ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)

Наука та прогрес транспорту. Вісник Дніпропетровського національного університету залізничного транспорту, 2017, № 6 (72)

UDC 629.46.028

L. V. URSULYAK[1*], A. O. SHVETS[2*]

[1*]Dep. «Theoretical and Structural Mechanics», Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan, Lazaryan St., 2, Dnipro, Ukraine, 49010, tel. +38 (095) 008 70 53, e-mail lydm.urs@gmail.com, ORCID 0000-0001-5957-6926

[2*]Dep. «Theoretical and Structural Mechanics», Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan, Lazaryan St., 2, Dnipro, Ukraine, 49010, tel. +38 (050) 214 14 19, e-mail angela_Shvets@ua.fm, ORCID 0000-0002-8469-3902

IMPROVEMENT OF MATHEMATICAL MODELS FOR ESTIMATION OF TRAIN DYNAMICS

Purpose. Using scientific publications the paper analyzes the mathematical models developed in Ukraine, CIS countries and abroad for theoretical studies of train dynamics and also shows the urgency of their further improvement. **Methodology**. Information base of the research was official full-text and abstract databases, scientific works of domestic and foreign scientists, professional periodicals, materials of scientific and practical conferences, methodological materials of ministries and departments. Analysis of publications on existing mathematical models used to solve a wide range of problems associated with the train dynamics study shows the expediency of their application. **Findings**. The results of these studies were used in: 1) design of new types of draft gears and air distributors; 2) development of methods for controlling the movement of conventional and connected trains; 3) creation of appropriate process flow diagrams; 4) development of energy-saving methods of train driving; 5) revision of the Construction Codes and Regulations (SNiP II-39.76); 6) when selecting the parameters of the autonomous automatic control system, created in DNURT, for an auxiliary locomotive that is part of a connected train; 7) when creating computer simulators for the training of locomotive drivers; 8) assessment of the vehicle dynamic indices characterizing traffic safety. Scientists around the world conduct numerical experiments related to estimation of train dynamics using mathematical models that need to be constantly improved. **Originality**. The authors presented the main theoretical postulates that allowed them to develop the existing mathematical models for solving problems related to the train dynamics. The analysis of scientific articles published in Ukraine, CIS countries and abroad allows us to determine the most relevant areas of application of mathematical models. **Practical value**. The practical value of the results obtained lies in the scientific validity and applied orientation of theoretical studies using mathematical models, the improvement of which will expand the range of problems to be solved, and increase the level of reliability of the results obtained.

Keywords: long train; train dynamics; mathematical models of longitudinal train oscillations; inter-car coupling modelling; science articles; longitudinal forces in the train; locomotive driving simulators

Introduction

With increasing speeds of movement, masses and lengths of trains, especially freight ones, increasing capacity of locomotives, it is required to control the longitudinal forces that arise during stationary and transitional train movements that affect the traffic safety. It should be borne in mind that from the standpoint of traffic safety, longitudinal forces of quasistatic character or forces of shock nature containing such quasistatic components can be dangerous. Such forces can, under certain conditions, cause outsqueezing (or pulling out) of wagons from the train.

Earlier, the experimental method of studying transient modes of train movement was the main method used to obtain practically important results. The current level of theoretical methods for studying the transient modes of train movement, based on the use of modern PCs and IT, allows solving many technical problems in the field of train dynamics. In addition, computer modelling (numerical experiment) has significant advantages over field experiment.

First, there is no need to conduct an experiment on real physical objects, so the costs for various computer experiments are much less than for actual experiments. The scale of the experiments can be chosen at own discretion, and there is the possibility of conducting multiple experiments with gradual changes in the task input data.

Secondly, in the process of constructing mathematical models for carrying out a computational

doi 10.15802/stp2017/118002

ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)

Наука та прогрес транспорту. Вісник Дніпропетровського національного університету залізничного транспорту, 2017, № 6 (72)

experiment and during its investigation, it is possible to analyse and understand the characteristics of the object under study.

Purpose

Any scientific research should be based on knowledge of the scientific heritage of predecessors, and therefore one of the key stages of any scientific research is the analysis of the results of scientific research of predecessors. The need for such an analysis is due to the impossibility of allowing repetitions of the scientific result and the need for further development of science with the purpose of search for truth [30, 33].

The purpose of the publication is to analyse the results of scientific research conducted in Ukraine, CIS countries and abroad on the development of mathematical models for solving problems of train dynamics, and also to show the urgency of their further improvement.

Methodology. Analysis of publication

To solve these problems, Nikolai Egorovich Zhukovsky in 1919 proposed two train calculation models.

In this case, the train was viewed as an elastic rod with a load at the end. The rod mass and length was equal to the train mass and length, while the load mass – to the mass of the locomotive [9]. Then the motion of the train was described by the wave equation and the definition of longitudinal forces was reduced to the solution of the boundary value problem. Then the train was supposed to be considered as a system of solids connected by elastic links subordinate to Hooke's law, and the task was reduced to solving a system of differential equations for given initial conditions. The schemes described above represented conservative systems and allowed us to determine only the upper boundaries of longitudinal forces under unsteady modes.

V. A. Lazaryan specified the calculation models proposed by N.E. Zhukovsky. If the coupling gaps do not affect the course of transients (when the train pre-stretched from head starts, when the head locomotive of the head pre-compressed train brakes, when the stretched (compressed) train enters the summit or sag), then the train can be considered as an elastic-viscous rod with a load (locomotive) at the end [1, 4, 12, 15-17, 19, 36].

Fig. 1. Calculation model of train in the form of rod.

In this case, the longitudinal oscillations of the train are described by second-order partial differential equations.

Using such a model, the solution of the problem can be found analytically.

Vsevolod Arutyunovich Lazaryan proposed in his doctoral thesis to take into account the energy dissipation during oscillations and to consider the train as a one-dimensional system of solids connected by elastic-viscous bonds.

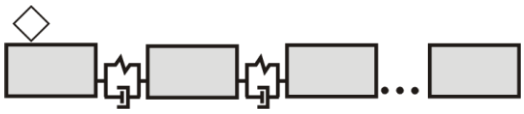

Fig. 2. Calculation model of train in the form of chain of bodies connected by elastic-viscous bonds

These calculation models were used in the works of V.A. Lazaryan, E.P. Blokhin, I.G. Barbas, T.A. Gorodetskyaya, A.I. Stukalov, A.A. Ulanov and F.V. Florinskii. Numerous special train experiments, conducted by V. A. Lazaryan in real conditions, confirmed the validity of application, in a number of cases, of the mentioned calculation models and allowed to find many characteristics of freight and passenger trains necessary for calculations (run speed, perturbations during start-up and braking, train longitudinal stiffness, coupling stiffness during loading and unloading, average statistical gaps in the inter-car couplings).

Naturally, in this case, transitional modes of motion were considered, not influenced by the gaps in the train coupling (starting of the pre-stretched and braking of the head pre-compressed trains, movement of the stretched train along the summit and sag). In all these cases, there is a practical coincidence of not only the curves of distribution of the maximum longitudinal forces along the train, obtained by calculation and based on the experiment results, but also the oscillograms of the longitudinal forces The linear formulation of the tasks made it possible to use analytical methods and the electric model created on the passive elements (R, L, C) in the rolling stock dynamics and strength laboratory of the DNURT.

doi 10.15802/stp2017/118002

ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)

Наука та прогрес транспорту. Вісник Дніпропетровського національного університету залізничного транспорту, 2017, № 6 (72)

The first studies of longitudinal forces, when the gaps influence the transient process, were carried out experimentally.

