https://doi.org/10.21122/2227-1031-2021-20-1-26-32

UDC 629.113.585

Control of Pneumatic Actuator for Automated Mechanical Transmission Dry Friction Clutch Base on the Pulse Width Modulation Signal

S. V. Kharytonchyk[1), V. A. Kusyak[1), Le Van Nghia[2)

[1)]Belarusian National Technical University (Minsk, Republic of Belarus),
[2)]Hanoi University of Science and Technology (Hanoi, Socialist Republic of Vietnam)

Abstract. To ensure quality of dry friction clutch engagement in automated mechanical transmission during vehicle starting-up and maneuvering the control range of clutch actuator has to be maximum wide. It depends on the consistency of the clutch actuator geometric parameters with the electrical characteristics of the used solenoid valves, the output stage of the controller and the PWM control signal frequency. In addition to precision electronic control the driver must be able to "manually" operate the dry friction clutch in emergency. That is why friction clutch must have two independent control circuits. The original automated drive with a duplicate pneumohydraulic circuit for the friction clutch is presented in the paper, as well as the research results of the PWM frequency influence on operating range of the clutch pneumatic actuator. The research was based on the analysis of semi-natural experiment for assessing the functional performance of the designed automated mechatronic control system for the truck mechanical transmission. Ecomat R360 controllers were used as a hardware base of the test bench information control system. The developed software for the controller with one-parameter feedback on the clutch release lever movement allows to provide the PWM signal of varying duty ratio to the proportional solenoid valve of the automated drive. A graphical representation of the research results was performed with visualization possibilities of CoDeSys V2.3. During the semi-natural experiment, the polynomial dependence between variation of the clutch actuator control range and the generated PWM signal frequency in the range up to 400 Hz was revealed as well as practical recommendations on the choice of the optimum PWM signal frequency are also given in activity. The research results can be used in an adaptive control algorithm for automated mechanical transmission of trucks and road trains to ensure precise control of the clutch actuator in the starting-up and maneuvering processes.

Keywords: automated mechanical transmission, automated mechatronic system, dry friction clutch, automated drive, pneumatic actuator, proportional solenoid valve, PWM

For citation: Kharytonchyk S. V., Kusyak V. A., Le Van Nghia (2021) Control of Pneumatic Actuator for Automated Mechanical Transmission Dry Friction Clutch Base on the Pulse Width Modulation Signal. *Science and Technique*. 20 (1), 26–32. https://doi.org/10.21122/2227-1031-2021-20-1-26-32

Управление пневматическим исполнительным механизмом сухого фрикционного сцепления автоматизированной механической трансмиссии на основе модулированного широтно-импульсного сигнала

Докт. техн. наук С. В. Харитончик[1), канд. техн. наук, доц. В. А. Кусяк[1), канд. техн. наук Ле Ван Нгиа[2)

[1)]Белорусский национальный технический университет (Минск, Республика Беларусь),
[2)]Ханойский университет науки и технологий (Ханой, Социалистическая Республика Вьетнам)

Реферат. Для обеспечения качества включения сухого фрикционного сцепления в автоматизированной механической трансмиссии в процессе трогания транспортного средства с места и маневрирования диапазон управления

Адрес для переписки
Кусяк Виктор Анатольевич
Белорусский национальный технический университет
ул. Я. Коласа, 12,
220013, г. Минск, Республика Беларусь
Тел.: +375 17 296-65-14
v.kusyak@bntu.by

Address for correspondence
Kusyak Victor A.
Belarusian National Technical University
12, Ya. Kolasa str.,
220013, Minsk, Republic of Belarus
Tel.: +375 17 296-65-14
v.kusyak@bntu.by

