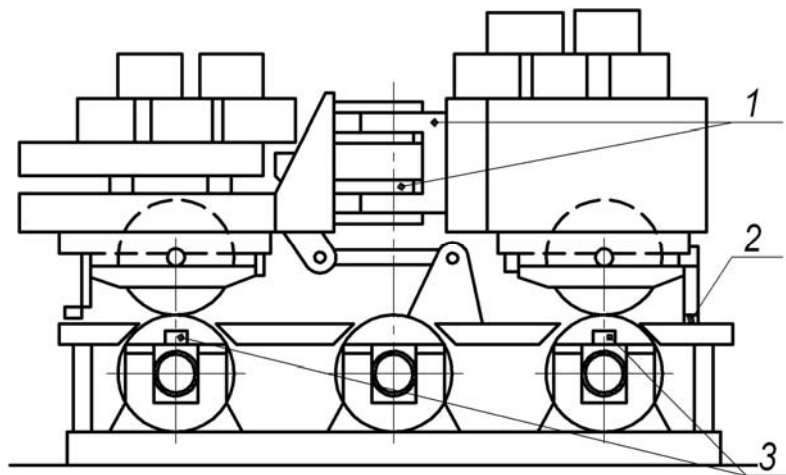**Fig. 2.** Scheme of acoustic emission formation from a wheel-rail contact

Fig. 3. Scheme of experimental carriage on the rolling bench: 1 – coupling bolt of semi-carriage, 2 – guide device with sensor of efforts, 3 – sensor of the lateral displacement

The possibility of determination the wheel attack angle on the rail has been grounded by the acoustic emission method, which was estimated by means of the experimental research.

Experimental research was conducted at the model rolling station (Fig. 3), experimental bench and diesel locomotive 2TE116.

It has been experimentally proved that the spectrum of acoustic emission is not equal, on some frequencies the level of the sound pressure exceeds the equivalent level of the sound pressure considerably.

The results of program processing of acoustic emission from a wheel-rail contact are presented on Fig. 4.

According to the experimental research data, an informative feature has been discovered on the basis of acoustic emission from a wheel-rail contact, and experimental dependence of the sound pressure level deviation has been obtained on the dominant frequency from the equivalent level of sound

pressure at different wheel attack angle on the rail.

In the range of frequencies from 200 to 300 Hertzs, there is a maximal deviation of sound pressure level from the equivalent level of sound pressure. By the size of a maximal deviation from the equivalent level of sound pressure on the indicated frequencies, it is possible to measure the wheel attack angle on the rail.

The functional dependence of sound pressure level from the attack angle on the dominant frequency of acoustic emission (AE) has been used for determination the wheel attack angle on the rail when forming the controlling effect of hydrocylinder on the wheel pair of locomotive when moving on the curve section of the track.

The determination of dominant frequency of AE from a a wheel-rail contact has been executed by means of the algorithm signal processing using wavelet-transformation with the use of wavelet-
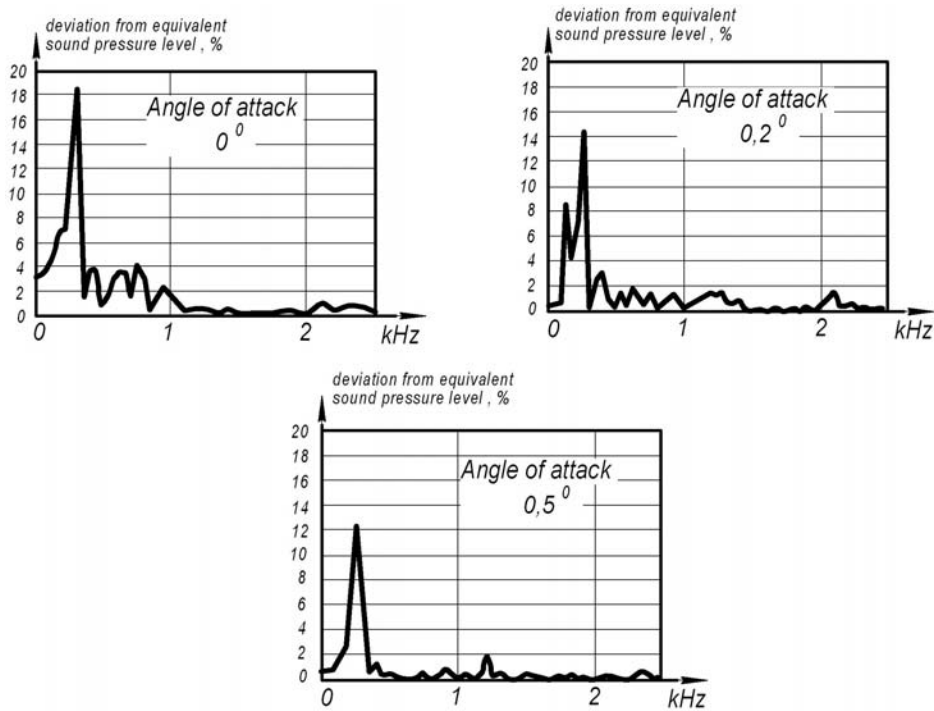
Fig. 4. Spectral analysis of acoustic emission from a wheel-rail contact at the speed of 15 m/s and different wheel attack angles on the rail