When the gaps in the inter-car couplings influence the transient process, V.A. Lazaryan proposed as a calculation model a system of solids connected by elements with elastic imperfections that take into account the gaps [3, 18, 20–23, 28].

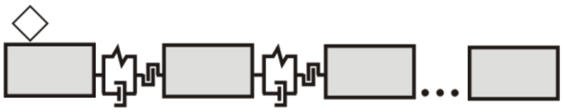

Fig. 3. Calculation model of train as a nonlinear system.

Fig. 3 differs from Fig. 2 by the presence of one more element, conditionally denoting the coupling gap, and the non-linearity of the power characteristics of the centre-coupler draft gear.

The presence of coupling gaps, in general, the nonlinearity of the power characteristics of the draft gears makes the train considered as a chain of solids connected by links with nonlinear characteristics. In this case, the mathematical model of longitudinal train oscillations is a system of essentially nonlinear differential equations, the order of which depends on the number of vehicles in a train. It is impossible to obtain a solution of this system analytically. Therefore, at the initial stage the DNURT research of the train movement transitional modes in the present formulation was carried out with the help of a special electronic train model made on the basis of three MPT-9 type analogue computers. It is known that one of the advantages of ACS (analogue computing system) is obtaining of the solutions on a real-time basis, which is very important in the case of automatic control systems.

With the advent of ECM (electronic computing machine), such studies have been carried out by numerical experiments.

In this case the problem was reduced to solving a system of ordinary differential equations using numerical integration methods. The works [2, 3, 11] are devoted to the method of mathematical modelling of train movement transitional modes using ECM.

The advent of digital computers and the use of modern computing methods have made it possible to significantly expand the range of important tasks for the industry. In this case, the oscillograms of longitudinal forces obtained as a result of solving the system of nonlinear differential equations can only be compared qualitatively with those obtained experimentally, but the distribution along the composition of the maximum values of the longitudinal forces found by calculation and experimentally agree fairly well. Naturally, such an agreement can only be obtained when calculation uses the significant driving characteristics of the train and the track layout, as well as data on the distribution of the gaps in the coupling before the beginning of the transient processes.

To obtain such characteristics, special experiments were carried out, with the trains homogeneous in wagon mass and draft gear type, within the station tracks in order to determine the numerical values of the parameters required for solving differential equations of train movement.

One of these parameters is the gap limit in inter-car couplings.

For the freight trains formed from the newly-manufactured freight wagons this gap is 45 mm. For the trains formed from freight wagons in service this gap is equal to 65 mm. For the passenger trains, the coupling gap is 45 mm. These values of the gaps were used in solving differential equations of train movement [3, 29, 48].

Rolling stock on the 1524 and 1520 mm gauge railways is equipped with elastic-corrugating draft gears, which are not stable in operation, therefore, often the inter-car have different characteristics. However, the experimental studies of train movement transitional modes revealed the general, integral properties for the whole system.

Integral values are necessary for analytical studies and modelling of transitional modes of train movement. They can be determined by the nature of the propagation of disturbances in the train, i.e. by the speed of propagation of the perturbations along the train, by the dispersion of the perturbation waves of various levels, by the damping of the oscillations, etc. [2, 3, 48].

The use of digital computers allowed studying the transitional modes of the movement of freight and passenger trains during their starting, braking and moving along the broken profile track. Herewith the study included the homogeneous and heterogeneous trains, as well as trains containing wagons with moving loads, equipped with draft gears of automatic couplers and air distributors of various types. The digital computers allowed solv-

doi 10.15802/stp2017/118002

ing the greatest number of tasks related to the longitudinal dynamics of the train and solved at different times [7, 29, 34, 45, 48, 56–59].

The results of these studies were used when designing new types of draft gears and air distributors [3, 5, 6, 10, 27, 31, 32], when developing the methods for controlling the movement of conventional and connected trains [2, 38, 40], when creating the appropriate process flow diagrams and developing the energy-saving methods of train driving [58, 62], when revising the Construction Codes and Regulations (SNiP II-39.76) [3, 29, 48], when selecting the parameters of the autonomous automatic control system, created in DNURT, for an auxiliary locomotive that is part of a connected train [29], when creating computer simulators for the training of locomotive drivers [24, 26, 37, 50–52, 54, 64].

In these days, freight trains weighing several tens of thousands of tons with locomotives distributed along the train have long been in use in a number of countries in America, Asia, Africa, and Canada.

In order to increase the carrying capacity of railways, to reduce operating costs, the weight norms of freight trains in a number of countries are being revised. For example, the weight norm of 4,000 tons was replaced in Russia by 6,000 tons on the most common 1524 and 1520 mm gauge. The double freight trains of 12,000 tons with locomotives distributed along the train were put into regular operation on the most heavily loaded tracks of Russian railways [13, 25, 39, 44, 46].

Herewith, in order to ensure the permissible level of longitudinal forces in the most dangerous mode of driving – braking – it is necessary to drive the locomotives in a coordinated manner.

In trains of increased mass and especially length during braking, there are longitudinal loads, which can be dangerous from the point of traffic safety.

Numerous special experiments, conducted in different years at the Pridneprovskaya Railway, DNURT, the Central Research Institute of the Ministry of Railways, and in a number of cases with the participation of MSURE, with trains weighing 6, 8 and 10 thousand tons have shown that in case of emergency and service braking even in homogeneous trains weighing up to 10 thousand tons the cars can experience, with a low probability (of order of thousandths), the forces, which exceed the permissible strength.

During regulation braking, the maximum values of compressive forces observed in the experiments with a statistical probability of 0.009 exceed by 20–60% the values of the longitudinal loads (±1 MN) allowed for the III calculation mode. For the tensile forces that arise during «recoil», the excess reached 20%, but with greater probability by several times.

A lot of works [3, 11, 28, 35, 38, 43, 44, 47–49, 53, 60, 61, 63] are devoted to the study of longitudinal dynamics in the braking of long trains using mathematical models.

When operating the long trains, special attention is paid to the assessment of the dynamic performance of vehicles, among which the most important is the indicator characterizing the vehicle movement safety – the derailment stability factor.

For this purpose, there are used mathematical models of spatial oscillations of the car (or group of cars), moving in the train [8, 14, 26, 41–42, 55]. In this case, the vehicle model is divided into separate objects and the connections between them. The objects, for example, can be the all inertial features or some of them, which can be combined into one object; while the others can act as separate objects.

Findings

Information base of the research was official full-text and abstract databases, scientific works of domestic and foreign scientists, professional periodicals, materials of scientific and practical conferences, methodological materials of ministries and departments.

The analysis of publications on the development of mathematical models for solving the train dynamics problems shows the multiplicity of the investigated aspects. Scientists around the world conduct numerical experiments related to the evaluation of the train dynamics using mathematical models, which must be constantly improved.

The research results have found their scientific use in a number of publications of authors in special and scientific publications, speeches at scientific conferences.

doi 10.15802/stp2017/118002

Originality and practical value

The originality of the study is the presentation of the main theoretical provisions and methodological recommendations for the improvement of mathematical models for solving the train dynamics problems. The carried out analysis of scientific publications makes it possible to determine the most relevant studies in the field of train safety that are impossible without mathematical modelling.

