

## Study of Proportional Pressure Modulator on the Basis of Electromagnetic-Type Linear Motor

M. Yu. Zalohin<sup>1)</sup>, B. A. Liubarskyi<sup>2)</sup>, S. N. Schuklinov<sup>1)</sup>, M. G. Mychalevych<sup>1)</sup>, D. N. Leontiev<sup>1)</sup>

<sup>1)</sup>Kharkiv National Automobile and Highway University (Kharkiv, Ukraine),

<sup>2)</sup>National Technical University "Kharkiv Polytechnic Institute" (Kharkiv, Ukraine)

© Белорусский национальный технический университет, 2018  
Belarusian National Technical University, 2018

**Abstract.** The paper deals with a workflow of a proportional pressure modulator equipped with a linear electric motor of electromagnetic type (LEMET). A schematic diagram consisting of a power supply and control system has been constructed to determine the performance of LEMET. The power supply system is a self-contained half-bridge inverter. The converter input is supplied with 12 V DC voltage. The motor phase is powered by an inverter which includes transistor switches and diodes. The control system of the autonomous inverter consists of two channels – a current limiting channel and a linear transfer channel. The study is based on the results of numerical and simulation modeling of LEMET workflows. Numerical simulation is performed and investigated by a finite element method in the FEMM environment. Geometry of the LEMET model lies in the region of air with an electromagnetic permeability of 1. An initial radius of the grid generation for the working gap area is 0.5 mm, while for other areas an adaptive generation method has been applied. In order to determine a continuous power function at any point within a current variation interval  $i$  and a displacement  $x$  current linkage and electromagnetic force functions have been approximated by polynomials use of the Curve Fitting application. The simulation LEMET model of a proportional modulator has been built in the MatLab Simulink environment. The implicit Runge-Kutta method using the second-order inverse differentiation formulas with a variable step has been applied for solution of a mathematical model in the MatLab Simulink system. The equation of an electrical circuit for an inductor motor phase has been compiled according to the second law of Kirchhoff. The LEMET traction characteristics have been obtained by moving a locking and adjusting element (LCE) from 0 to 6 mm in steps of 1 mm while changing the MMF in the winding from 0 to 2 A in steps of 0.1 A. It has been established that in order to move the LCE by 6 mm with the speed of 40 mm/s with a resolution of 0.15 mm, the maximum value of the current in the LEMET winding is equal to 2.5 A. In this case the value of the electromagnetic force is 120 N. This makes it possible to improve an accuracy of the brake drive pressure regulation by 12.3 %. Solutions have been proposed to increase the LEMET speedwork. Characteristics of the engine have been described and numerical parameters of LEMET have been determined in the paper. The developed simulation model allows to investigate functional properties and dynamic characteristics of the proportional modulator with a relative error of 4.07 %.

**Keywords:** proportional pressure modulator, linear motor of electromagnetic type, finite element method, simulation, workflow

**For citation:** Zalohin M. Yu., Liubarskyi B. A., Schuklinov S. N., Mychalevych M. G., Leontiev D. N. (2018) Study of Proportional Pressure Modulator on the Basis of Electromagnetic-Type Linear Motor. *Science and Technique*. 17 (5), 440–446. <https://doi.org/10.21122/2227-1031-2018-17-5-440-446>

## Исследование пропорционального модулятора давления на основе линейного двигателя электромагнитного типа

Канд. техн. наук, доц. М. Ю. Залогин<sup>1)</sup>, докт. техн. наук, проф. Б. А. Любарский<sup>2)</sup>,  
докт. техн. наук, проф. С. Н. Шуклинов<sup>1)</sup>, канд. техн. наук, доц. Н. Г. Михалевич<sup>1)</sup>,  
канд. техн. наук, доц. Д. Н. Леонтьев<sup>1)</sup>

<sup>1)</sup>Харьковский национальный автомобильно-дорожный университет (Харьков, Украина)

<sup>2)</sup>Национальный технический университет «Харьковский политехнический институт» (Харьков, Украина)

**Реферат.** Проведено исследование рабочего процесса пропорционального модулятора давления с линейным электродвигателем электромагнитного типа (ЛЭДЭТ). Для определения рабочих характеристик ЛЭДЭТ составлена принци-

### Адрес для переписки

Залогин Максим Юрьевич  
Харьковский национальный  
автомобильно-дорожный университет  
ул. Ярослава Мудрого, 25,  
61002, г. Харьков, Украина  
Тел.: +375 057 707-37-69  
zalogin@khadi.kharkov.ua

