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RESEARCH OF LOCOMOTIVE MECHANICS BEHAVIOR

Purpose. The main purpose of the study is to compare and confirm the results of theoretical studies of locomotive motion along the straight and curved track sections in the set range of operating speeds, which is essential for determining their dynamic qualities. The conducted research complex is one of the prerequisites for improving the reliability of the rolling stock mechanics, in particular the bogie parameters. **Methodology.** The research was carried out by numerical integration of the dynamic loading of a railway vehicle using one of the modern software complexes. In this study we used the mathematical model of locomotive spatial oscillations obtained using Lagrangian equations of the second kind. **Findings.** Authors carried out theoretical research and performed the analysis of the vehicle behavior during the motion along the track section, which in the vertical plane has no geometric defects, and taking into account the inequalities on the example of the main locomotive. The researches were carried out both analytically and with the help of the modern software complex. Comparison of the graphs shows that the results obtained by different methods coincide with sufficient accuracy. **Originality.** Based on the results of many years of work, the authors present the General Classification of Locomotive Mechanics, which may be useful to researchers, who are involved in the assessment of the dynamic qualities of new and upgraded types of rolling stock. **Practical value.** A new licensed modern software complex has been applied, which makes it possible to use it in the design, modeling of units of rolling stock and their elements; during theoretical and experimental studies, comparison of their results. The results of theoretical research can be taken into account for the preliminary research during creating the reliable constructions of a new vehicle, further improvement of the mechanics, modernization of the existing units of rolling stock during field tests.

Keywords: vehicle; rolling stock; locomotive; vehicle mechanics; bogie; software complex

Introduction

Designs of the new generation of traction rolling stock allows to provide its high performance: to reduce power consumption for traction; to reduce the impact on the track at a given load from the wheel set axle on the rails; to improve the working conditions of locomotive crews and passenger comfort; to reduce the emission of harmful substances into the atmosphere, etc. [10, 18, 19, 21].

As is known from the history of rail transport, the mechanics of the first locomotives consisted of a body, wheel sets with bearing units, traction drive, draw gear and brakes (Fig. 1, a). Over time, the design of the mechanics changed several times – its features depended on changing requirements to the traction rolling stock, increased design speed, the locomotive purpose, the type of motion, the need to take into account the growing demand of consumers and many other factors [3, 5, 7, 9, 10, 21–24]. Due to achievements of modern machine building and the development of scientific and technological progress the main components of the mechanics of the first locomotives received significant improvement (Fig. 1, b, c) and railway machinery manufacturers are not ready to rest on the results obtained [8, 10]. Modern locomotives have, as a rule, rotary bogies with one or two stages of spring suspension (elastic and dissipative elements), body-bogie mounting point, elements of the transmission of longitudinal forces between the bogie and the body, quasi-elastic cross-links between them, turn-over fixtures and units for uniform distribution of vertical loads between wheel sets (Fig. 1, c).

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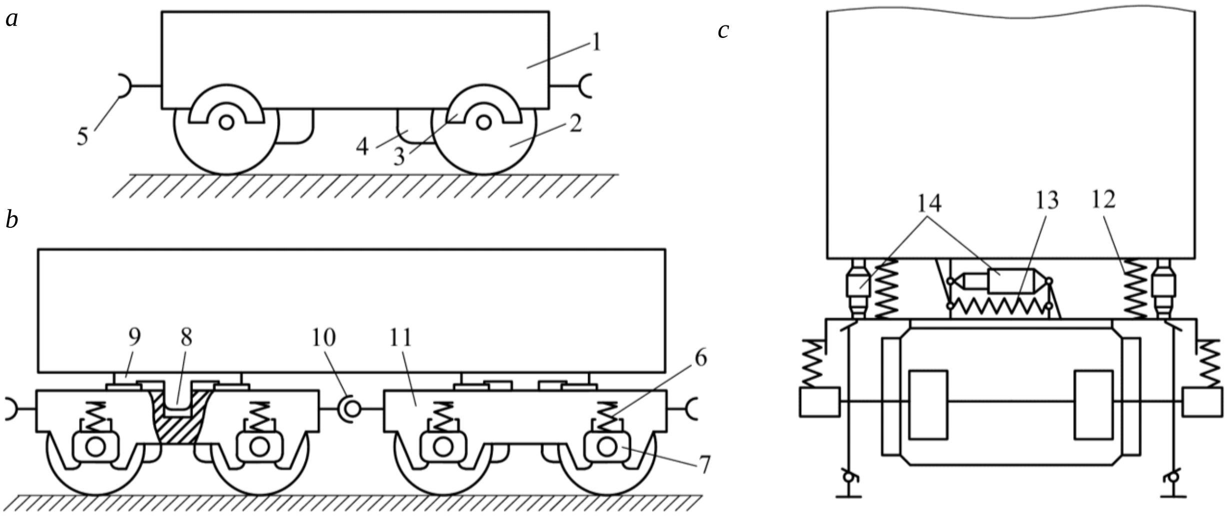