function $W_f(t,a)$ for the different moments of time t. From the statistical data of sound pressure level depending on the wheel attack angle on the rail, has been executed neuro-fuzzy adaptation on the basis of which a set of rules and a surface for determination of the wheel attack angle on the rail has been obtained [5].

To get the digital sequence, the wavelet-transformation using the wavelet-function $W_f(t,a)$ for the different moments of time t has been done [29].

Wavelet -transformation:

$$W_f(t,a) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} \Psi(\frac{x-t}{a}) \cdot f(x)dx, \quad (1)$$

where: $f(x)$ – is the research signal
$\Psi(x)$ – it is a wavelet-function,

$$\Psi(x) = (\cos x + i \cdot \sin x) \cdot e^{-\frac{x^2}{50}},$$

where: t – is the time
a – is a scale of wavelet-function.

A frequency spectrum is obtained by means of processing the acoustic emission signals according to the Furie algorithm of rapid transformation.

The determination of direction on the curve section of the track seems reasonable by sharing the satellite navigation and inertial system.

Joint processing of the calculated coordinates has been carried out by the synchronization of signals from a satellite receiver and inertial block. The increase of exactness has been provided due to the suppression of errors in the each system [24].

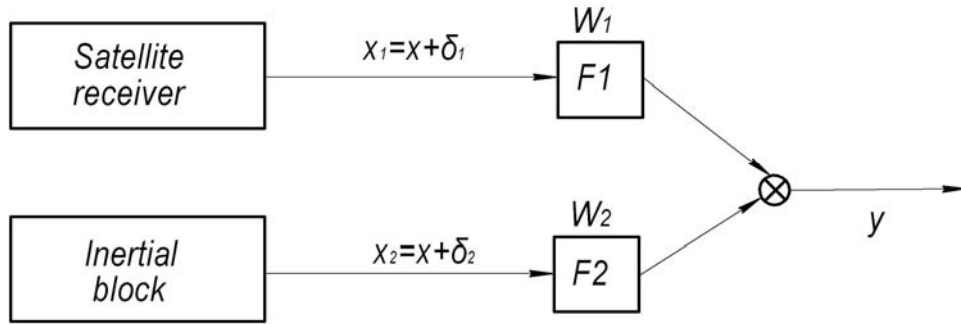The scheme of complexion joint work of the satellite receiver and inertial block has been presented on Fig. 5.