The practical value of the results obtained lies in the scientific validity and applied orientation of theoretical studies using mathematical models, the improvement of which will expand the range of problems to be solved, and increase the level of reliability of the results obtained.

Conclusions

The analysis of scientific publications on mathematical modelling of train dynamics allowed drawing the following conclusions:

1. Despite the variety and the large number of issues considered and solved in the field of transitional modes for the movement of tank trains, the problem of the train dynamics, in particular that of train longitudinal oscillations, remains relevant, especially at the most dangerous driving mode – braking.
2. Recently, especially in Europe, much attention has been paid to modelling the movement of trains of increased mass and length.
3. Mathematical models should be used to solve problems concerning the influence of perspective rolling stock on the train dynamics.
4. The existing mathematical train models require improvement, taking into account the tasks that arise during the operation of the rolling stock.

LIST OF REFERENCE LINKS

1. Барбас, И. Г. Аналитическое определение усилий, возникающих в упряжных приборах при движении через перелом профиля пути / И. Г. Барбас // Сб. науч. тр. ДИИТа. – Днепропетровск, 1962. – Вып. 42. – С. 4–12.
2. Блохин, Е. П. Выбор режимов ведения поездов как стохастическая задача векторной оптимизации / Е. П. Блохин, В. В. Скалозуб // Транспорт : зб. наук. пр. / Дніпропетр. держ. техн. ун-т залізн. трансп. – Дніпропетровськ, 2002. – Вип. 7. – С. 28–31.
3. Блохин, Е. П. Динамика поезда (нестационарные продольные колебания) / Е. П. Блохин, Л. А. Манашкин. – Москва : Транспорт, 1982. – 222 с.
4. Блохин, Е. П. О влиянии неоднородности поезда на динамические усилия, возникающие в упряжных приборах при трогании с места / Е. П. Блохин // Тр. ДИИТа. – Москва, 1958. – Вып. 26. – С. 4–12.
5. Болдырев, А. П. Характеристики перспективных поглощающих аппаратов в поездных условиях эксплуатации / А. П. Болдырев, А. М. Гуров, Э. А. Фатьков // Вісн. Дніпропетр. нац. ун-ту залізн. трансп. ім. акад. В. Лазаряна. – Дніпропетровськ, 2007. – Вип. 15. – С. 146–153.
6. Болдырев, А. П. Эффективность применения высокоэнергоемких поглощающих аппаратов на грузовых вагонах / А. П. Болдырев, А. М. Гуров // Трансп. Рос. Федерации. – 2014. – № 3 (52). – С. 43–44.
7. Верескун, В. Д. Многомассовая модель подвижной единицы для исследования продольной динамики грузового поезда / В. Д. Верескун, Д. Е. Притыкин // Вестн. Ростов. гос. ун-та путей сообщения. – 2014. – № 2 (54). – С. 16–27.
8. Воронова, Ю. В. Динамика грузовых вагонов на кривых малого радиуса / Ю. В. Воронова, Н. П. Рычков // Транспортная инфраструктура Сибирского региона : материалы Шестой междунар. науч.-практ. конф. (30 сент.–03 окт. 2015 г.). – Иркутск, 2015. – Т. 2. – С. 445–449.
9. Жуковский, Н. Е. Работа (усилие) русского сквозного и американского несквозного тягового прибора при трогании поезда с места и в начале его движения / Н. Е. Жуковский // Бюллетень Экспериментального института путей сообщения. – 1919. – № 13. – С. 31–57.
10. Исследование продольной нагруженности грузовых вагонов, оснащенных фрикционными поглощающими аппаратами нового исполнения, при переходных режимах движения поезда / А. С. Васильев, А. П. Болдырев, Б. Г. Кеглин, А. М. Гуров // Вестн. Брянск. гос. техн. ун-та. – 2014. – № 1 (41). – С. 12–17.

doi 10.15802/stp2017/118002

11. Карпычев, В. А. Уменьшение продольных силовых возмущений при распределенном управлении торможением поезда (РУТП) / В. А. Карпычев, С. Г. Чуев // Вестник Института проблем естественных монополий: Техника железных дорог. – 2017. – № 1 (37). – С. 66–72.
12. К вопросу о математическом описании процессов, происходящих при переходных режимах движения поездов с зазорами в упряжи / В. А. Лазарян, Е. П. Блохин, Л. А. Манашкин, Л. В. Белик // Тр. ДИИТа. – Днепропетровск, 1971. – Вып. 103 : Вопросы динамики подвижного состава и применение математических машин. – С. 18–28.
13. Компаниец, Д. И. Тяжеловесное движение как фактор оптимизации перевозочного процесса / Д. И. Компаниец // Научные исследования: теория, методика и практика : материалы Междунар. науч.-практ. конф. (Чебоксары, 21 мая 2017 г.). – Чебоксары, 2017. – С. 303–305.
14. Коссов, В. С. Исследования продольной динамики и воздействия на путь соединенных поездов массой 12 600 т / В. С. Коссов, А. А. Лунин // Тяжелое машиностроение. – 2016. – № 9. – С. 21–26.
15. Лазарян, В. А. Исследование неустановившихся режимов движения поезда / В. А. Лазарян. – Москва : Трансжелдориздат, 1949. – 135 с.
16. Лазарян, В. А. Исследования переходных режимов движения поездов при сплошном торможении и при переходах через переломы продольного профиля пути / В. А. Лазарян // Труды ДИИТа. – Днепропетровск, 1953. – Вып. 23. – С. 5–23.
17. Лазарян, В. А. Исследования усилий, возникающих при переходных режимах движения в стержнях с различными упругими несовершенствами / В. А. Лазарян // Труды ДИИТа. – Днепропетровск, 1956. – Вып. 25. – С. 5–50.
18. Лазарян, В. А. К вопросу о выборе расчётной схемы при исследовании переходных режимов движения поездов / В. А. Лазарян // Техника железных дорог. – 1952. – № 6. – С. 17–19.
19. Лазарян, В. А. О динамических усилиях в упряжных приборах поезда при немонотонном изменении силы тяги / В. А. Лазарян // Труды ДИИТа. – Днепропетровск, 1948. – Вып. 19. – С. 63–82.
20. Лазарян, В. А. О математическом моделировании движения поезда по переломам продольного профиля пути / В. А. Лазарян, Е. П. Блохин // Труды МИИТа. – Москва, 1974. – Вып. 444. – С. 83–123.
21. Лазарян, В. А. О переходных режимах движения поезда / В. А. Лазарян // Труды ДИИТа. – Днепропетровск, 1973. – Вып. 152. – С. 3–43.
22. Лазарян, В. А. Об усилиях в грузовых поездах при торможении локомотива прямодействующим тормозом / В. А. Лазарян, Е. П. Блохин, И. Г. Барбас // Труды МИИТа. – Москва, 1974. – Вып. 444. – С. 67–73.
23. Лазарян, В. А. Электрическое моделирование движения однородных поездов через переломы продольного профиля пути / В. А. Лазарян, И. Г. Барбас, Л. А. Манашкин // Труды ДИИТа. – Днепропетровск, 1964. – Вып. 50. – С. 5–20.
24. Модульний тренажер машиніста / А. С. Акулов, К. І. Желєзнов, О. М. Заболотний [та ін.] // Локомотив-інформ. – 2017. – №7/8. – С. 42–49.
25. Обеспечение экологической безопасности железнодорожной инфраструктуры при эксплуатации тяжеловесных поездов / Р. М. Куртиков, А. А. Сидраков, Е. А. Кузнецова, Е. А. Иванникова // Современные проблемы проектирования, строительства и эксплуатации железнодорожного пути : тр. XIII Междунар. науч.-техн. конф. – Москва, 2016. – С. 191–194.
26. Определение допустимых сил при оценке устойчивости грузовых вагонов от выжимания в поездах / А. А. Швец, К. И. Железнов, А. С. Акулов, А. Н. Заболотный, Е. В. Чабанюк // Наука та прогрес транспорту. – 2016. – № 1 (61). – С. 189–192. doi: 10.15802/stp2016/61045.
27. Оценка эффективности работы фрикционных металлокерамических элементов поглощающих аппаратов при различных условиях эксплуатации / А. П. Болдырев, П. Д. Жиров, А. С. Васильев, С. В. Боровикова // Вестн. Брянск. гос. техн. ун-та. – 2013. – № 2 (38). – С. 22–31.
28. Пудовиков, О. Е. Моделирование режима регулировочного торможения длинносоставного поезда / О. Е. Пудовиков, С. А. Муров // Мир транспорта. – 2015. – Т. 13, № 2 (57). – С. 28–33.
29. Расчеты и испытания тяжеловесных поездов / Е. П. Блохин, Л. А. Манашкин, Е. Л.Стамблер, Л. Г. Маслеева, В. М. Михайличенко, Н. И. Грановская. – Москва : Транспорт, 1986. – 263 с.
30. Секерова, Ш. А. Анализ научно-исследовательских работ по продольной динамике грузового поезда / Ш. А. Секерова, Е. Г. Адильханов, Ж. С. Мусаев // Вестн. Казах. акад. трансп. и коммуникаций им. М. Тынышпаева. – 2010. – № 6 (67). – С. 32–36.