### Address for correspondence

Zalohin Maksim Yu.  
Kharkiv National  
Automobile and Highway University  
25 Yaroslava Mudrogo str.,  
61002, Kharkov, Ukraine  
Tel.: +375 057 707-37-69  
zalogin@khadi.kharkov.ua

пиальная схема, состоящая из системы питания и управления. Система питания представляет собой автономный полумостовой инвертор. На вход преобразователя подается постоянное напряжение 12 В. Фаза двигателя питается от инвертора, в состав которого входят транзисторные ключи и диоды. Система управления автономным инвертором состоит из двух каналов – канала ограничения тока и канала линейного перемещения. Исследование основано на результатах численного и имитационного моделирования рабочих процессов ЛЭДЭТ. Численное моделирование выполнено и исследовано методом конечных элементов в среде FEMM. Геометрия модели ЛЭДЭТ заключена в область воздуха с электромагнитной проницаемостью, равной 1. Начальный радиус генерации сетки для области рабочего зазора составляет 0,5 мм, а для других областей установлен адаптивный метод генерации. Для определения непрерывной степенной функции в любой точке интервала варьирования тока  $i$  и перемещения  $x$  функции потокосцепления и электромагнитной силы аппроксимированы полиномами при помощи приложения Curve Fitting. Имитационная модель ЛЭДЭТ пропорционального модулятора построена в среде MatLab Simulink. Для решения математической модели в системе MatLab Simulink выбран неявный метод Рунге – Кутты, использующий формулы обратного дифференцирования 2-го порядка с переменным шагом. Уравнение электрической цепи фазы индукторного двигателя составлено согласно второму закону Кирхгофа. Тяговые характеристики ЛЭДЭТ получены путем перемещения запорно-регулирующего элемента (ЗРЭ) от 0 до 6 мм с шагом 1 мм при изменении магнито-движущей силы (МДС) в обмотке от 0 до 2 А с шагом 0,1 А. Установлено, что для перемещения ЗРЭ на 6 мм при скорости 40 мм/с с дискретностью 0,15 мм максимальное значение силы тока в обмотке ЛЭДЭТ равно 2,5 А. При этом значение электромагнитной силы равно 120 Н. Это позволяет повысить точность регулирования давления в тормозном приводе на 12,3 %. Предложены решения, повышающие быстродействие ЛЭДЭТ. Описаны характеристики двигателя и определены численные параметры ЛЭДЭТ. Разработанная имитационная модель позволяет исследовать функциональные свойства и динамические характеристики пропорционального модулятора с относительной погрешностью 4,07 %.

**Ключевые слова:** пропорциональный модулятор давления, линейный двигатель электромагнитного типа, метод конечных элементов, моделирование, рабочий процесс

**Для цитирования:** Исследование пропорционального модулятора давления на основе линейного двигателя электромагнитного типа / М. Ю. Залогин [и др.] // *Наука и техника*. 2018. Т. 17, № 5. С. 440–446. <https://doi.org/10.21122/2227-1031-2018-17-5-440-446>

## Introduction

It is a well-known fact that the development of measures to improve the structural safety of the car has a global character nowadays. The reason for this is the increasing complexity of road traffic, which in turn poses problems to the driver while steering the car that one may not always be able to cope with. The above problems can only be solved by on-board computer systems, since other administrative measures do not lead to sustained decline in the number and complexity of accidents. In this regard, on-board computer systems, processing the streaming information, can systemize it, record it, and if there is a necessity, provide or modify the appropriate steps in the light of prevailing traffic conditions. From this point of view, the most modern braking system is the electro-pneumatic brake system (EPBS). The air pressure in the brake circuits of such a system is formed by electronic control pressure modulators. The control is carried out by means of electronics based on sensor information included in the configuration of any automated system. The quality of control is determined by the executive devices (modulators) whose structure many parameters of traffic safety depend

upon. Increasing the speed of modulators helps in solving a number of technical problems, while improving their design leads to the reduction of the cost of production of brake equipment and the brake system as a whole.

## Analysis of publications

The works of A. K. Alexander, L. V. Gurevich, A. I. Popova; L. A. Ryzhykh [1], D.N. Leontiev [2] deal with the creation and improvement of EPBS. At the Automobile Department of KhNAHU there was developed and introduced into manufacture a proportional modulator EPBS designed on the basis of a rotary electric stepper motor FL57STH76-2084B with a gear-train rack pinion. It is established that the range of the rotary stepper electric motor operation in the proportional modulator is very narrow, which is irrational. To address this shortcoming, in this paper it is proposed to apply a gearless drive based on the linear electric motor of the electromagnetic type (LEMET). Drives based on the linear electric motor of the electromagnetic type are widespread in the field of railway technology for drives of the body tilt systems of high speed electric rolling stock [3], and in the switches of sleeper type [4].