исполнительным механизмом сцепления должен быть максимально широким. Ширина диапазона зависит от согласованности геометрических параметров исполнительного механизма сцепления с электрическими характеристиками используемых электромагнитных клапанов, выходным каскадом контроллера и частотой управляющего ШИМ-сигнала. Помимо прецизионного электронного управления водитель должен иметь возможность «вручную» управлять сухим фрикционным сцеплением в аварийной ситуации, вследствие чего последнее должно иметь два независимых контура управления. В статье представлены оригинальный автоматизированный привод фрикционного сцепления с дублирующим пневмогидравлическим контуром, а также результаты исследования влияния частоты ШИМ-сигнала на рабочий диапазон управления пневматическим исполнительным механизмом сцепления. Исследования базировались на анализе результатов полунатурного эксперимента по оценке функциональной работоспособности спроектированной автоматизированной мехатронной системы управления механической трансмиссией грузового автомобиля. В качестве аппаратной основы информационной системы управления испытательным комплексом использовались контроллеры Ecomat R360. Разработанное программное обеспечение контроллеров с однопараметрической обратной связью по перемещению рычага выключения сцепления позволяет подавать ШИМ-сигнал переменной скважности на пропорциональный электромагнитный клапан автоматизированного привода. Графическое представление результатов исследований производилось с помощью средств визуализации CoDeSys V2.3. В ходе полунатурного эксперимента выявлена полиномиальная зависимость между изменением диапазона управления исполнительным механизмом сцепления и частотой генерируемого ШИМ-сигнала в интервале до 400 Гц, а также даны практические рекомендации по выбору оптимальной частоты модулированного широтно-импульсного сигнала. Результаты исследований могут быть использованы в адаптивном алгоритме управления автоматизированной механической трансмиссией грузовых автомобилей и автопоездов для обеспечения прецизионного управления исполнительным механизмом сцепления в процессах трогания с места и маневрирования.

Ключевые слова: автоматизированная механическая трансмиссия, автоматизированная мехатронная система, сухое фрикционное сцепление, автоматизированный привод, пневматический исполнительный механизм, пропорциональный электромагнитный клапан, широтно-импульсная модуляция

Для цитирования: Харитончик, С. В. Управление пневматическим исполнительным механизмом сухого фрикционного сцепления автоматизированной механической трансмиссии на основе модулированного широтно-импульсного сигнала / С. В. Харитончик, В. А. Кусяк, Ле Ван Нгиа // *Наука и техника*. 2021. Т. 20, № 1. С. 26–32. https://doi.org/10.21122/2227-1031-2021-20-1-26-32

Overview of transmission mechatronic systems showed that automated drive of dry friction clutch has, as a rule, an additional duplicate control circuit [1–5]. The electronic components of mechatronic systems, despite their relatively high reliability, characterized by intermittent faults and suddenness of failures occurrence. Additionally, working medium may leak from the actuator circuit that reduces or eliminates the control system operability and vehicle mobility.

Considering the above, as well as using the experience of foreign companies, specialists of the BNTU Automobile Department have developed an original duplex drive [6] of dry friction clutch, which is integrated into powertrain control mechatronic system (Fig. 1) and has two independent control loops.

Automated drive, as the primary circuit, includes a pneumatic actuator 14 and the proportional solenoid valve 13 installed on the gearbox (Fig. 1). Duplicate hydraulic drive consists of a pedal 8 with a hydraulic cylinder 7, pipeline and pneumo-hydraulic booster 6 (Fig. 1, 2). Clutch release node is a lever mechanism, which consists of two levers 16 and 17 mounted on the bush of clutch fork shaft. One of the levers is connected with a power actuator of the clutch automated drive. Another one comes into the duplicate hydraulic drive.

Calculation of the actuator active diameter is based on the maximum clutch disengagement force, the drive ratio and system's nominal pressure. When designing automated dry clutch for serial production, the actuator active diameter is tended to choose from a standard series of pneumatic cylinders. As known well about actuator on cylindrical type, the dead zone and friction between the piston and the cylinder surface are changed during operation of the vehicle, that influence on the control quality of the clutch transition process. At the test stand of the BNTU, a brake chamber (type 16) with diaphragm type was used as a clutch actuator to improving the control quality by reducing the dead zone and friction.

At the clutch engagement in the automatic mode, for example during starting or maneuvering, in order to control proportional solenoid valve 13, the strategy of the Direct Semi-Active Control [7] is offered to use. The meaning of the strategy is applied to the solenoid coil PWM signal with a subsequent change of its duty ratio according to a predetermined algorithm.