Fig. 1. Evolution of the mechanics in the locomotive:
a – mechanics of the first locomotives:
1 – body; *2* – wheel set; *3* – bearing unit; *4* – traction drive; *5* – draw gear and brakes;
b – improved design of the mechanics:
6 – elastic elements; *7* – axle box; *8* – pivot; *9* – body support; *10* – bogie coupling; *11* – bogie frame;
c – construction of the modern locomotives` mechanics:
12 – secondary suspension; *13* – spring of lateral suspension; *14* – special devices (dampers)

Purpose

The main purpose of the study is to compare and confirm the results of theoretical studies of locomotive motion along the straight and curved track sections in the set range of operating speeds, which is essential for determining their dynamic qualities. The conducted research complex is one of the prerequisites for improving the dynamic qualities of the rolling stock mechanics, in particular the bogie parameters.

Methodology

The research was carried out by numerical integration of the dynamic loading of a railway vehicle using one of the modern software complexes. We used in this study the mathematical model of locomotive spatial oscillations obtained using Lagrangian equations of the second kind.

The mechanics of the railway rolling stock, which is affected by the weight of the equipment, participates in the transfer of tractive effort from the locomotive to the train, accepts the dynamic loads that arise when moving along the straight and curved sections of the track. Therefore, in order to ensure its normal and trouble-free operation:

– All components of the mechanics corresponded to the strength requirements at the most unfavourable combination of operating loads;

– The mechanics was sufficiently strong, met the safety requirements and railway operating rules;

– The mechanics was a simple and reliable construction, especially its bogie.

Therefore, based on the analysis of the traction rolling stock structures [4, 8, 10, 12, 13, 15, 18, 19, 21], the ideas and achievements of locomotive construction [1, 2, 5, 7, 8–10, 13, 17–19, 21], the results of numerous studies [3, 5, 7, 9, 21–24], the authors of the paper, in terms of systematic originality, proposed a variant of the General Classification of Locomotive Mechanics (Fig. 2).

One of the necessary conditions for improving the traction rolling stock of railways is to determine the parameters of its bogie [2, 4, 8–10, 18, 19, 21]. Therefore the important task is to determine the dynamic qualities of locomotives, taking into account the selected technical solutions in the bogie design, for example, the presence and location of connections between the body and the bogie, the secondary suspension system, devices for transmission of longitudinal and transverse forces, etc.