## Goal and problem statement

The aim of the given work is to determine the possibility of using in the pressure modulator of the electro-pneumatic brake system a linear electric motor of electromagnetic type.

To achieve this goal it is necessary to solve the following tasks: to develop a mathematical model of linear electromagnetic motor; to develop a mathematical model of the proportional pressure modulator with a linear electric motor of the electromagnetic type; perform a simulation study of the workflow of proportional pressure modulator with a linear stepper electric motor.

## Modeling of working processes is proportional to the pressure modulator

To select the main parameters of the proportional modulator with a linear electric motor of the electromagnetic type as well as build its static characteristics, the following initial data is required:  $z$  – increment of the locking control element (LCE);  $t$  – time of the full stroke of the shut-off control element.

Discreteness of the locking control element displacement is determined by the dependence of the locking control element displacement and outlet pressure. In the traditional proportional (servo) machines, namely, in brake valves, the gradation of the output pressure is one of the indicators of pneumatic actuator quality. Regulations are not proposed. There is no specified gradation change of the output pressure in proportional devices. Pro-

ceeding from other recommendations, the permissible value of the pressure degree in the pneumatic brake actuator should not exceed 3–4 % of the maximum pressure and 0.02 MPa [5, 6].

Thus, the discrete displacement of the locking control element can be determined by the following formula.

$$z = \frac{P_{\max}}{P_{\deg}}, \quad (1)$$

where  $P_{\max}$  – the maximum pressure in the actuator;  $P_{\deg}$  – measure of the degree of change in pressure.

The minimal time of the locking control element turn in serial brake valves is determined by the time of brake-pedal actuation during emergency braking, which is regulatory established to be 0.2 s [5, 7]. Thus, the maximum travel time of LCE in the proportional modulator shall not exceed 0.2 s and the minimum time is limited by the inertial parameters of the linear electric motor of electromagnetic type. The design scheme is proportional to the pressure modulator with a linear stepper electric motor shown in fig. 1.

The mathematical model of the linear electric motor of the electromagnetic type consists of equations of electric circuits and the movement of armature. The equations of the electric circuit describe the workflow of the linear electric motor of electromagnetic type whose phases are based on the solution of the Lagrange equations for electromechanical systems [8, 9].

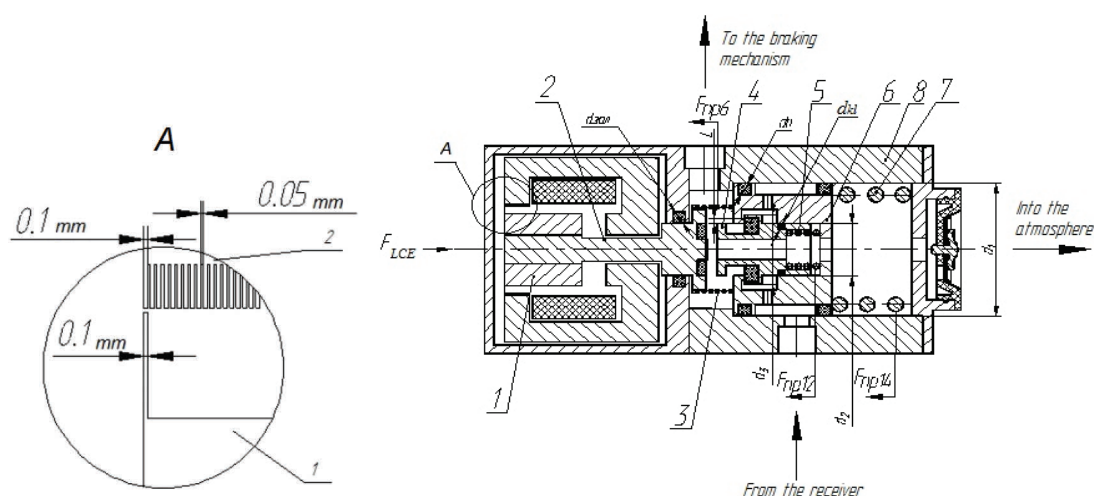


Fig. 1. Analytical model of proportional modulator:

- 1 – anchor, LEET; 2 – LSE rod; 3 – return spring; 4 – double-seat valve; 5 – spring of double-seat valve; 6 – follow-up air piston; 7 – follow-up air piston spring; 8 – case of modulator

Transforming it with respect to the derivative of the current, we obtain the differential equation of the first order in the form of:

$$\frac{di}{dt} = \frac{U - iR - vK}{L}, \quad (2)$$

where  $U$  – voltage;  $i$  – current strength;  $R$  – resistance of the winding field;  $v$  – linear speed;  $K = \partial\psi/\partial x$  – private derivative of the flux linkage to move  $x$ , at constant current  $i$ ;  $L = \partial\psi/\partial i$  – partial derivative of the flux linkage according to current  $i$ , at constant displacement of  $x$ ;  $\psi$  – flux linkage of the motor phase.

According to the Newton's second law, the equation of armature motion takes the following form:

$$\frac{d^2x}{dt^2} = \frac{F_e - F_s}{m}, \quad (3)$$

where  $m$  – is the mass of the moving parts of the proportional modulator;  $F_e$  – is the electromagnetic force of the linear electric motor of electromagnetic type;  $F_s$  – is the force of resistance.

Expressions for determining the flux linkage  $\psi$  and its derivatives according to the current and the displacement, as well as the electromagnetic force  $F_e$  are the functions of linear displacement  $x$  and the current  $i$ :

$$\psi = f(x, i); \quad F_e = f(x, i). \quad (4)$$

The definition of parameters  $\psi$ ,  $L$ ,  $K$ ,  $F_e$  are performed using the finite element method and the subsequent regression analysis. Modeling and study of LEMET of the proposed design was carried out in the FEMM environment [10]. When building the model, the following basic parameters and assumptions were taken into account: the magnetic system is axially symmetric; the body material and the motor armature is made of steel 2020, the stator winding is made of copper with MDS 1000 A; the eddy currents and hysteresis in the magnetic core are not taken into account, the keys of the converter have ideal current-voltage characteristics [11–13]. The estimated area of LEMET is limited to a sphere (fig. 2a, item 4) filled with air. On the border of region  $A$  they set the boundary condition of Dirichlet [3]. This makes it possible to keep the magnetic flux within this area. Finally, the total force is determined by integrating the differential force on the loop around the anchor. This contour is automatically determined by the software package FEMM. As a result of generation of the finite element mesh the model contains 25798 nodes and 51528 elements (fig. 2b). To obtain a family of traction characteristics LEMET, they carried out a set of numerical experiments by varying the movement of LCE and the anchor  $x$  in the range from 0.1 to 8.0 mm with increments of 0.1 mm and with the current change in the coil from 0 to 2 in increments of 0.1 A.

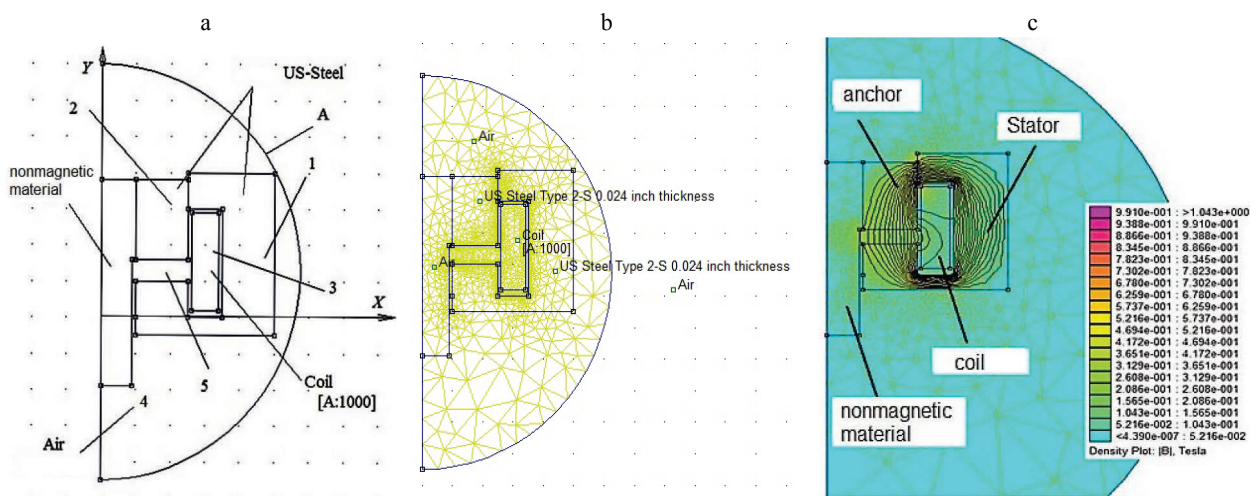


Fig. 2. Finite element model of LEMET

At each step of calculation they carried out automatic calculation of the electromagnetic field (fig. 2c), the magnitude of the traction force  $F_e$  and the flux linkage  $\psi$  for the current value  $i$  and displacement  $x$ . The values of these parameters were measured according to the method presented in [11].