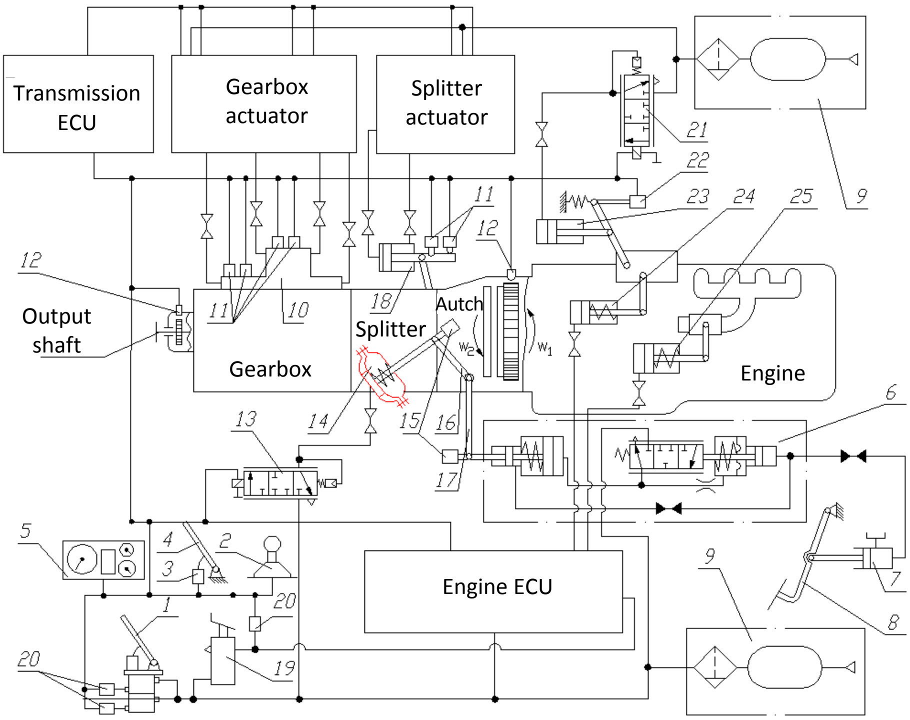

Fig. 1. Schematic diagram of powertrain control mechatronic system with clutch duplex drive:
1 – brake pedal; 2 – mode selector; 3 – position sensor; 4 – accelerator pedal; 5 – display; 6 – pneumo-hydraulic booster; 7 – hydraulic cylinder; 8 – clutch pedal; 9 – air supply; 10 – gearbox actuator; 11 – contact sensors; 12 – speed sensors; 13, 21 – proportional solenoid valves; 14 – clutch actuator; 15, 22 – displacement sensors; 16, 17 – clutch release levers; 18 – splitter actuator; 19 – auxiliary brake valve; 20 – pressure sensors; 23 – engine actuator; 24 – pneumatic cylinder for engine turn off; 25 – engine brake actuator

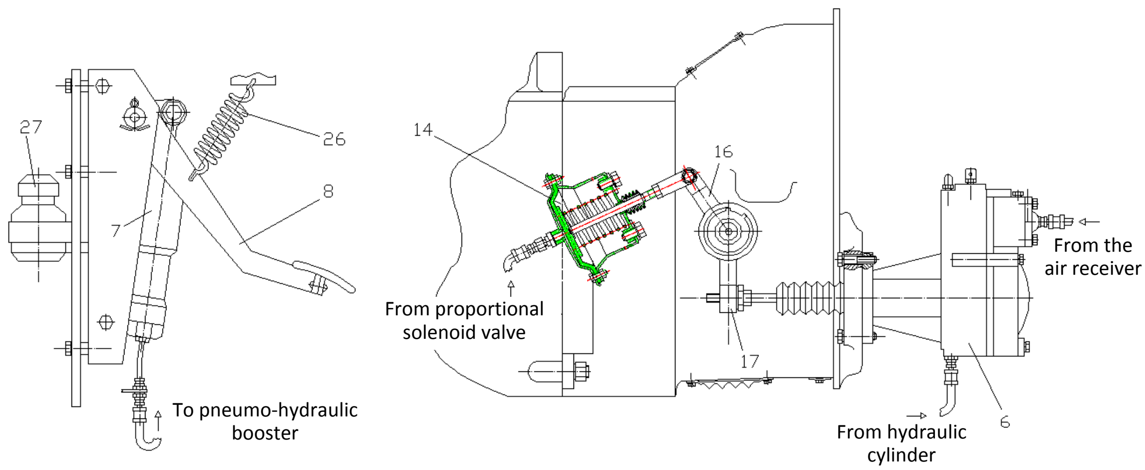

Fig. 2. Duplex drive of dry friction clutch: 6 – pneumo-hydraulic booster; 7 – hydraulic cylinder; 8 – clutch pedal with return spring 26; 14 – clutch actuator; 16, 17 – clutch release levers; 27 – expansion tank

At all transient processes electronic system has to provide such a clutch engagement tempo that would to avoid dynamic overloads in the transmission on the one hand and not to exceed the criterial limits for energy loading of friction clutch, evaluated by specific work and power of slipping [8], on the other.