doi 10.15802/stp2017/118002

31. Селенская, Т. В. Качество функционирования и функциональная надежность автосцепных амортизаторов, работающих в случайно сформированном грузовом поезде / Т. В. Селенская, Е. И. Селенский // Вестн. Брянск. гос. техн. ун-та. – 2014. – № 2 (42). – С. 57–63.
32. Ступин, Д. А. Исследование влияния энергоемкости поглощающих аппаратов на продольные усилия в наливном поезде / Д. А. Ступин, В. И. Беляев // Вестник научно-исследовательского института железнодорожного транспорта. – 2016. – № 3. – С. 154–160.
33. Теоретические аспекты оценки безопасности систем железнодорожного транспорта / О. В. Дружинина, В. П. Сычев, Ю. М. Черкашин, В. В. Качалкин // Внедрение современных конструкций и передовых технологий в путевое хозяйство. – 2014. – Т. 7, № 7. – С. 168–181.
34. Фатьков, Э. А. Программный комплекс для моделирования и расчета задач продольной динамики поезда / Э. А. Фатьков // Новые материалы и технологии в машиностроении. – 2009. – № 10. – С. 130–133.
35. Феоктистов, В. П. Учет ограничений по продольной динамике при регулировании пускового режима электропоездов / В. П. Феоктистов, А. В. Невинский, Д. В. Назаров // Мир транспорта. – 2015. – Т. 13, № 3 (58). – С. 94–100.
36. Экспериментальные исследования продольных усилий в грузовых поездах массой до 10 тыс. тонн при переходных режимах движения / Е. П. Блохин, О. Г. Бойчевский, П. Т. Гребенюк, И. Б. Феоктистов // Труды ЦНИИ МПС. – Москва, 1970. – Вып. 425. – С. 55–85.
37. Языков, В. Н. Численное моделирование динамики поезда в режиме реального времени / В. Н. Языков // Вестн. Брянск. гос. техн. ун-та. – 2015. – № 2 (46). – С. 123.
38. Assessment of the curving performance of heavy haul trains under braking conditions / L. Yang, Y. Kang, Sh. Luo [et al.] // Journal of Modern Transportation. – 2015. – Vol. 23, No. 3. – P. 169–175. doi:10.1007/s4053.
39. Castagnetti, F. The MARATHON 1500 m train opening up new horizons in rail freight transport in Europe / Franco Castagnetti, Armand Toubol. – Brussels : Drifosett, 2014. – 220 c.
40. Dos Santos, G. F. M. Safety analysis of a railway car under the periodic excitation from the track / G. F. M. dos Santos, R. S. Barbosa // Cogent Engineering. – 2016. – Vol. 3, No. 1. – P. 1–12. doi: 10.1080/23311916.2016.1263027.
41. Experimental and numerical determination of the wheel-rail angle of attack / D. Milkovic, G. Simic, J. Tanaskovic [et al.] // Facta universitatis-series mechanical engineering. – 2015. – Vol. 13, No. 2. – P. 123–131.
42. Ivanov, V. Systematization of Integrated Motion Control of Ground Vehicles / Valentin Ivanov, Dzmitry Savitski // IEEE ACCESS. – 2015. – Vol. 3. – P. 2080–2099. doi:10.1109/ACCESS.2015.2496108.
43. Lee, D. C. A mechanical brake hardware-in-the-loop simulation of a railway vehicle that accounts for hysteresis and pneumatic cylinder dynamics / Dong-Chan Lee, Chul-Goo Kang // Advances in mechanical engineering. – 2016. – Vol. 7, No. 11. – P. 1–11. doi: 10.1177/1687814015616086.
44. Longer trains Facts & Experiences in Europe : Results of the CER working group on longer and heavier trains, May 2016. – Brussels : CER aisbl, 2016. – 81 c.
45. Mathematical Modeling of Dynamic Loading of Cassette Bearings for Freight Cars / S. Myamlin, O. Lunys, L. Neduzha, O. Kyryl’chuk // Transport Means : Proc. of 21st Intern. Scientific Conf. – Kaunas, 2017. – P. 973–976.
46. Multi-Train Energy Saving for Maximum Usage of Regenerative Energy by Dwell Time Optimization in Urban Rail Transit Using Genetic Algorithm / F. Lin, Sh. Liu, Zh. Yang [et al.] // ENERGIES. – 2016. – Vol. 9, No. 208. – P. 1–21. doi: 10.3390/en9030208.
47. Naeimi, M. Dynamics of the monorail train subjected to the braking on a straight guideway bridge / Meysam Naeimi, Meisam Tatari, Amin Esmaeilzadeh // Archive of mechanical engineering. – 2015. – Vol. 62, No. 3. – P. 363–375. doi: 10.1515/meceng-2015-0021.
48. Nestacionarieji ir kvazistatiniai geležinkelio traukinių judčjimo režimai / Eug. Blochinas, St. Dailydka, L. Lingaitis, L. Ursuliak. – Vilnius :Technika, 2016. – 168 p. doi: 10.3846/2321-M.
49. Niu, G. Failure Prognostics of Locomotive Electro-Pneumatic Brake Based on Bond Graph Modeling / Gang Niu, Xiaofan Huang // IEEE ACCESS. – 2017. – Vol. 5. – P. 15030–15039. doi:10.1109/ACCESS.2017.2734120.
50. Object oriented simulation of longitudinal trair dynamics efficient tools to optimize sustainability and efficiency of railway systems / A. Frilli, M. Enrico, N. Daniele, P. Luca, R. Andrea // AEIT International Annual Conference (14–16 Oct. 2015). – Naples, Italy, 2015. doi: 10.1109/AEIT.2015.7415257.