Using the MatLab Curve Fitting application, regression analysis was carried out and the continuous dependence of functions  $\psi = f(x, i)$  and  $F_e = f(x, i)$ , in the form of polynomials 4 and 5 degree was, respectively, obtained. Then, the partial derivatives of the flux linkage according to the movement ( $K$ ) and current ( $L$ ) were determined analytically.

A simulation model of the actuator of proportional modulator on the basis of the linear electric motor of electromagnetic type was built in the MatLab Simulink environment, which reflects the consistent transfer of energy from the power source to the executive element – LSE, given the law of the input signal and structural parameters of the linear stepper motor (fig. 3). It contains: the unit INVERTOR simulating the operation of the inverter and the control system of the drive, the unit ID\_EL describing the work of energy transformation in the LEMET and MEHANIKA block in which they simulate a dynamic process of the mechanical part of the drive.

To solve the mathematical model in the MatLab Simulink system, the implicit Runge-Kutt method using the reverse differentiation formula of the 2<sup>nd</sup> order as well as in the further solution with a variable pitch [8] was chosen. The simulation time constituted  $t = 0.5$  s. The integration step was equal to  $10^{-9}$ . The current analysis of dynamic processes in the given model was performed using Scope blocks. To analyze and evaluate the dynamic dependencies in the function on parameters of the modulator the simulation results are

stored as a dataset in an Excel file, using the blocks To Workspace. The results of simulation of the workflow of proportional modulator reflects the dependence of the force  $F_e$ , the displacement  $x$ , and the current  $i$  in the modulator on the time  $t$ .

Fig. 4a shows the dependence  $F = f(t)$  at different maximum speeds of movement of the rod LSE 20 mm/s and 40 mm/s, respectively. The graph shows that the maximum value of the force which is required to overcome the resistance forces is achieved during 0.2 seconds with maximum speed of 40 mm/s and varies in proportion to the resistance force  $F_c$ . While analyzing the characteristics of the workflow, it was established that at the maximum set speed of movement of LSE 20 mm/s, the output of operational performance relative the established procedure increased by 34.8 %.

The dynamic fluctuations that occur in the established mode, testify to the automatic adjustment of the workflow characteristics that is a consequence of PID controller application in the simulation model. Fig. 4b reflects the graph of dependence  $x = f(t)$ . The figure shows that a full stroke of LSE is achieved within 0.2 s, which corresponds to the requirements of normative documents [14]. Fluctuations that are observed in the established mode occur within 0.1 mm, which practically does not affect the working process of the electropneumatic braking system, as they are in the dead zone of the actuator.

Fig. 4c shows the dependence  $i = f(t)$ . The graph indicates that in the mode of gathering the power, as well as actuation of the locking and regulating element, the maximum value of the current is 2.5 A, which is 20 % higher than the calculated value. This suggests that at the initial stage of designing a linear stepper motor, one has to calculate its operational performance for the maximum current of 3–4 A.