Fig. 5. Structural scheme of complexion: y – is a coordinate of the locomotive site, W1, W2 – are transmission functions of filters, F1, F2 – are filters, x1, x2 – is a representation of useful signal of x(t), ε1 and ε2 – is a representation of satellite receiver and inertial block errors
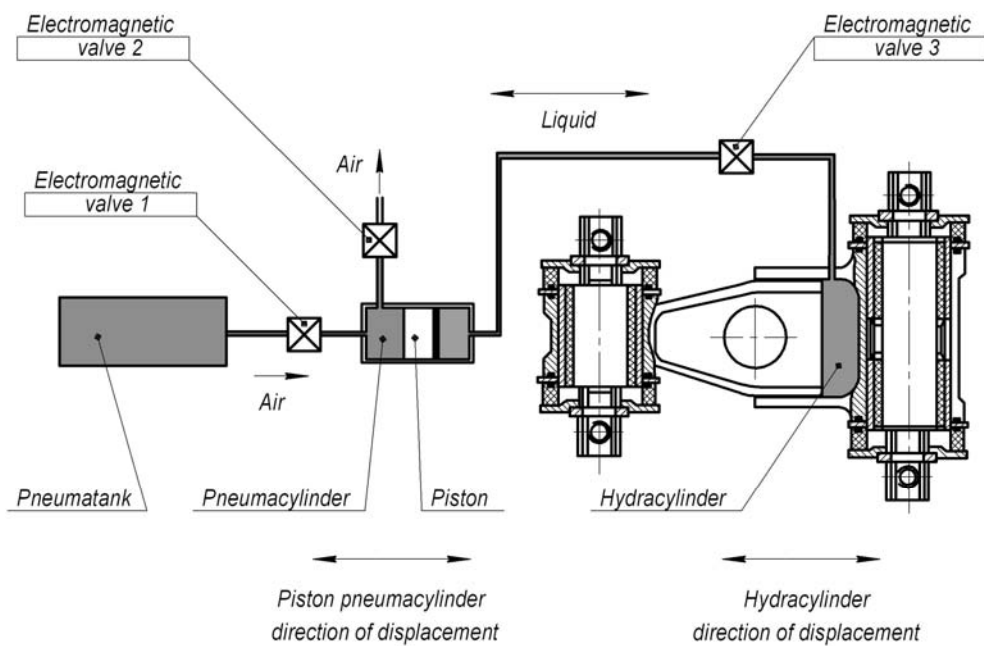

Fig. 6. Regulated length leash

$$y = (W1+W2)x + W1\varepsilon1 + W2\varepsilon2, \qquad (2)$$

$$\varepsilon1(t) = b + m \cdot \sin(nt), \qquad (3)$$

where: b – is a permanent part (constructive error),

m – is an amplitude of dynamic error,

m·sin(nt) – is a high-frequency constituent of error (dynamic error), n – is angular frequency of vibrations,

t – is the time

$$\varepsilon2(t) = r \cdot t. \qquad (4)$$

where: r – is the average speed of inertial block drift.

Principle scheme of the executive device is shown on Fig. 6.

Hydrocylinders are set on the utmost wheel pair of the bogie.

Structural scheme of the closed loop automatic control system with the position of the wheel pair in the rail track is presented on Fig. 7.

Transmission function of the closed loop system of $W_L(p)$:

$$W_3(p) = \frac{a_1 p + 1}{a_3 p^3 + a_2 p^2 + a_1 p + 1} \qquad (5)$$

where: $a_3 = \dfrac{T_1 T^2}{k_2 k_3 k_5}$, $a_2 = \dfrac{2\xi T_1 T}{k_2 k_3 k_5}$,