doi 10.15802/stp2017/118002

51. Qi, Zh. Simulation of longitudinal dynamics of long freight trains in positioning operations / Zhaohui Qi, Zhihao Huang, Xianchao Kong // Journal Vehicle System Dynamics International Journal of Vehicle Mechanics and Mobility. – 2012. – Vol. 50. – Iss. 9. – P. 1409–1433. doi: org/10.1080/00423114.2012.661063.
52. Regenerative braking in high speed railway applications: Analysis by different simulation tools / M. Ceraolo, G. Lutzemberger, A. Frilli, L. Pugi // Environment and Electrical Engineering (EEEIC) : IEEE 16th International Conference. – Florence, Italy, 2016. – P. 1–5. doi:10.1109/EEEIC.2016.7555474.
53. Shabana, A. A. Use of the non-inertial coordinates in the analysis of train longitudinal forces / A. A. Shabana, A. K. Aboubakr, L. Ding // Journal of Computational and Nonlinear Dynamics. – 2012. – No. 7 (1). – P. 1–10. doi: 10.1115/1.4004122.
54. Simulation of Longitudinal Train Dynamics: Case Studies Using the Train Energy and Dynamics Simulator (TEDS) / M. F. Stewart, S. K. (John) Punwani, D. R. Andersen, G. F. Booth, S. P. Singh, A. Prabhakaran // Joint Rail Conference (March 23–26, 2015). – San Jose, California, USA, 2015. – P. V001T02A011. doi: 10.1115/JRC2015-5760 2015.
55. Spatial Kinetics Model of Supercavitating Vehicles Reflecting Conic-Like Oscillation / Ch. Huang, K. Luo, J. Dang [et al.] // Mathematical problems in engineering. – 2017. – Vol. 2017. – P. 1–12. doi: org/10.1155/2017/3671618.
56. Su, Sh. Evaluation of Strategies to Reducing Traction Energy Consumption of Metro Systems Using an Optimal Train Control Simulation Model / Sh. Su, T. Tang, Y. Wang // Energies. – 2016. – Vol. 9, No. 2. – P. 2–19. doi: 10.3390/en9020105.
57. Tavan, N. An optimal integrated longitudinal and lateral dynamic controller development for vehicle path tracking / N. Tavan, M. Tavan, R. Hosseini // Latin American journal of solids and structures. – 2015. – Vol. 12, No. 6. – P. 1006–1023. doi:10.1590/1679-78251365.
58. The Energy-Efficient Operation Problem of a Freight Train Considering Long-Distance Steep Downhill Sections / X. Lin, Q. Wang, P. Wang [et al.] // ENERGIES. – 2017. – Vol. 10, No. 6. – P. 1–26. doi: 10.3390/en10060794.
59. Ursuljak, L. On the problem of dynamic response of the long trains including joint ones with the liquid cargo / L. Ursuljak, Ya. Romanjuk // Transbaltica 2011 : Proc. of 7th Intern. Scientific Conf. (May 5–6, 2011). – Vilnius, 2011. – P. 269–275.
60. Varazhun, I. Determination of Longitudinal Forces in the Cars Automatic Couplers at Train Electrodynamic Braking / I. Varazhun, A. Shimanovsky, A. Zavarotny // Engineering. – 2016. – Vol. 134 : Transbaltica 2015 : Proc. of the 9th Intern. Scientific Conf. (May 7–8, 2015). – P. 415–421. doi:10.1016/j.proeng.2016.01.032.
61. Wang, X. Optimal control of heavy haul train based on approximate dynamic programming / X. Wang, T. Tang, H. He // Advances in mechanical engineering. – 2017. – Vol. 9, No. 4. – P. 1–15. doi: 10.1177/1687814017698110.
62. Wang, X. Optimal operation of high-speed train based on fuzzy model predictive control / X. Wang, T. Tang // Advances in mechanical engineering. – 2017. – Vol. 9, No. 3. – P. 1–14. doi: 10.1177/1687814017693192.
63. Wei, W. Influence of train tail exhaust device on longitudinal force of train / W. Wei, Y. Hu // Journal of Traffic and Transportation Engineering. – 2012. – No. 12 (5). – P. 43–49.
64. Wu, Q. Longitudinal dynamics and energy analysis for heavy haul trains / Q. Wu, Sh. Luo, C. Cole // J. Mod. Transport. – 2014. – No. 22 (3). – P. 127–136. doi: 10.1007/s40534-014-0055-x.

Л. В. УРСУЛЯК[1*], А. О. ШВЕЦЬ[2*]

[1*] Каф. «Теоретична та будівельна механіка», Дніпропетровський національний університет залізничного транспорту імені академіка В. Лазаряна, вул. Лазаряна, 2, Дніпро, Україна, 49010, тел. +38 (095) 008 70 53, ел. пошта lydm.urs@gmail.com, ORCID 0000-0001-5957-6926
[2*] Каф. «Теоретична та будівельна механіка», Дніпропетровський національний університет залізничного транспорту імені академіка В. Лазаряна, вул. Лазаряна, 2, Дніпро, Україна, 49010, тел. +38 (050) 214 14 19, ел. пошта angela_Shvets@ua.fm, ORCID 0000-0002-8469-3902

ВДОСКОНАЛЕННЯ МАТЕМАТИЧНИХ МОДЕЛЕЙ ДЛЯ ОЦІНКИ ДИНАМІКИ ПОЇЗДА

doi 10.15802/stp2017/118002

ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)

Наука та прогрес транспорту. Вісник Дніпропетровського національного університету залізничного транспорту, 2017, № 6 (72)

Мета. Використовуючи наукові публікації, у роботі необхідно провести аналіз математичних моделей, розроблених в Україні, країнах СНД та за кордоном, які використовуються для теоретичних досліджень динаміки поїзда, а також показати актуальність подальшого їх удосконалення. **Методика.** Інформаційною базою дослідження були офіційні повнотекстові та реферативні бази даних, наукові праці вітчизняних і зарубіжних вчених, професійні періодичні видання, матеріали науково-практичних конференцій, методичні матеріали міністерств та відомств. Аналіз публікацій про існуючі математичні моделі, які використовуються для вирішення широкого кола завдань, пов'язаних із дослідженням динаміки поїзда, показує доцільність їх застосування. **Результати.** Отримані результати досліджень були використані: 1) при проектуванні нових типів поглинаючих апаратів та розподільників повітря; 2) при розробці способів управління рухом звичайних і з'єднаних поїздів; 3) при створенні відповідних режимних карт; 4) при розробці енергозберігаючих способів ведення поїздів; 5) при перегляді Строительных норм и правил (СНиП II-39.76); 6) при виборі параметрів для створеної у ДІІТі автономної системи автоматичного керування допоміжним локомотивом, що знаходиться в складі об'єднаного поїзда; 7) при створенні на базі комп'ютерних технологій тренажерів для навчання машиністів; 8) при оцінюванні динамічних показників екіпажів, що характеризують безпеку руху. Вчені всього світу проводять чисельні експерименти, пов'язані з оцінкою динаміки поїзда, за допомогою математичних моделей, які необхідно постійно вдосконалювати. **Наукова новизна.** Авторами викладені основні теоретичні положення, на підставі яких розроблені існуючі математичні моделі для вирішення задач динаміки поїзда. Проведений аналіз наукових статей, опублікованих в Україні, країнах СНД та за кордоном, дозволяє визначити найбільш актуальні сфери застосування математичних моделей. **Практична значимість.** Практичне значення отриманих результатів полягає у науковій обґрунтованості та прикладній спрямованості теоретичних досліджень із використанням математичних моделей, удосконалення яких дозволить розширити коло вирішуваних завдань, підвищити рівень достовірності отриманих результатів.