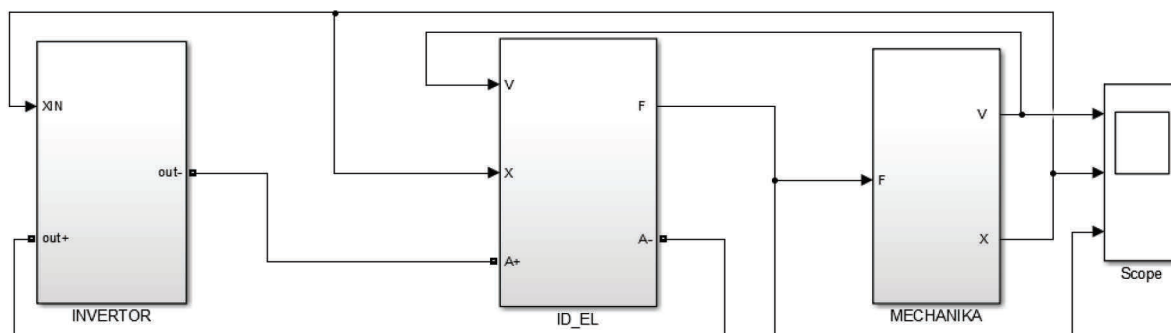


Fig. 3. Simulation model of LEMET drive



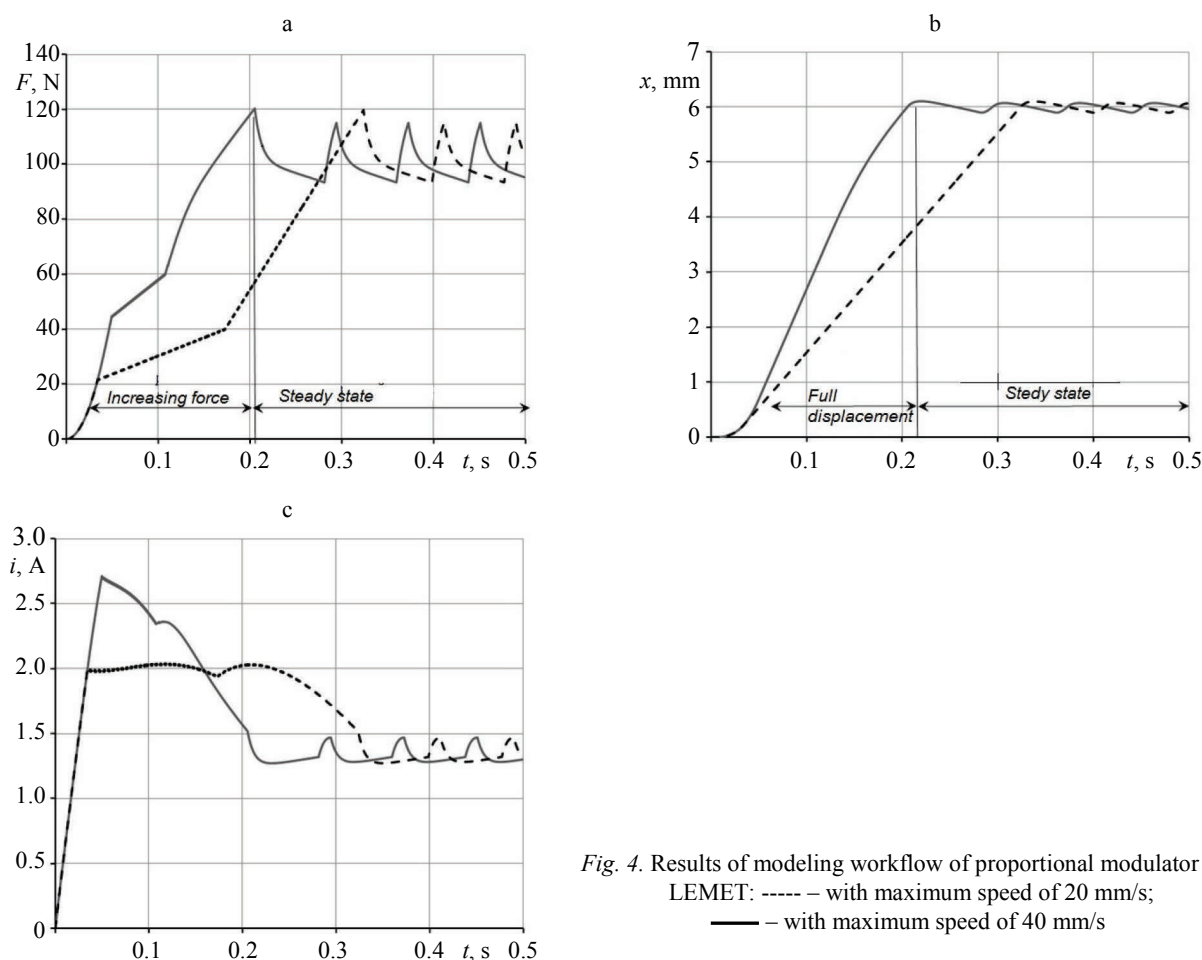


Fig. 4. Results of modeling workflow of proportional modulator with LEMET: ----- – with maximum speed of 20 mm/s; ——— – with maximum speed of 40 mm/s

It is also clear that at a steady state, the value of the current is reduced by about 40 %. In the result of theoretical study, the physical model of the LEMET drive of the proportional pressure modulator is developed with the following parameters: the discrete displacement of LCE  $z$  equals 0.15 mm, and allows to adjust the accuracy of pressure regulation in the brake system by 4.5 %; the power delivered to the drive of the linear motor of electromagnetic type is not more than 30 W, which allows to economize the electric power of the car by 17.2 %.