$a_1 = \dfrac{k_4}{k_3}$, $T = \sqrt{\dfrac{J}{c}}$, $\xi = \dfrac{b}{2 \cdot c}$, $k_5 = \dfrac{M_H - M_C}{c}$.
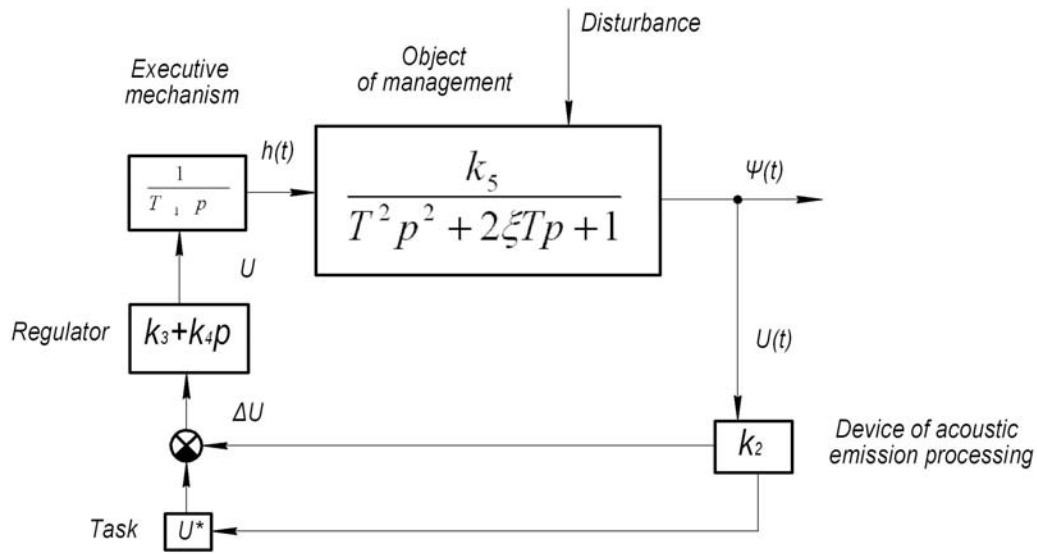
Fig. 7. Structural scheme of closed loop automatic control system of a position of wheel pair in rail track
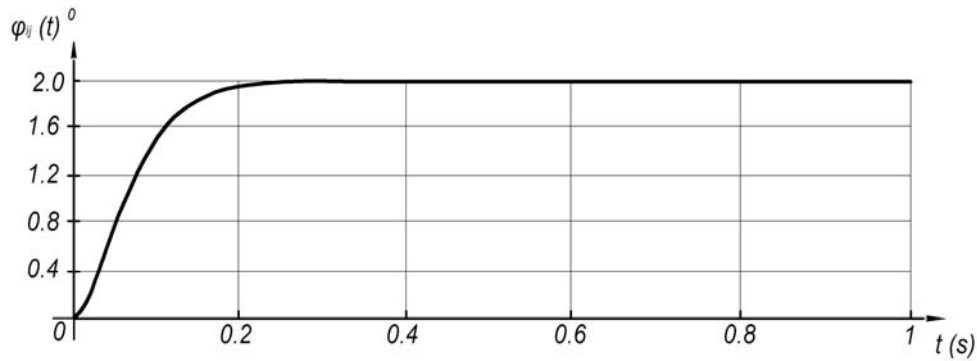

Fig. 8. Graph of transitional process of ACS when having the controlling effect

J – is a moment of inertia of the wheel pair, c, b – elastic and dissipative constituent of the spring suspension, M_C – is a friction forces moment at the turn of the wheel pair, M_H – is a moment of external loading, k_2 – is a sensor transmission ratio, k_3, k_4 – is a regulator transmission ratio.

RESULTS OF RESEARCH

With the parameters of the system: $T = 0,96$ with, $T_1 = 0,02$ with $k_2 = 2$, $k_3 = 5$, $k_4 = 4$, $k_5 = 2,7$, $\xi = 0,1$, a transitional function has been shown on Fig. 8. The analysis of the graph of transitional process shows that ACS is stable, transitional process has aperiodical character, the time of transitional process does not exceed 0,36 seconds [28].

The usage of the of automatic control system with the position of the locomotive wheel pair in a horizontal plane keeps the set attack angle of the wheel pair on the rail when moving on the curve sections of the track.

It has been experimentally proved that ACS provides the needed quality of regulation.

The attack angle of the wheel pair as to the bogie frame is determined by the differential equation [28]:

$$a_3 \frac{d^3\varphi_{ij}}{dt^3} + a_2 \frac{d^2\varphi_{ij}}{dt^2} + a_1 \frac{d\varphi_{ij}}{dt} + \varphi_{ij} =$$
$$= a_1 \frac{dM(t)}{dt} + M(t) \qquad (6)$$

where: M(t) is a difference of moment of friction forces during turning of the wheelepair and moment of the external loading, φ_{ij} – is a angle attack of the wheel pair.

A model contains twenty one nonlinear differential equation with changeable ratios which are determined on every step of the integration.