Ключові слова: довгосоставні поїзда; динаміка поїзда; математичні моделі поздовжніх коливань поїзда; моделювання міжвагонних з'єднань; наукові статті; поздовжні сили в поїзді; тренажери машиністів локомотивів

Л. В. УРСУЛЯК[1*], А. А. ШВЕЦ[2*]

[1*]Каф. «Теоретическая и строительная механика», Днепропетровский национальный университет железнодорожного транспорта имени академика В. Лазаряна, ул. Лазаряна, 2, Днипро, Украина, 49010, тел. +38 (095) 008 70 53, эл. почта lydm.urs@gmail.com, ORCID 0000-0001-5957-6926
[2*]Каф. «Теоретическая и строительная механика», Днепропетровский национальный университет железнодорожного транспорта имени академика В. Лазаряна, ул. Лазаряна, 2, Днипро, Украина, 49010, тел. +38 (050) 214 14 19, эл. почта angela_Shvets@ua.fm, ORCID 0000-0002-8469-3902

СОВЕРШЕНСТВОВАНИЕ МАТЕМАТИЧЕСКИХ МОДЕЛЕЙ ДЛЯ ОЦЕНКИ ДИНАМИКИ ПОЕЗДА

Цель. Используя научные публикации, в работе необходимо провести анализ математических моделей, разработанных в Украине, странах СНГ и за рубежом для теоретических исследований динамики поезда, а также показать актуальность дальнейшего их совершенствования. **Методика.** Информационной базой исследования являлись официальные полнотекстовые и реферативные базы данных, научные труды отечественных и зарубежных ученых, профессиональные периодические издания, материалы научно-практических конференций, методические материалы министерств и ведомств. Анализ публикаций о существующих математических моделях, используемых для решения широкого круга задач, связанных с исследованием динамики поезда, показывает целесообразность их применения. **Результаты.** Полученные результаты исследований были использованы: 1) при проектировании новых типов поглощающих аппаратов и воздухораспределителей; 2) при разработке способов управления движением обычных и соединенных поездов; 3) при создании соответствующих режимных карт; 4) при разработке энергосберегающих способов ведения поездов; 5) при пересмотре Строительных норм и правил (СНиП II-39.76); 6) при выборе параметров для созданной в ДИИТе автономной системы автоматического управления вспомогательным локомотивом, находящимся в составе соединенного поезда; 7) при создании на базе компьютерных технологий тренажеров для обучения машинистов; 8) при оценке динамических показателей экипажей, характеризующих безопасность движения. Ученые всего мира проводят численные эксперименты, связанные с оценкой динамики поезда, с помощью математических моделей, которые необходимо постоянно совершенствовать. **Научная новизна.** Авторами изложены основные теоретические положения, на основании которых разра-

doi 10.15802/stp2017/118002

ботаны существующие математические модели для решения задач динамики поезда. Проведенный анализ научных статей, опубликованных в Украине, странах СНГ и за рубежом, позволяет определить наиболее актуальные области применения математических моделей. **Практическая значимость**. Практическое значение полученных результатов заключается в научной обоснованности и прикладной направленности теоретических исследований с использованием математических моделей, совершенствование которых позволит расширить круг решаемых задач, повысить уровень достоверности получаемых результатов.

Ключевые слова: длинносоставные поезда; динамика поезда; математические модели продольных колебаний поезда; моделирование межвагонных соединений; научные статьи; продольные силы в поезде; тренажеры машинистов локомотивов

REFERENCES

1. Barbas, I. G. (1962). Analiticheskoye opredeleniye usiliy, voznikayushchikh v upryazhnykh priborakh pri dvizhenii cherez perelom profilya puti. *Sbornik nauchnykh trudov DIITa, 42*, 4-12. (in Russian)
2. Blokhin, Y. P., & Skalozub, V. V. (2002). Vybor rezhimov vedeniya poyezdov kak stokhasticheskaya zadacha vektornoy optimizatsii. *Transport: Proceedings Scientific publication*, *7*, 28-31. (in Russian)
3. Blokhin, Y. P., & Manashkin, L. A. (1982). *Dinamika poyezda (nestatsionarnyye prodolnyye kolebaniya)* [Monograph]. Moscow: Transport. (in Russian)
4. Blokhin, Y. P. (1958). O vliyanii neodnorodnosti poyezda na dinamicheskiye usiliya, voznikayushchiye v upryazhnykh priborakh pri troganii s mesta. *Trudy DIITa*, *26*, 4-12. (in Russian)
5. Boldyrev, A. P., Gurov, A. M., & Fatkov, E. A. (2007). The promising characteristics of shock-absorbing devices in the train operating conditions. *Bulletin of Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan*, *15*, 146-153. (in Russian)
6. Boldyrev, A. P., & Gurov, A. M. (2014). Efficiency of using high energy-consumption cushioning devices in freight wagons. *Transport Rossiyskoy Federatsii*, *3*(52), 43-44. (in Russian)
7. Vereskun, V.D., & Pritykin, D. E. (2014). Mnogomassovaya model podvizhnoy edinitsy dlya issledovaniya prodolnoy dinamiki gruzovogo poyezda. *Vestnik RGUPS*, *2*, 16-27. (in Russian)
8. Voronova, Y. V., & Rychkov, N. P. (2015). Dinamika gruzovykh vagonov na krivykh malogo radiusa. *Proceeding of the International Conference on Transport Infrastructure of the Siberian region*, *2*, 445-449. Retrieved from https://www.irgups.ru/sites/default/files/irgups/journal/tom_2_0.pdf (in Russian)
9. Zhukovskiy, N. Y. (1919). Rabota (usiliye) russkogo skvoznogo i amerikanskogo neskvoznogo tyagovogo pribora pri troganii poyezda s mesta i v nachale ego dvizheniya. *Byulleten Eksperimentalnogo instituta putey soobshcheniya*, *13*, 31-57. (in Russian)
10. Vasilev, A. S., Boldyrev, A. P., Keglin, B. G., & Gurov, A. M. (2014). Research of freight car's longitudinal loading equipped new frictional absorbing devices. *Bulletin of Bryansk State Technical University*, *1*, 12-17. (in Russian)
11. Karpychev, V. A., & Chuev, S. G. (2017). Umensheniye prodolnykh silovykh vozmushcheniy pri raspredelennom upravlenii tormozheniyem poyezda (RUTP). *Tekhnika zheleznykh dorog*, *1*, 66-72. (in Russian)
12. Lazaryan, V. A., Blokhin, Y. P., Manashkin, L. A., & Belik, L. V. (1971). K voprosu o matematicheskom opisanii protsessov, proiskhodyashchikh pri perekhodnykh rezhimakh dvizheniya poyezdov s zazorami v upryazhi. *Trudy DIITa*, *103*, 18-28. (in Russian)
13. Kompaniets, D. I. (2017). Tyazhelovesnoye dvizheniye kak faktor optimizatsii perevozochnogo protsessa. Proceedings of the International Scientific Conference Nauchnyye issledovaniya: teoriya, metodika i praktika, *1*, 303-305. (in Russian)
14. Kossov, V. S., & Lunin, A. A. (2016). Studies of longitudinal dynamics and impact of articulated trains weighing 12600 t on the rail track. *Tyazheloye Mashinostroeniye*, *9*, 21-26. (in Russian)
15. Lazaryan, V. A. (1949). Issledovaniye neustanovivshikhsya rezhimov dvizheniya poyezda. Moscow: Transzheldorizdat. (in Russian)
16. Lazaryan, V. A. (1953). Issledovaniya perekhodnykh rezhimov dvizheniya poyezdov pri sploshnom tormozhenii i pri perekhodakh cherez perelomy prodolnogo profilya puti. *Trudy DIITa*, *23*, 5-23. (in Russian)
17. Lazaryan, V. A. (1956). Issledovaniya usiliy, voznikayushchikh pri perekhodnykh rezhimakh dvizheniya v sterzhnyakh s razlichnymi uprugimi nesovershenstvami. *Trudy DIITa*, *25*, 5-50. (in Russian)
18. Lazaryan, V. A. (1952). K voprosu o vybore raschetnoy skhemy pri issledovanii perekhodnykh rezhimov dvizheniya poyezdov. *Tekhnika zheleznykh dorog*, *6*, 17-19. (in Russian)
19. Lazaryan, V. A. (1948). O dinamicheskikh usiliyakh v upryazhnykh priborakh poyezda pri nemonotonnom izmenenii sily tyagi. *Trudy DIITa*, *19*, 63-82. (in Russian)