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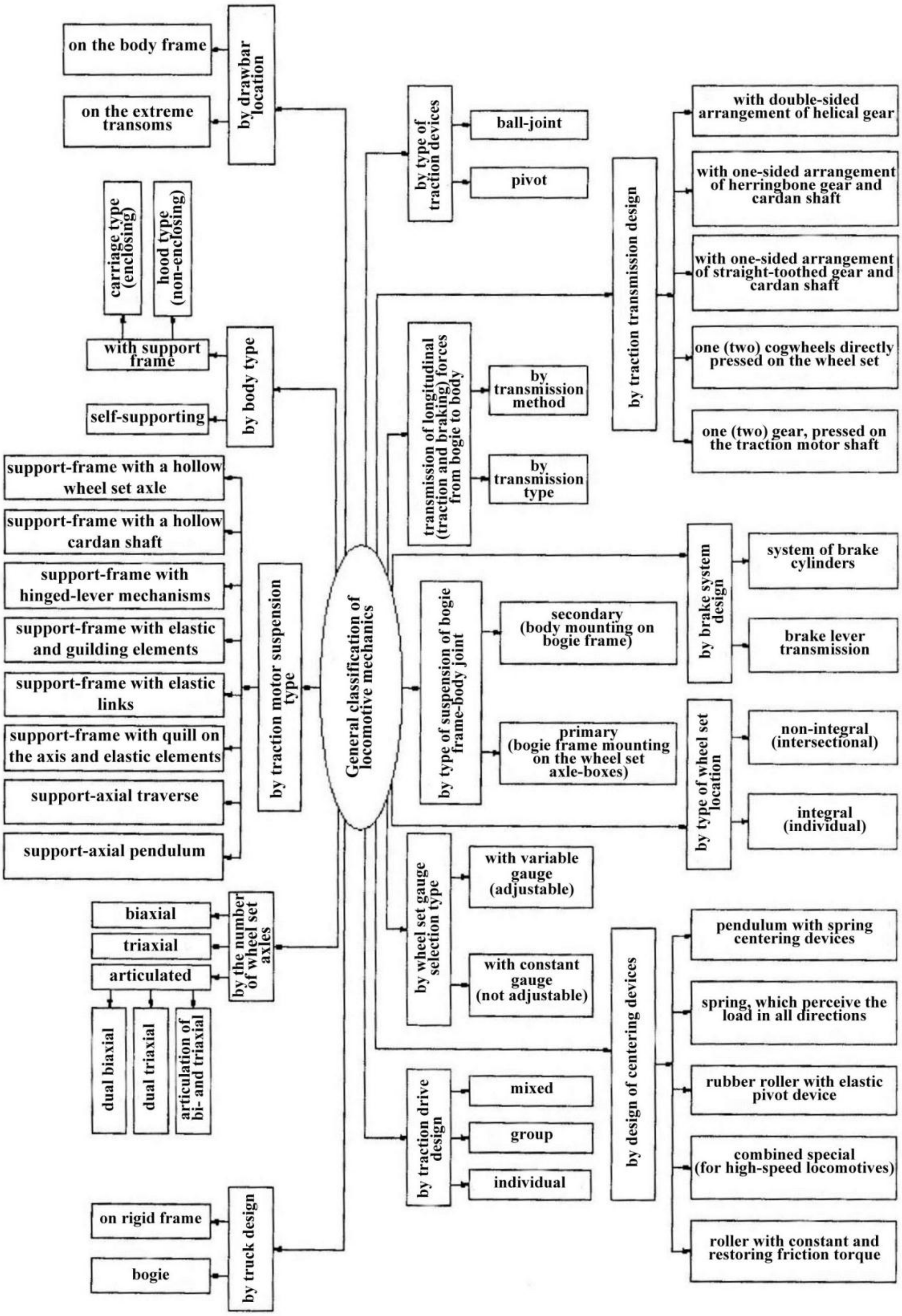

Fig. 2. General Classification of Locomotive Mechanics

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This work presents the research conducted for the main line electric locomotive of the DS series, which was created in cooperation with Siemens Concern at the Dnipropetrovsk Electric Locomotive Building Plant (DELBP) with the participation of a number of scientific and production organizations, including the Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan (DNURT) [10, 18, 19, 21]. Its bogie (Fig. 3) is two-axle, ball-joint, with support-frame suspension of traction electric motors. For the transmission of longitudinal forces of traction (braking), a tilt rod is installed between each bogie and body, which is pivotally connected to the bogie traction unit and with an equilateral balancer, whose ends are connected with the rods by means of the pivot-hinged bearings [10, 13, 18, 19].