If the mode selector 2 is subsequently set by the driver (Fig. 1) to the “D” position (drive) and the accelerator pedal is pressed, the transmission ECU sends a signal to the clutch control proportional solenoid valve 13 and in parallel by CAN the information about the current position mode selector and accelerator pedal 4 is transmitted to the engine ECU. As soon as the clutch is disengaged, the transmission ECU generates sequential control signals to the solenoid valve block of gearbox and splitter actuators for the first selecting the rod, and then enabling the optimum gear step by actual driving conditions as: actual vehicle speed and mass, the rotation speeds of the engine crankshaft and driving wheels, the number of the previous gear steps. After that, the signal on the solenoid valve 13 is modified and the clutch is engaged on the set rate. Depending on the degree to which the clutch is engaged, the fuel supply gradually increases in proportion to the position of the accelerator pedal set by the driver in the initial phase.

AMT start-up adaptive algorithm [9] in the automatic mode of the power unit is the following sequence of operations: transmission mode selector control – full clutch disengagement – main and additional gearbox control – engine control – full clutch engagement.

After moving the mode selector 2 to the "D" (drive) position (Fig. 1), the driver presses on the accelerator pedal 4 for vehicle starting-up. The proportionality between the pedal rotation angle (by position sensor 3) and the movement of the fuel injection pump regulator lever (by displacement sensor 22) is provided by the engine ECU by pulse-width modulation (PWM) signal to a proportional solenoid valve 21 with using feedback on the movement of the fuel injection pump regulator lever and the engine crankshaft rotation frequency [10]. The required rate of vehicle star-t-up is determined by the "gas" pedal press speed, on the basis of which the transmission ECU calculates the pro-required clutch engagement rate and the enable gear number. In parallel, while receiving signals from the mode selector limit switch, the engine speed sensor, the fuel supply position sensor and the accelerator pedal position sensor, the transmission ECU generates a control signal to open the proportional solenoid valve 13. The valve is activated and the compressed air comes from the receiver of the supply part 9 into the clutch actuator 14 (pneumatic chamber), as the result of which the clutch is disengaged. After working out the signal from the clutch lever sensor 15, the transmission ECU sequentially generates signals to the solenoid valve block of the gearbox actuator, as well as the air-control valve for shifting the splitter. After shifting on the required gear (the respective gearshift limit switches are closed), the transmission ECU sends a PWM-signal to the proportional solenoid valve 13, increasing the duty cycle of the signal by a certain amount depending on the "gas" pedal press speed. The compressed air from the clutch actuator – pneumatic chamber 14 through the proportional solenoid valve 13 is gradually discharged into the atmosphere, providing the required clutch engagement rate. To avoid "overloading" of the clutch, feedback is introduced into the control circuit according to the increment by time of difference between angular velocities of the driving and driven clutch parts ($d\Delta\omega/dt$). The feedback is also entered into the engine control circuit to avoid ICE stalling by the reduction in the crankshaft angular velocity ω_1 while the clutch is engaging.

Control algorithm adaptation occurs when the mechanical and (or) electrical characteristics of the mechatronic system components vary, as well as the driving behavior or the vehicle weight state change.

The functionality of the developed AMT mechatronic system (Fig. 1) and the operational integrity of the vehicle start-up adaptive algorithm are confirmed by the result of a semi-real experiment on test complex BNTU.

Clearly, that the control quality of dry friction clutch will depend on the width of the PWM signal range. The range value is influenced by the consistency of the actuator geometrical parameters, solenoid valve operating characteristics and the controller output stage. At constant parameters of the last dominant influence on control range has generated the PWM signal frequency.

For debugging powertrain automated mechatronic system a special test bench was created in the laboratory of the BNTU Automobile Department. The test bench consists of diesel engine, dry friction clutch, mechanical gearbox, inertial mass and a load device. Ecomat R360 controllers of CR2500 series were used as a hardware basis of the designed control system.