doi 10.15802/stp2017/118002

20. Lazaryan, V. A. & Blokhin, Y. P. (1974). O matematicheskom modelirovanii dvizheniya poyezda po perelomam prodolnogo profilya puti. *Trudy MIITa*, 444, 83-123. (in Russian)
21. Lazaryan, V. A. (1973). O perekhodnykh rezhimakh dvizheniya poyezda. *Trudy DIITa*, *152*, 3-43. (in Russian)
22. Lazaryan, V. A., Blokhin, Y. P., & Barbas, I. G. (1974). Ob usiliyakh v gruzovykh poyezdakh pri tormozhenii lokomotiva pryamodeystvuyushchim tormozom. *Trudy MIITa*, *444*, 67-73. (in Russian)
23. Lazaryan, V. A., Barbas, I. G., & Manashkin, L. A. (1964). Elektricheskoye modelirovaniye dvizheniya odnorodnykh poyezdov cherez perelomy prodolnogo profilya puti. *Trudy DIITa*, *50*, 5-20. (in Russian)
24. Akulov, A. S., Zheleznov, K. I., Zabolotnyi, O. M., Ursulyak, L. V., Chabanyuk, E. V., Chernyaev, D. V., & Shvets, A. O. (2017). Modulnyi trenazher mashynista. *Lokomotyv-Inform*, *7-8*, 42-49. (in Ukrainian)
25. Kurtikov, R. M., Sidrakov, A. A., Kuznetsova, Y. A., & Ivannikova, Y. A. (2016). Obespecheniye ekologicheskoy bezopasnosti zheleznodorozhnoy infrastruktury pri ekspluatatsii tyazhelovesnykh poyezdov. *Proceedings of the International Scientific Conference Sovremennyye problemy proektirovaniya, stroitelstva i ekspluatatsii zheleznodorozhnogo puti*, 191-194. (in Russian)
26. Shvets, A. A., Zheleznov, K. I., Akulov, A. S., Zabolotny, A. N., & Chabanyuk, E. V. (2016). Determination the permissible forces in assessing the lift resistant factor of freight cars in trains. *Science and Transport Progress*, *1*(61), 189-192. doi: 10.15802/stp2016/61045. (in Russian)
27. Boldyrev, A. P., Zhirov, P. D., Vasilyev, A. S., & Borovikova, S. V. (2013). Assessment of overall performance of the frictional ceramic-metal elements of absorbing devices under various service conditions. *Bulletin of Bryansk State Technical University*, *2*(38), 22-31. (in Russian)
28. Pudovikov, O. E., & Murov, S. A. (2015) Modelirovaniye rezhima regulirovochnogo tormozheniya dlinnosostavnogo poyezda. *World of Transport and Transportation*, *2*(57), 28-33. (in Russian)
29. Blokhin, Y. P., Manashkin, L. A., Stambler, Y. L., Masleeva, L. G., Mikhaylichenko, V. M., & Granovskaya, N. I. (1986). *Raschety i ispytaniya tyazhelovesnykh poyezdov*. Moscow: Transport. (in Russian)
30. Sekerova, S. A., Adilkhanov, Y. G., & Musaev, Z. S. (2010). Analiz nauchno-issledovatelskikh rabot po prodolnoy dinamike gruzovogo poyezda. *The Bulletin of KazAT*, *6*(67), 32-36. (in Russian)
31. Selenskaya, T. V., & Selenskiy, E. I. (2014). Quality of service and reliability of railway vehicle autocoupling shock absorbers operating in randomly grouped freight trains. *Bulletin of Bryansk State Technical University*, *2*(42), 57-63. (in Russian)
32. Stupin, D. A., & Belyaev, V. I. (2016). Research of influence of energy consumption of draft gears on longitudinal forces in the tank car train. *Vestnik of the Railway Research Institute*, *75*(3), 154-160. (in Russian)
33. Druzhinina, O. V., Sychev, V. P., Cherkashin, Y. M., & Kachalkin, V. V. (2014) Teoreticheskiye aspekty otsenki bezopasnosti sistem zheleznodorozhnogo transporta. *Vnedreniye sovremennykh konstruktsiy i peredovykh tekhnologiy v putevoye khozyaystvo*, *7*(7), 168-181. (in Russian)
34. Fatkov, E. A. (2009) Programmnyy kompleks dlya modelirovaniya i rascheta zadach prodolnoy dinamiki poezda. *New Materials and Technologies in Machinebuilding*, *10*, 130-133. (in Russian)
35. Feoktistov, V. P., Nevinsky, A. V., & Nazarov, D. V. (2015) Uchet ogranicheniy po prodolnoy dinamike pri regulirovanii puskovogo rezhima elektropoyezdov. *World of Transport and Transportation*, *3*(58), 94-100. (in Russian)
36. Blokhin, Y. P., Boychevskiy, O. G., Grebenyuk, P. T., & Feoktistov, I. B. (1970). Eksperimentalnyye issledovaniya prodolnykh usiliy v gruzovykh poyezdakh massoy do 10 tys. tonn pri perekhodnykh rezhimakh dvizheniya. *Trudy TsNII MPS*, *425*, 55-85. (in Russian)
37. Yazykov, V. N. (2015). Numerical simulation of train dynamics in real time mode. *Bulletin of Bryansk State Technical University*, *2(46)*, 123-126. (in Russian)
38. Yang, L., Kang, Y., Luo, S., & Fu, M. (2015). Assessment of the curving performance of heavy haul trains under braking conditions. *Journal of Modern Transportation*, *23*(3), 169-175. doi: 10.1007/s4053. (in English)
39. Castagnetti, F., & Toubol, A. (Eds.) (2014). *The MARATHON 1500 m train opening up new horizons in rail freight transport in Europe*. Brussels: Drifosett. (in English)
40. Dos Santos, G. F. M., & Barbosa, R. S. (2016). Safety analysis of a railway car under the periodic excitation from the track. *Cogent Engineering*, *3*(1), 1-12. doi: 10.1080/23311916.2016.1263027. (in English)
41. Milković, D., Simić, G., Tanasković, J., Jakovljević, Ž., & Lučanin, V. (2015). Experimental and numerical determination of the wheel-rail angle of attack. *Facta Universitatis, Series Mechanical Engineering*, *13*(2), 123-131. (in English)
42. Ivanov, V., & Savitski, D. (2015). Systematization of Integrated Motion Control of Ground Vehicles. *IEEE ACCESS*, *3*, 2080-2099. doi: 10.1109/ACCESS.2015.2496108. (in English)