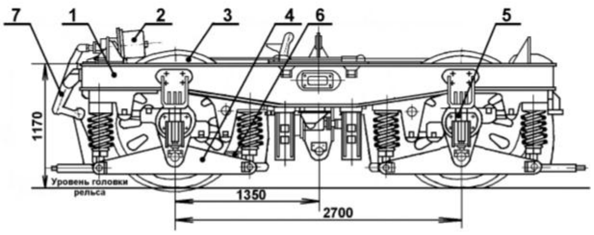

Fig. 3. Bogie drawing:
1 – bogie frame; *2* – brake cylinder; *3* – wheel set;
4 – balancer of the first stage of spring suspension;
5 – shock absorber; *6* – wheel flange lubricator;
7 – lever braking system

As it is known, the locomotive mechanics is a complex system with many bodies that have many degrees of freedom.

This paper describes the first (simplified) stage of research that considers the simplest computational dynamic model of the vehicle, i.e. a single-mass system, whose degree of freedom is equal to one, with the parameters of the reduced object. We construct the Lagrange equation of the second kind for the oscillations of this system. Let the body (possibly a body of a rolling stock unit) of mass *m* with the help of an elastic element and a viscous drag damper is attached to a wheel set (the mass of which so far neglected), and moves along the track, which in the vertical plane has no geometric defects (without regard to track irregularities) (Fig. 4). The coordinate axis *y*, along which the body moves, is oriented down. The elastic element has rigidity *c*, the damper viscous drag coefficient we denote as β. Figure 4 shows the calculation model, plane and spatial image of this scheme.

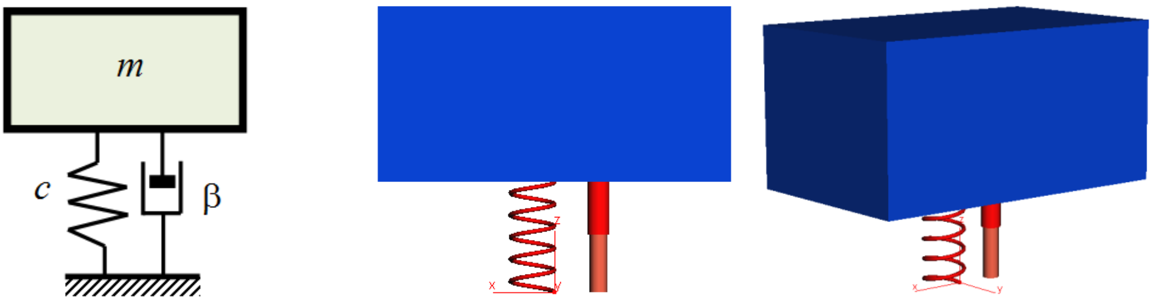

Fig. 4. Object of research without regard to track irregularities

Since the system has one degree of freedom, that is $n=1$; for a generalized coordinate, we choose the displacement of the body along the vertical axis $q_1 = y$; generalized speed $\dot{q}_1 = \dot{y}$.

The kinetic energy of the body, the potential energy accumulated in the elastic element, the function of energy dissipation in the viscous drag damper are determined by the known formulas [2, 6, 11, 14].

The generalized force, as is known from theoretical mechanics, can have two components: a generalized force that has the potential $Q_i^{**} = -\frac{\partial \Pi}{\partial q_i}$ and a generalized force that has no potential Q_i^{*}. That is $Q = Q_i^{*} + Q_i^{**}$. Since the load is not affected by a perturbing external force that has no potential, then the corresponding generalized force $Q_i^{*} = 0$.

Using the Lagrange equations of the second kind

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$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right)-\frac{\partial T}{\partial q_i}+\frac{\partial \Phi}{\partial \dot{q}_i}+\frac{\partial \Pi}{\partial q_i}=0,$$

we obtain an equation of body motion $m\ddot{q}_1+\beta\dot{q}_1+cq_1=0$, in the canonical form it will be as follows

$$\ddot{q}+2b\dot{q}+k^2 q=0.$$

Let us denote $b=\frac{\beta}{2m}$, $k^2=\frac{c}{m}$.

Its solution has the form [2, 6, 11, 14]

$$q=e^{-bt}\left(A\cos k_1 t+B\sin k_1 t\right),$$

where $k_1=\sqrt{k^2-b^2}$, A, B – constants derived from the initial conditions. Physical content: k_1 – frequency of oscillations with regard to friction, k – frequency of free oscillations (without friction).