## CONCLUSIONS

1. Theoretical studies of the physical model of the linear stepper motor of the brake system modulator made it possible to increase the accuracy of pressure regulation by 4.5 %. At the same time, the economy of the vehicle electricity consti-

tuted 17.2 % in comparison with the stepper motor described in [1].

2. It is established that at the maximum speed of movement of the regulating element of the linear stepper motor, the speed of more than 0.2 sec is achieved. It was also revealed that the speed increased by 35 %.

3. To overcome the resistance forces in the modulator at the maximum speed of movement of regulating element of 40 mm, it is necessary to create an electromagnetic force of 120 N.

4. On the whole, the performed simulation studies showed that the developed mathematical model makes it possible at the stage of preliminary design to analyze the effects of various parameters on the performance and dynamic characteristics of the proportional pressure modulator with a linear motor of the electromagnetic type. The expediency of the linear electric motor of the electromagnetic type application and the relative error of the results of investigation of 4.07 % are established.

# REFERENCES

1. Ryzhikh L. A., Leontiev N. (2011) Peculiarities of Electronic Pneumatic Brake System of Transport Facilities. *Avtomobil'nyi Transport: Sbornik Nauchnykh Trudov = Automobile Transport: Scientific Papers Collection*. Kharkiv, Kharkiv National Automobile and Highway University, (29), 68–70 (in Russian).
2. Leont'ev D. N., Serikova E. A., Bykadarov A. V., Don E. Yu. (2012) Analysis and Selection of Principles to Control Electro-Pneumatic Modulators of Primary Braking Systems in Vehicles. *Visnik Natsional'nogo Tekhnichnogo Universitetu «Kharkivs'kii Politekhnicnii Institut». Seriya: Avtomobile- ta Traktorobuduvannya = Bulletin of National Technical University "Kharkiv Polytechnical Institute". Series: "Automobile and Tractor Construction"*, (60), 67–72 (in Russian).
3. Yeritsyan B. Kh., Liubarsky B. G., Yakunin D. I. (2016) Modeling of Combined System to Tilt Body of High Speed Rolling Stock of Railway Transport. *Skhidno-Evropeis'kii Zhurnal Peredovikh Tekhnologii = Eastern-European Journal of Enterprise Technologies*, 80 (9), 4–17 (in Ukrainian).
4. Buryakovskii S. G., Maslii Ar. S., Lyubarskii B. G., Maslii An. S. (2015) Mathematical Model for Operation of Electric Actuator in Assembly Switch on the Basis of Linear Motor. *Informacijno-Keruuci Sistemi na Zaliznicnomu Transporti = Information and Control Systems at Railway Transport*, (3), 59–65 (in Ukrainian).
5. Thoms E. K. (1983) The Human Aspect in the Design of Footbrake Valve. *Braking of Road Vehicle: Conf. Proc.* London, 59–64.
6. Mikhalevich N. G., Turenko A. N., Bogomolov V. A., Klimenko V. I., Ryzhikh L. A., Leont'ev D. N., Krasnyuk A. N. (2015) *Realization of Intellectual Functions in Electronic-Pneumatic Braking Control of Vehicles*. Kharkiv, Kharkiv National Automobile and Highway University. 450 (in Russian).
7. Lomaka S. I., Ryzhikh L. A., Leont'ev D. N., Cheban A. A., Krasnyuk A. N. (2009) Automatic Control Systems and Practical Implementation of Algorithm for Controlling their Executing Mechanisms. *Visnik Natsional'nogo Tekhnichnogo Universitetu «Kharkivs'kii Politekhnicnii Institut». Seriya: Transportnoe mashinostroenie = Bulletin of National Technical University "Kharkiv Polytechnical Institute". Series: Transport engineering*, (47), 9–18 (in Russian).
8. Chernykh I. V. (2007) *Simulation of Electrical Devices in MatLab. SimPowerSystem and Simulink*. Moscow, DMK Press Publ.; St. Petersburg, Piter Publ. 288 (in Russian).
9. White D., Woodson G. (1959) *Electromechanical Energy Conversion*. Wiley. 646.
10. Information on <http://femm.berlios.de>.
11. Lyubarskii B. G., Severin V. P., Parfenyuk T. V., Zyzin D. Yu., Glebova M. L., Gordeeva N. A. (2010) Simulation Modeling of Electric Drive on the Basis of Linear Step Motor Drive. *Visnik Natsional'nogo Tekhnichnogo Universitetu «Kharkivs'kii Politekhnicnii Institut». Seriya: Transportnoe mashinostroenie = Bulletin of National Technical University "Kharkiv Polytechnical Institute". Series: Transport Engineering*, (38), 62–71 (in Russian).
12. Meeker D. (2013) Finite Element Method Magnetics. *Magnetics Tutorial*. Available at: <http://www.femm.info/wiki/MagneticsTutorial>.
13. Sylvester P. P. (1996) *Finite Elements for Electrical Engineers*. Cambridge University Press. 495. <https://doi.org/10.1017/CBO9781139170611>.
14. DSTU [State Standards of Ukraine] 3649–97. *Road Vehicles. Operational Safety Requirements to Technical Conditions and Control Methods*. Kyiv: Publishing House "Derzhstandart Ukrainy", 1998. 13 (in Ukrainian).