doi 10.15802/stp2017/118002

43. Lee, D. C., & Kang, C.-G. (2016). A mechanical brake hardware-in-the-loop simulation of a railway vehicle that accounts for hysteresis and pneumatic cylinder dynamics. *Advances in Mechanical Engineering*, *7* (11), 1-11. doi: 10.1177/1687814015616086. (in English)
44. CER. (2016). *Longer trains Facts & Experiences in Europe: Results of the CER working group on longer and heavier trains*. Brussels: Community of European railway and infrastructure companies. (in English)
45. Myamlin, S., Lunys, O., Neduzha, L., & Kyryl'chuk, O. (2017). Mathematical Modeling of Dynamic Loading of Cassette Bearings for Freight Cars. *Proceedings of 21st International Conference on Transport Means 2017, Lithuania*, *3*, 973-976. (in English)
46. Lin, F., Liu, S., Yang, Z., Zhao, Y., Yang, Z., & Sun, H. (2016). Multi-Train Energy Saving for Maximum Usage of Regenerative Energy by Dwell Time Optimization in Urban Rail Transit Using Genetic Algorithm. *Energies*, *9* (208), 1-21. doi: 10.3390/en9030208. (in English)
47. Naeimi, M., Tatari, M., & Esmaeilzadeh, A. (2015). Dynamics of the monorail train subjected to the braking on a straight guideway bridge. *Archive of Mechanical Engineering*, *62* (3), 363-375. doi: 10.1515/meceng-2015-0021. (in English)
48. Blochinas, E., Dailydka, S., Lingaitis, L., & Ursuliak, L. (2016). *Nestacionarieji ir kvazistatiniai geležinkelio traukinių judėjimo režimai*. Vilnius: Technika. (in Lithuanian)
49. Niu, G., & Huang, X. (2017). Failure Prognostics of Locomotive Electro-Pneumatic Brake Based on Bond Graph Modeling. *IEEE Access*, *5*, 15030-15039. doi: 10.1109/ACCESS.2017.2734120. (in English)
50. Frilli, A., Meli, E., Nocciolini, D., Pugi, L., & Rindi, A. (2015). Object oriented simulation of longitudinal trair dynamics efficient tools to optimize sustainability and efficiency of railway systems. *AEIT International Annual Conference, 14-16 Oct. 2015, Naples, Italy*. doi: 10.1109/AEIT.2015.7415257. (in English)
51. Qi, Z., Huang, Z., & Kong, X. (2012). Simulation of longitudinal dynamics of long freight trains in positioning operations. *Vehicle System Dynamics*, *50*(9), 1409-1433. doi: 10.1080/00423114.2012.661063. (in English)
52. Ceraolo, M., Lutzemberger, G., Frilli, A., & Pugi, L. (2016). Regenerative braking in high speed railway applications: Analysis by different simulation tools. *16th International Conference on Environment and Electrical Engineering (EEEIC), 7-10 June 2016, Florence, Italy*, 1-5. doi: 10.1109/EEEIC.2016.7555474. (in English)
53. Shabana, A. A., Aboubakr, A. K., Ding, L. (2012). Use of the non-inertial coordinates in the analysis of train longitudinal forces. *Journal of Computational and Nonlinear Dynamics*, *7*(1), 1-10. doi: 10.1115/1.4004122. (in English)
54. Stewart, M. F., Punwani, S. K., Andersen, D. R., Booth, G. F., Singh, S. P., Prabhakaran, A. (2015). Simulation of Longitudinal Train Dynamics: Case Studies Using the Train Energy and Dynamics Simulator (TEDS). *Joint Rail Conference, San Jose, California, USA, March 23-26, 2015*. doi: 10.1115/JRC2015-5760. (in English)
55. Huang, C., Luo, K., Dang, J., Qin, K., & Li, D. (2017). Spatial Kinetics Model of Supercavitating Vehicles Reflecting Conic-Like Oscillation. *Mathematical Problems in Engineering*, *2017*, 1-12. doi: 10.1155/2017/3671618. (in English)
56. Su, S., Tang, T., & Wang, Y. (2016). Evaluation of Strategies to Reducing Traction Energy Consumption of Metro Systems Using an Optimal Train Control Simulation Model. *Energies*, *9*(2), 2-19. doi: 10.3390/en9020105. (in English)
57. Tavan, N., Tavan, M., & Hosseini, R. (2015). An optimal integrated longitudinal and lateral dynamic controller development for vehicle path tracking. *Latin American Journal of Solids and Structures*, *12*(6), 1006-1023. doi: 10.1590/1679-78251365. (in English)
58. Lin, X., Wang, Q., Wang, P., Sun, P., & Feng, X. (2017). The Energy-Efficient Operation Problem of a Freight Train Considering Long-Distance Steep Downhill Sections. *Energies*, *10* (6), 1-26. doi: 10.3390/en10060794. (in English)
59. Ursuljak, L., & Romanjuk, Y. (2011). On the problem of dynamic response of the long trains including joint ones with the liquid cargo. *Proceedings of the 7th International Scientific Conference Transbaltica 2011, May 5-6, 2011, Vilnius, Lithuania*, 269-275. Retrieved from http://leidykla.vgtu.lt/conferences/Transbaltica_2011/pdf/052.pdf. (in English)
60. Varazhun, I., Shimanovsky, A., & Zavarotny, A. (2016). Determination of Longitudinal Forces in the Cars Automatic Couplers at Train Electrodynamic Braking. *Proceedings of the 9th international scientific conference Transbaltica-2016, May 7-8, 2016, Vilnius, Lithuania*, *134*, 415-421. doi: 10.1016/j.proeng.2016.01.032. (in English)
61. Wang, X., Tang, T., & He, H. (2017). Optimal control of heavy haul train based on approximate dynamic programming. *Advances in Mechanical Engineering*, *9*(4), 1-15. doi: 10.1177/1687814017698110. (in English)

doi 10.15802/stp2017/118002

62. Wang, X., & Tang, T. (2017). Optimal operation of high-speed train based on fuzzy model predictive control. *Advances in Mechanical Engineering, 9*(3), 1-14. doi: 10.1177/1687814017693192. (in English)
63. Wei, W., & Hu, Y. (2012). Influence of train tail exhaust device on longitudinal force of train. *Journal of Traffic and Transportation Engineering, 12*(5), 43-49. (in English)
64. Wu, Q., Luo, S., & Cole, C. (2014). Longitudinal dynamics and energy analysis for heavy haul trains. *Journal of Modern Transportation, 22*(3), 127-136. doi: 10.1007/s40534-014-0055-x. (in English)

Prof. V. L. Horobets, Dr. Sc. (Techn.) (Ukraine); Prof. K. S. Zabolotnyi, Dr. Sc. (Techn.) (Ukraine) recommended this article to be published

Received: July 31, 2017
Accessed: October 30, 2017

doi 10.15802/stp2017/118002