The mathematical model of the mechanical system of the improved locomotive bogie design has been executed on the diesel locomotive sample 2TE116, in the program package of Matlab/Simulink.

The developed simulation model of carriage motion allows to conduct the research of dynamics when moving on the track with random curves. The verification of authenticity of the results obtained and the research of dynamic processes has been executed both at controlled and non-controlled locomotive motion in the curve section of the track.

Theoretical research of the motion on the diesel locomotive sample 2TE116 in the curve section of the track has been executed from the initial data which comply with the parameters of the experiment.

The compared results of the simulated motion of serial diesel locomotive 2TE116 and the improved locomotive with the axial formula of 3o-3o on curve section of the track with the radius of 300 m and at the speed of 70 km/h has been presented on Fig. 9.

The theoretical values of the guiding efforts on the first wheel pair of the improved locomotive at the controlled and non-controlled motion have been shown on Fig. 10.
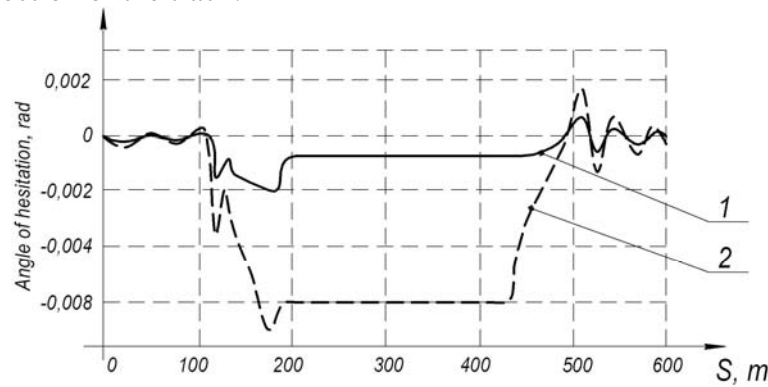

Fig. 9. Theoretical values of the wagging of the first wheel pair of diesel locomotive at controlled and non-controlled passing of the improved locomotive on the curve section of the track: 1 –controlled motion, 2 – non-controlled motion
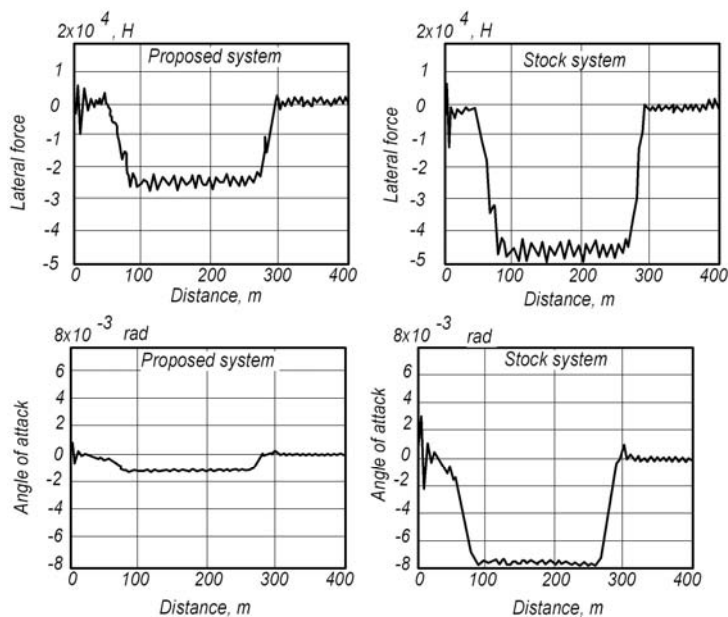

Fig. 10. Compared modeling results of carriage motion of serial locomotive 2TE116 and locomotive with the improved carriage

The fourth section represents the software and hardware choice that has been executed to realize ACS with a position of the wheel pair in the rail track, calculation of economic efficiency from applying the improved design of the locomotive carriage by means of the complemented system of the automatic control with a position of the wheel pair in rail track [22, 20, 23].