Let us consider the case when the body of mass m with the help of an elastic element and a viscous drag damper is attached to a wheel set, the mass of which is so far neglected, moves along a track, which in the vertical plane has the irregularity given by the equation $\eta=\eta_0\sin\omega t$. Figure 5 shows the calculation model, plane and spatial image of this scheme.

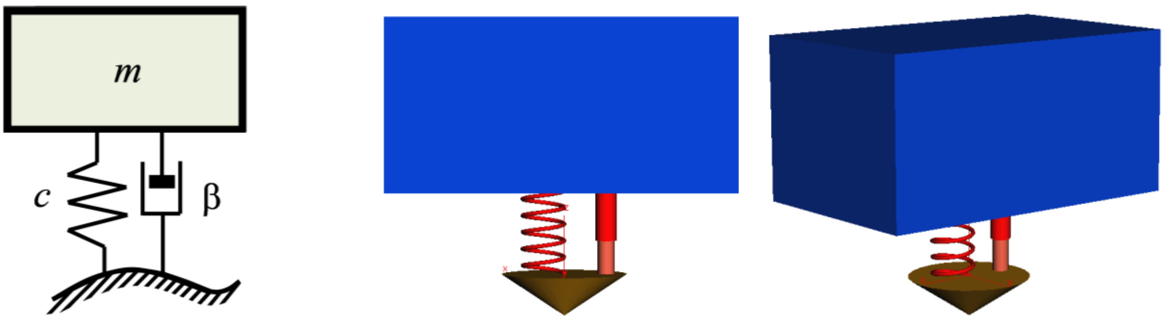

Fig. 5. Object of research with regard to track irregularities

Then the differential equation of body motion obtained by means of the Lagrange equation of the second kind has the form [2, 6, 11, 14]:

$$m\ddot{q}_1+\beta\left(\dot{q}_1-\dot{\eta}\right)+c\left(q_1-\eta\right)=0,$$

or:

$$m\ddot{q}_1+\beta\dot{q}_1+cq_1=\beta\dot{\eta}+c\eta.$$

This equation can be rewritten in a different way:

$$m\ddot{q}_1+\beta\dot{q}_1+cq_1=c\eta_0\sin\omega t+\beta\omega\eta_0\cos\omega t,$$

where η_0 – amplitude value of rail deflection, ω – frequency of sinusoidal perturbation.

In this case, the solution has the form

$$q_1=e^{-bt}\left(A\cos k_1 t+B\sin k_1 t\right)+D_1\sin\omega t+D_2\cos\omega t,$$

where D_1, D_2 – constants of integration that satisfy the initial conditions.

Findings

Example 1. Let us consider the real mechanical system of the electric locomotive DS3 as a single-mass system, which moves along the track, which in the vertical plane has no geometric defects (without taking into account the irregularities) (Fig. 4).

System parameters:

$$c=2\,950\ \frac{\text{kN}}{\text{m}},\ m=50\ \text{t},\ \beta=180\ \frac{\text{kN}\cdot\text{s}}{\text{m}},$$

$$k^2=\frac{c}{m}=\frac{2\,950}{50}=59,\ k=\sqrt{59}=7.68\ \text{s}^{-1},$$

$$b=\frac{\beta}{2m}=\frac{180}{100}=1.8\ \text{s}^{-1},$$

$$k_1=\sqrt{59-3,24}=7.47\ \text{s}^{-1}.$$

For the initial conditions $q_0=25\cdot10^{-3}=2.5\cdot10^{-2}$ m, $\dot{q}_0=0$ we will obtain

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$A = 2.5 \cdot 10^{-2}$ m, $B = 3.93 \cdot 10^{-3}$ m. Then the final result of the problem has the following form

$$q = e^{-0,45t}\left(2.5 \cdot \cos 2.86t + 0.393 \cdot \sin 2.86t\right) \cdot 10^{-2} \text{ m.}$$

The graph of this coordinate behavior, obtained by analytical calculations and using the software complex, is presented in Figure 6 and Figure 9 respectively.