To investigate the influence of PWM signal frequency to control range of clutch actuator, a special software has developed. It allows to initialize the signal generator and to provide the PWM signal of varying duty ratio (but a certain frequency) in automatic mode to the proportional solenoid valve VEP 3121-1 that controls the clutch actuator. During the experiments, PWM frequency was varied from 150 to 250 Hz in steps of 10 Hz. The clutch lever position, fixed by the potentiometric sensor MY-615A of angular displacements, was used as a feedback. A graphical representation of the semi-natural experiment results was performed with visualization possibilities of CoDeSys V2.3. Some records of engagement/disengagement of dry friction clutch are shown at Fig. 3.

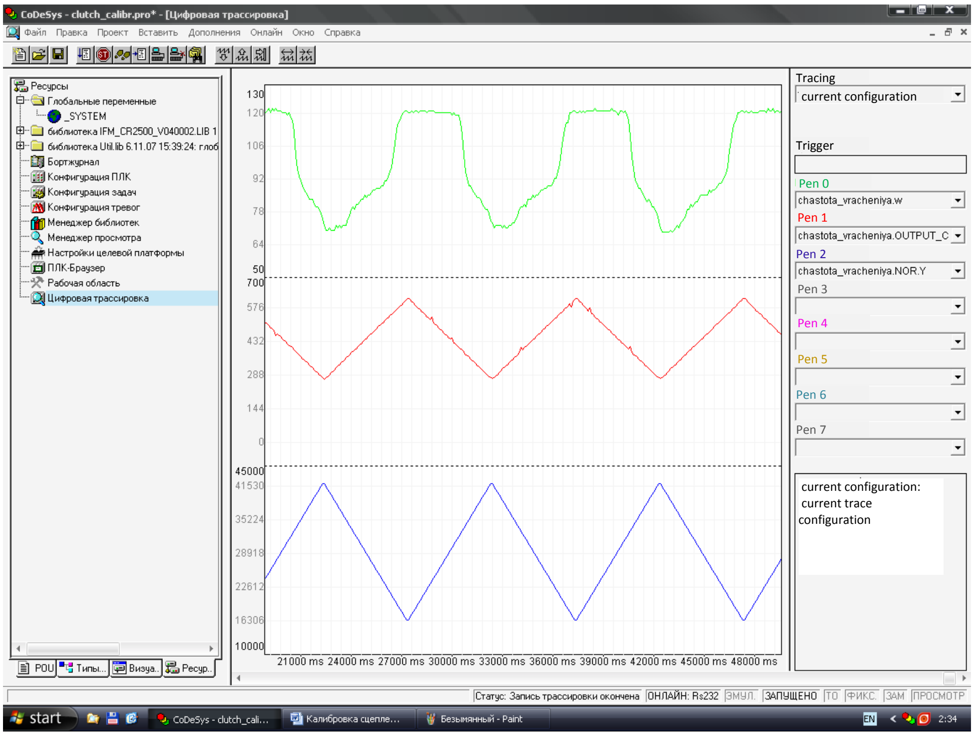

Fig. 3. Oscillogram of clutch engagement/disengagement process at PWM frequency of 150 Hz: first screen – digitizing the signal from the clutch lever position sensor, bits; second screen – current to the coils of the solenoid valve, mA; third screen – PWM reload value, bit

As shows the results of experiments the PWM signal range was the greatest at a frequency of 150 Hz. Its value was 40.7 %. There is a steady trend towards a narrowing of the control range with frequency increasing. Already at 200 Hz control range decreased by 26.04 % and was 30.1 %. At 250 Hz the range decreased by 34.15 % and was 26.8 %. The above described control range dependence of the PWM frequency is illustrated in Fig. 4.

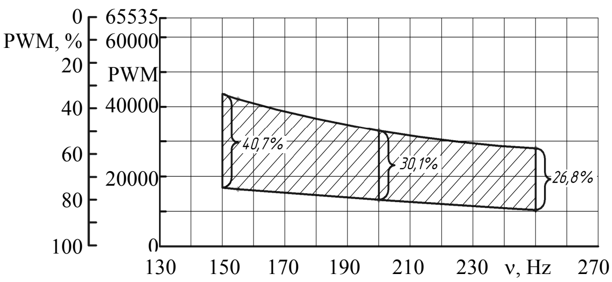

Fig. 4. Control range dependence of the PWM signal frequency

During the vehicle operation, the friction plates of the clutch are wore and resulting of which is a change in the control range of actuator. To improve the quality of the clutch transition process when starting-up vehicle, adaptation of the control algorithm is required. Adaptation to control range of clutch actuator can be implemented at the software level by the dependence of the control range variation on the PWM signal frequency in an analytical form. The dependence of the control range variation on the frequency of the control PWM signal can be expressed by an approximating polynomial whose coefficients are obtained by processing experimental data using the Polyfit function [11, p. 379] in the MatLab package.