The realization of ACS with a position of the locomotive wheel pair is carried out on the diesel locomotive sample 2TE116 by a controlling computer which works in the real-time mode on the basis of the real-time operating system QNX. The control over the electromagnetic valve of EV210B has been carried out by the automatic system of pressure regulation [20, 23].

The developed microprocessor block of control is connected to the unified microprocessor control system and diagnostics through interface RS485.

The improved bogie design and automatic control system with a position of the wheel pair in the rail track has got a patent.

The application of the improved locomotive bogie design with the complemented automatic control system with a position of the wheel pair in the rail track allows to reduce:

- attack angle of the leading wheel pair in the curve by radius of 300 and 600 m accordingly in 7,5 and 3,5 times,
- level of force interaction on the track in the curve sections less than 400 m in 2-3 times,
- wear of the wheel flange band in 4,5 times,
- wear of the bands on the rolling circle up to 60%.

The net discounted income from the implantation of the system of radial wheel pair setting has made 154,5 thousand UAH per diesel locomotive, the expenses payback period is 4,2 years.

CONCLUSIONS

1. The analysis of the question showed that the dynamic properties of the carriage in a horizontal plane and the lateral wear of the wheel flange and the head of the rail depended on the wheel attack angle on the rail, state of the carriage part of a locomotive, on which it is possible to influence effectively by means of the rational choice of locomotives design.

2. It has been shown that the perspective direction when solving how to reduce the level of force interaction of wheel is the usage of rational designs of the locomotive carriage part complemented by the system of active control over the turn of the wheel pair in a horizontal plane.

3. It has been experimentally proved that ACS with a position of the wheel pair in the rail track is steady and provides the necessary quality of regulation at aperiodic character of the transitional process, which does not exceed 0,3 seconds.

4. It has been found by experimental research that the determination of the wheel attack angle on the rail is possible when using the acoustic emission method, the research of which shows that in the spectrum of acoustic emission from the contact interaction of wheel with a rail there is a range of frequencies, which is an informative indication, that allows to use it for control of wheel attack angle on the rail. An informative indication is a maximal deviation of the sound pressure level from the equivalent sound pressure level in the range of frequencies from 200 to 300 Hertzs, on the magnitude of which it is possible to measure the wheel attack angle on the rail.

5. The application of the improved design of the locomotive carriage complemented by the ACS with a position of the wheel pair in a horizontal plane, allows:

- to reduce the level of force interaction in the curve sections of the track less than 400 m in 2-3 times,
- to increase the durability of the exploited rolling stock,
- to remove the skewness of the wheel pair in the locomotive bogie when moving it in straight sections of the track.

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СНИЖЕНИЕ УРОВНЯ СИЛОВОГО ВЗАИМОДЕЙСТВИЯ КОЛЕС С РЕЛЬСАМИ АВТОМАТИЧЕСКИМ УПРАВЛЕНИЕМ ПОЛОЖЕНИЕМ КОЛЕСНЫХ ПАР ЛОКОМОТИВА

Виталий Ульшин, Сергей Клюев

А н н о т а ц и я . Работа посвящена вопросу снижению уровня силового взаимодействия колеса с рельсом при движении локомотива на криволинейных участках пути автоматическим управлением положением колесных пар локомотива на основе акустического метода определения угла набегания колеса на рельс и навигационной системы определения направления закругления.

Выбран и исследован акустический метод контроля угла набегания колеса на рельс.

Усовершенствована конструкция тележки локомотива и разработана математическая модель движения локомотива с усовершенствованной конструкцией тележки локомотива с регулируемым поводком с осевой формулой 3о-3о, с учетом динамики САУ положением колесных пар в горизонтальной плоскости.

Разработана система автоматического управления положением колесных пар в прямолинейных и криволинейных участках пути.

Проведены теоретические исследования и выполнено сравнение с экспериментальными значениями динамических процессов, возникающих в механической части локомотива серийного исполнения и усовершенствованной конструкции тележки локомотива с управлением и без при прохождении криволинейных участков пути.

К л ю ч е в ы е слова. локомотив, угол набегания, система автоматического управления, акустическая эмиссия, силовое взаимодействие.