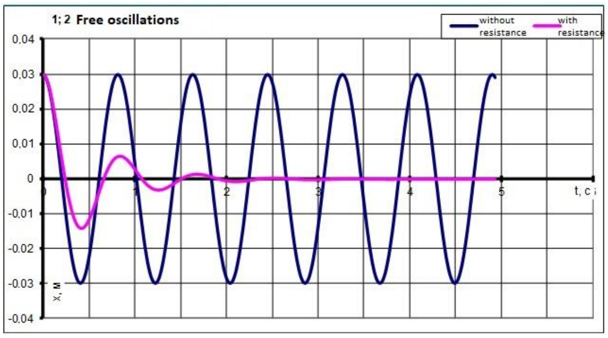

Fig. 6. Graph of free oscillations obtained by analytical calculation

Since designers are interested in the forces that arise in elastic elements, we find acceleration of the body

$$\ddot{q} = -3.24 \cdot e^{-1.8t}\left(2.5 \cdot \cos 7.47t + 0.602 \cdot \sin 7.47t\right) -$$

$$-3.6 \cdot e^{-1.8t}\left(-18.68 \cdot \sin 7.47t + 4.50 \cdot \cos 7.47t\right) +$$

$$+e^{-1.8t}\left(-139.50 \cdot \cos 7.47t - 33.60 \cdot \sin 7.47t\right)\left(\frac{\text{cm}}{\text{s}^2}\right).$$

Example 2. The results of the motion of the same vehicle (under the same conditions and values of parameters) along the track, having irregularities in the vertical plane (Fig. 7).

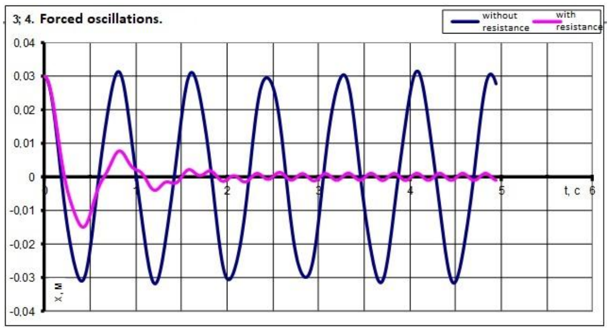

Fig. 7. Graph of forced oscillations obtained by analytical calculation

Example 3. Amplitude-frequency response of the same vehicle shows the ratio of the amplitude of body oscillation with the mass m and the amplitude of track inequalities depending on the frequency of its inequalities (Fig. 8).

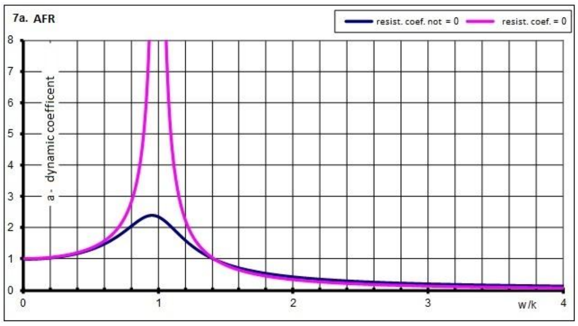

Fig. 8. Graph of amplitude-frequency response obtained by analytical calculation

The results obtained using the modern software system [17, 20] are presented in Fig. 9 – 11 respectively.