Justification of the polynomial degree choice was carried out on the basis of the smallest modules criterion MAPE (Mean absolute percentage error) [12, p. 1104, (1)], which makes a possible to estimate the approximation error by the formula

$$\mathrm{MAPE} = \frac{1}{h}\sum_{j}^{h}\frac{|e_j|}{y_j}\cdot 100\ \% = \frac{1}{h}\sum_{j}^{h}\frac{|y_j - y_j^p|}{y_j}\cdot 100\ \%, \quad (1)$$

where e_j – prediction step error; y_j, y_j^p – actual and predicted trend point value (PWM control range, %); h – number of points.

The errors calculation results of the approximating by polynomial on various degree are presented in Tab. 1.

Table 1

The errors of the approximating polynomial

Coefficient	Degree of approximating polynomial				
	I	II	III	IV	V
*b*0	59.91281818	118.1773636	142.5556	177.362515	161.286182
*b*1	–0.14097090	–0.73855599	–1.1155831	–1.83458	–1.4192847
*b*2	–	–0.00149396	0.003407	0.0089159	0.00466
*b*3	–	–	–3.19E-06	–2.17E-05	–1.22E-07
*b*4	–	–	–	2.32E-08	–3.13E-08
*b*5	–	–	–	–	5.45E-11
Criterion MAPE, %	3.630	0.224	0.088	1.328	0.117

For a given approximation error less than 0.1 %, the dependence of the control range variation on the frequency of the control PWM signal is described by a 3nd order polynomial as in formula

$$D_{\mathrm{PWM}} = 142.56 - 1.116\nu + \\ + 0.0034\nu^2 - 3.19E - 06\nu^3, \quad (2)$$

where D_{PWM} – control rate of clutch actuator, %; ν – frequency of control PWM signal, Hz.

The variation of PWM frequency does not influence on the current range. During the clutch lever movement the magnitude of the current to the solenoid valve coils varies from 0.272 to 0.614 A (Fig. 3), i. e. operating current range is 0.342 A. Taking into account operating characteristic of the used solenoid valve and its zone of stable operation it is 50.3 %, which is a satisfactory result. Clutch actuator hysteresis is shown in Fig. 5.

Clutch actuator hysteresis should be integrated in AMT adaptive control algorithm of vehicle starting-up process. The semi-real experience results of start-up process when debugging of AMT adaptive control algorithm with PWM frequency 150 Hz on test complex BNTU are shown in Fig. 6.

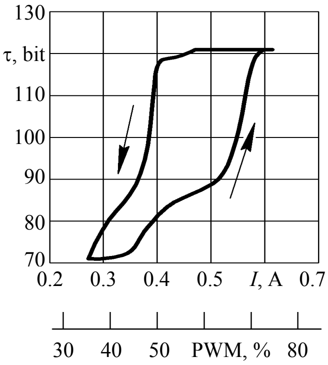

Fig. 5. Clutch actuator hysteresis: *I* – current to the solenoid valve, A; τ – digitizing the signal from the clutch lever position sensor, bit