Received: 09.10.2017

Accepted: 16.03.2018

Published online: 28.09.2018

# ЛИТЕРАТУРА

1. Рыжих, Л. А. Особенности электронно-пневматической тормозной системы транспортных средств / Л. А. Рыжих, Д. Н. Леонтьев // Автомобильный транспорт: сб. науч. трудов. Харьков: Харьковский национальный автомобильно-дорожный ун-т, 2011. № 29. С. 68–70.
2. Анализ и выбор принципов управления электропневматическими модуляторами рабочей тормозной системы автомобилей / Д. Н. Леонтьев [и др.] // Вісник Національного технічного університету «Харківський політехнічний інститут». Сер. Автомобіле- та тракторобудування. 2012. № 60. С. 67–72.
3. Єрціян, Б. Х. Моделювання комбінованої системи нахилу кузову швидкісного рухомого складу залізничного транспорту / Б. Х. Єрціян, Б. Г. Любарський, Д. І. Якунін // Східно-Європейський журнал передових технологій. 2016. Т. 80, № 9. С. 4–17.
4. Математична модель роботи електропривода стрілочного переводу на базі лінійного двигуна / С. Г. Буряковський [и др.] // Інформаційно-керуючі системи на залізничному транспорті. 2015. № 3 С. 59–65.
5. Thoms, E. K. The Human Aspect in the Design of Footbrake Valve / E. K. Thoms // Braking of Road Vehicle: Conf. Proc. London, 1983. P. 59–64.
6. Реализация интеллектуальных функций в электронно-пневматическом тормозном управлении транспортных средств / А. Н. Туренко [и др.]. Харьков: ХНАДУ, 2015. 450 с.
7. Системы автоматического регулирования и практическая реализация алгоритма управления их исполнительными механизмами / С. И. Ломака [и др.] // Вісник Національного технічного університету «Харківський політехнічний інститут». Сер. Транспортне машиностроение. 2009. № 47. С. 9–18.
8. Черных, И. В. Моделирование электротехнических устройств в MatLab, SimPowerSystem и Simulink / И. В. Черных. М.: ДМК Пресс; СПб.: Питер, 2008. 288 с.
9. Уайт, Д. Электромеханическое преобразование энергии / Д. Уайт, Г. Вудсон. М.: Энергия, 1964. 528 с.
10. Information on <http://femm.berlios.de>.
11. Имитационное моделирование электропривода на базе линейного шагового привода / Б. Г. Любарский [и др.] // Вісник Національного технічного університету «Харківський політехнічний інститут». Сер. Транспортне машиностроение. 2010. № 38. С. 62–71.
12. Meeker, D. Finite Element Method Magnetics [Electronic resource] / D. Meeker. 2013. Magnetics Tutorial. Available at: <http://www.femm.info/wiki/MagneticsTutorial>.
13. Sylvester, P. P. Finite Elements for Electrical Engineers / P. P. Sylvester. Cambridge University Press, 1990.
14. ДСТУ 3649–97: Засоби транспортні дорожні. Експлуатаційні вимоги безпеки до технічного стану та методи контролю. Київ: Держстандарт України, 1998. 13 с. (Національний стандарт України).

Поступила 09.10.2017

Подписана в печать 16.03.2018

Опубликована онлайн 28.09.2018