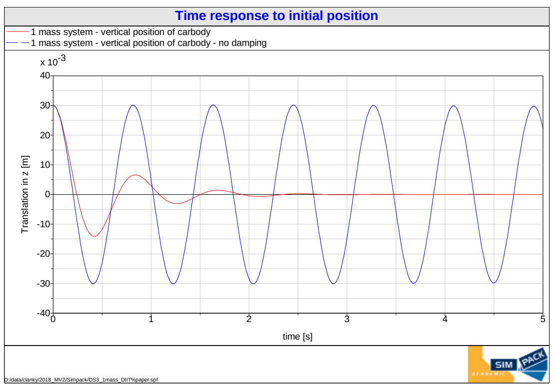

Fig. 9. Graph of free oscillations obtained using software complex

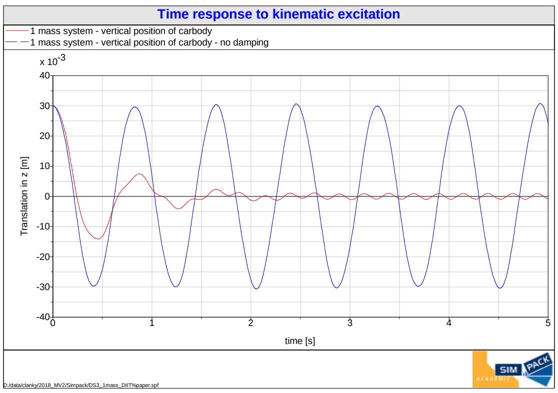

Fig. 10. Graph of forced oscillations obtained using software complex

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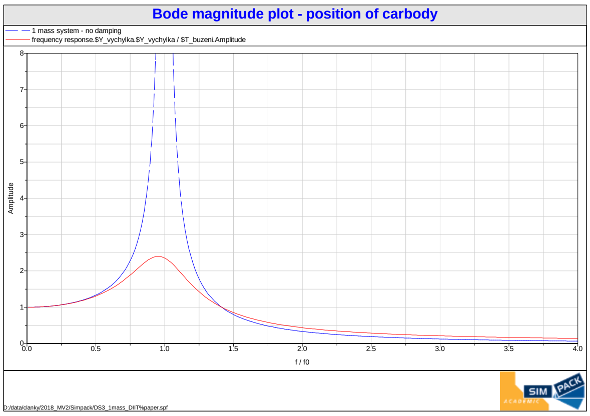

Fig. 11. Graph of amplitude-frequency response obtained using software complex

When comparing these graphs, it is easy to understand that we have the same results in both cases. Unlike the analytical solving, we can achieve these results easer with the help of software system.

The software complex automatically creates an equation of motion, finds a solution and displays results. This advantage can be used in order to create complex models with many degrees of freedom (Fig. 12).

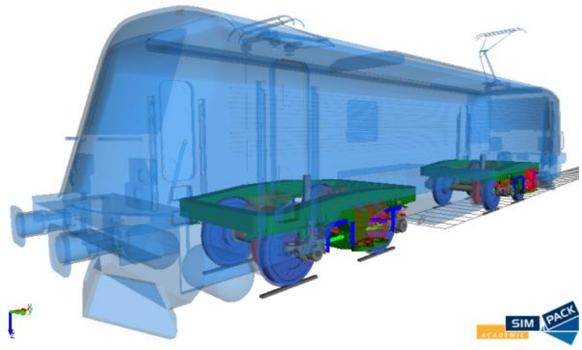

Fig. 12. Spatial nonlinear electric locomotive model with 124 degrees of freedom

Without the use of modern software, the creation of such a model will be very complex and time-consuming. Modern software complexes allow creating and calculating such a model within a few days.

Originality and practical value

Based on the results of many years of work, the authors present the General Classification of Locomotive Mechanics, which may be useful to researchers, who are involved in the assessment of the dynamic qualities of new and upgraded types of rolling stock.

A new licensed modern software complex has been utilized. This program complex is applicable in the design, modeling of units of rolling stock and their elements; during theoretical and experimental studies, comparison of their results.

The results of theoretical research can be taken into account for preliminary study during creating the reliable constructions of a new vehicle, further improvement of the vehicle mechanics, and modernization of the units of rolling stock during field tests.

Conclusions

When creating and improving the structures of rolling stock, the actual is generalization of theoretical, scientific-methodical and experimental researches, which are directed on improvement of qualities of a vehicle in general, and locomotive mechanics in particular.

The article analyses the behavior of a vehicle during motion along the track section, which in the vertical plane does not have geometric defects, and taking into account the irregularities using the example of the main locomotive. The research was carried out both analytically and with the help of modern software complex.

Comparison of graphs (Fig. 6 – 8 and Fig. 9 – 11) shows that the results obtained by different methods coincide with sufficient accuracy.

The use of modern computing tools makes it easier and faster to get results compared to using the analytical methods.

The implementation of the results of theoretical researches can give an opportunity of simultaneous increase in vehicle velocity, provision of necessary dynamic parameters of a railway vehicle, reduce its impact on the track and improve the level of railway traffic safety.