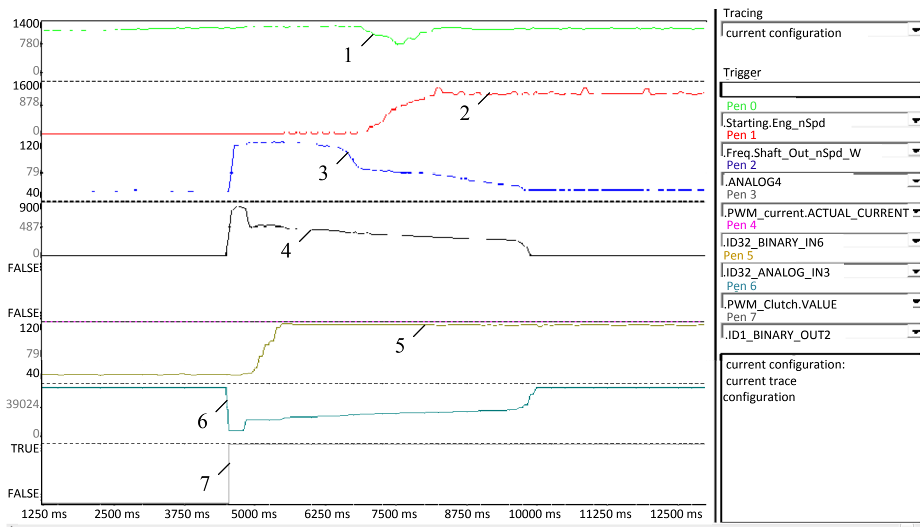

Fig. 6. Oscillograms of start-up process on test stand BNTU: 1, 2 – engine crankshaft speed ω_1 and driven cluth part speed ω_2, rev/min; 3 – movement of the clutch lever, bit; 4 – current on clutch control valve, mA; 5 – movement of the splitter shift lever, bit; 6 – PWM, bit; 7 – sign stage «1» straight line of splitter solenoid control valve

CONCLUSION

The research has shown that the PWM frequency has a significant influence on the actuator control range: change in frequency of 50 Hz results in a change of the PWM control range for about 4–10 % (Fig. 4). However, at too high or low frequencies valve coils heating or periodic instability of the whole system is possible. The last one expressed in a substantial increment of clutch lever displacement with a slight change of the PWM signal. Therefore, the choice of the optimum frequency must be done on the basis of the specific features of the designed system.

REFERENCES

1. Brugger F., Moser F., Ruhl T. (1988) *Clutch Operating Cylinder for a Pressure-Medium Operated Clutch*: Pat. USA No 4745999.
2. Bates J. (1999) *Actuator System for Vehicle Automated Clutches with Electric Motor Actuator and Pressurized Fluid Override*: Pat. USA No 5934432.
3. Inoue A. (2003) *Clutch Operating System and a Hydraulic Mechanism Used in the Same*: Pat. USA No 6607060 B2.
4. Leigh-Monstevens K. V., Branum L. P. (1991) *Dual Mode Motor Vehicle Clutch Control System*: Pat. USA No 5002166.
5. Ishihara M., Yamamoto Y. (1999) *Clutch Disconnection/ Connection Device*: Pat. USA No 5954176.
6. Bakhanovich A., Kusyak V., Filimonov A., Belevich A. (2013) *Automated Dry Friction Drive Vehicle Clutch*: Pat. Republic of Belarus No 20801 (in Russian).
7. Lee H.-W., Oh J.-S., Jung G.-H. (2000) A Study on Full Electronic Control of Automatic Transmission: Direct Active Shift Control. *F2000A101: Materials of FISITA World Automotive Congress, Seoul, Korea*, 1–6.
8. Rukteshel O. S., Kusyak V. A. (2002) Modelling of Pre-Selector Gearshift in the Urban Bus Transmission. *SAE Technical Paper Series*, 2002-01-2203. https://doi.org/10.4271/2002-01-2203.
9. Nghia Le Van, Kusyak V. A., Nguyen T. H. (2017) The Research on Threshold Values Determination of One-Parameter Feedback in the Automated Friction Clutch Control Circuit for Truck Start-Up Process. *Paper from the 10th National Conference on Mechanical Engineering, 8–9 Decem., Le Quy Don Technical University and Vietnam Association of Mechanic, Hanoi, Vietnam*. Hanoi, LQDTU, 25–32.
10. Bakhanovich A. G., Kusyak V. A., Gurin A. N., Van Ngia Le (2017) Electronic Control of Diesel Engine Fuel Supply Based on Programmed PID Control. *Nauka i Tekhnika = Science and Technology*, 16 (1), 28–37. https://doi.org/10.21122/2227-1031-2017-16-1-28-37 (in Russian).
11. Anufriev I. E. (2004) *Self-Instruction Manual MatLab 5.3*. St. Petersburg, BHV-Petersburg. 720 (in Russian).
12. Romanov A. A. (2011) Application of the F-Transformation Method for Forecasting the Trend and Numerical Representation of the Time Series. *Izvestiya Samarskogo Nauchnogo Tsentra Rossiiskoi Akademii Nauk = Izvestia of Samara Scientific Center of the Russian Academy of Sciences,* 13 (4), 1103–1109 (in Russian).

Received: 17.11.2020
Accepted: 15.01.2021
Published online: 29.01.2021