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ДОСЛІДЖЕННЯ ПОВЕДІНКИ МЕХАНІЧНОЇ ЧАСТИНИ ЛОКОМОТИВА

Мета. Основною метою роботи є порівняння й підтвердження результатів теоретичних досліджень руху локомотива по прямолінійним та криволінійним ділянкам колії у встановленому діапазоні експлуатаційних швидкостей, що є головним для визначення їх динамічних якостей. Проведений комплекс досліджень є однією з передумов поліпшення динамічних якостей механічної частини рухомого складу, зокрема параметрів ходової частини. **Методика.** Дослідження проведені методом чисельного інтегрування динамічної навантаженості залізничного транспортного засобу з використанням одного із сучасних програмних комплексів. У роботі застосовано математичну модель просторових коливань локомотива, отриманих за допомогою рівнянь Лагранжа другого роду. **Результати.** Проведено теоретичні дослідження й виконано аналіз поведінки транспортного засобу під час руху по ділянці колії, яка у вертикальній площині не має геометричних дефектів, та з урахуванням нерівностей на прикладі магістрального локомотива. Дослідження проведено як аналітично, так і за допомогою сучасного програмного комплексу. Порівняння графіків показує, що результати, отримані різними методами, збігаються з достатньою точністю. **Наукова новизна.** За результатами багаторічної роботи автори представили загальну класифікацію механічної частини локомотивів, що може стати в нагоді науковцям, які досліджують динамічні якості нових і модернізованих засобів рейкового рухомого складу. **Практична значимість.** Застосовано новий ліцензований сучасний програмний комплекс, який можна використовувати під час проектування, моделювання одиниць рухомого складу та їх елементів під час проведення теоретичних й експериментальних досліджень, порівняння їх результатів. Результати теоретичних досліджень можуть бути враховані для проведення попередніх досліджень під час створення надійних конструкцій нового транспортного засобу, подальшого поліпшення механічної частини, модернізації одиниць рухомого складу, під час проведення натурних випробувань.

Ключові слова: транспортний засіб; рухомий склад; локомотив; механічна частина; візок; програмний комплекс

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ИССЛЕДОВАНИЕ ПОВЕДЕНИЯ МЕХАНИЧЕСКОЙ ЧАСТИ ЛОКОМОТИВА

Цель. Основной целью работы является сравнение и подтверждение результатов теоретических исследований движения локомотива по прямолинейным и криволинейным участкам пути в установленном диапазоне эксплуатационных скоростей, что является главным для определения их динамических качеств. Проведенный комплекс исследований является одним из условий улучшения динамических качеств механической части подвижного состава, в частности параметров ходовой части. **Методика**. Исследования проведены методом численного интегрирования динамической нагруженности железнодорожного транспортного средства с использованием одного из современных программных комплексов. В работе применена математическая модель пространственных колебаний локомотива, полученных с помощью уравнений Лагранжа второго рода. **Результаты**. Проведены теоретические исследования и выполнен анализ поведения транспортного средства во время движения по участку пути, который в вертикальной плоскости не имеет геометрических дефектов, и с учетом неровностей на примере магистрального локомотива. Исследование проведено как аналитически, так и с помощью современного программного комплекса. Сравнение графиков показывает, что результаты, полученные разными методами, совпадают с достаточной точностью. **Научная новизна.** По результатам многолетней работы авторы представили общую классификацию механической части локомотивов, которая может пригодиться ученым, исследующим динамические качества новых и модернизированных средств рельсового подвижного состава. **Практическая значимость.** Применен новый лицензированный современный программный комплекс, который можно использовать при проектировании, моделировании единиц подвижного состава и их элементов при проведении теоретических и экспериментальных исследований, сравнения их результатов. Результаты теоретических исследований могут быть учтены для проведения предварительных исследований при создании надежных конструкций нового транспортного средства, дальнейшего улучшения механической части, модернизации единиц подвижного состава, во время проведения натурных испытаний.

Ключевые слова: транспортное средство; подвижной состав; локомотив; механическая часть; тележка; программный комплекс

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