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Features of Controlling Electropneumatic Valves of Actuator to Control its Clutch with Acceleration Valve

O. A. Yaryta1), M. G. Mychalevych1), D. N. Leontiev1), V. I. Klymenko1), V. A. Bogomolov1), I. V. Gritsuk2), Y. B. Novikova1)

1)Kharkiv National Automobile and Highway University (Kharkiv, Ukraine),
2)Kherson State Maritime Academy (Kherson, Ukraine)

Abstract. The article deals with one of the ways to control an actuator of the automated clutch control system. The aim is to design control of the electropneumatic actuator, to control its coupling with the acceleration valve on the basis of experimental research as well as to provide rational parameters of the automated clutch control system for the robotic transmission. The feature of the system is an acceleration valve in the design of the electropneumatic actuator to control the clutch. New links demand to adjust the way to control the actuator. The connection of Pulse-Width Modulation (PWM) with single power supply pulses to control electropneumatic valves is substantiated. The quantitative characteristics of single control pulses and PWM ones are determined. The error of operation accuracy for various ways of the control of the electropneumatic actuator to control the clutch of the robotic transmission is determined. Obtained separate PWM area is designed to suppress the initial hysteresis when the rod of the clutch actuator is moved. An algorithm for the operation of a clutch control system is proposed, taking into account the use of two modes of operation of solenoid valves. A graphical interpretation of the clutch control algorithm is presented, which gives an idea of the location of the constant signal feeding zones to the solenoid valve, as well as the operation areas of the solenoid valve in PWM mode. The control algorithm of the clutch booster provides a mode of guaranteed absence of excess pressure in the pneumatic cylinder after releasing the clutch pedal, provided that two normally closed solenoid valves are used. This configuration of the electro-pneumatic clutch control system allows the use of an emergency clutch release system in case of voltage absence. The reference algorithm for filtering the array of data coming from the feedback sensor, as well as the numerical values of the delay caused by the presence of a filter, are given.

Keywords: automated clutch control system, actuator with acceleration valve, pulse-width modulation, electropneumatic valve

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Особенности управления электропневматическими клапанами исполнительного механизма управления сцеплением с ускорительным клапаном

А. А. Ярита1), кандидаты техн. наук, доценты Н. Г. Михалевич1), Д. Н. Леонтьев1), канд. техн. наук, проф. В. И. Клименко1), докт. техн. наук, проф. В. А. Богомолов1), докт. техн. наук, доц. И. В. Грицук2), канд. филолог. наук, доц. Е. Б. Новикова1)

1)Харьковский национальный автомобильно-дорожный университет (Харьков, Украина),
2)Херсонская государственная морская академия (Херсон, Украина)

Реферат. В статье рассмотрен один из способов управления исполнительным механизмом автоматизированной системы управления сцеплением. На основе экспериментальных исследований предложены способ управления электро-

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Адрес для переписки
Клименко Валерий Иванович
Харьковский национальный
автомобильно-дорожный университет
ул. Ярослава Мудрого, 25,
61002, г. Харьков, Украина
Тел.: +38 050 565-77-97
valeriy.klimenko@gmail.com

Address for correspondence
Klymenko Valery I.
Kharkiv National
Automobile and Highway University
25 Yaroslava Mudrogo str.,
61002, Kharkiv, Ukraine
Tel.: +38 050 565-77-97
valeriy.klimenko@gmail.com

пневматическим исполнительным устройством управления сцеплением с ускорительным клапаном, а также рациональные параметры автоматизированной системы управления сцеплением для роботизированной трансмиссии. Особенностью рассматриваемой системы является наличие в конструкции электропневматического исполнительного механизма управления сцеплением ускорительного клапана. Наличие новых связей требует корректировки способа управления исполнительным механизмом. Обосновано объединение широтно-импульсной модуляции с одиночными импульсами питания для управления электропневматическими клапанами. Определены количественные характеристики управляющих импульсов как для случая одиночных, так и в случае использования широтно-импульсной модуляции. Определена ошибка точности работы во время разных способов управления электропневматическим исполнительным устройством управления сцеплением роботизированной трансмиссии. Выделена отдельная зона широтно-импульсной модуляции, предназначенная для подавления начального гистерезиса при перемещении штока исполнительного устройства управления сцеплением. Предложен алгоритм работы системы управления сцеплением с учетом использования двух режимов работы электромагнитных клапанов. Представлена графическая интерпретация алгоритма управления сцеплением, дающая представление о расположении зон подачи постоянного сигнала на электромагнитный клапан, а также зон работы электромагнитного клапана в режиме широтно-импульсной модуляции. В алгоритме управления усилителем предусмотрен режим гарантированного сброса давления из пневматического цилиндра после отпускания педали сцепления при условии использования двух нормально закрытых электромагнитных клапанов. Такая конфигурация электропневматической системы управления сцеплением позволяет задействовать систему аварийного выключения сцепления при отсутствии электропитания. Приведены опорный алгоритм фильтрации массива данных, поступающих от датчика обратной связи, а также численные значения запаздывания, вызванного наличием фильтра.

Ключевые слова: автоматизированная система управления сцеплением, исполнительный механизм с ускорительным клапаном, широтно-импульсная модуляция, электропневматический клапан

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Introduction

A large number of freight vehicles and buses having the automated clutch control system (ACCS) with the electropneumatic actuator are produced nowadays. Most serial models of ACCS executive devices consist of a power cylinder and four electropneumatic valves that control air pressure in the power cylinder [1]. The availability of many electromagnetic valves causes the reduction in reliability and increase in the cost of the whole system. Besides, electromagnetic valve durability requirements are much higher compared to the reliability of the actuator mechanics. It is because of electropneumatic valve operating in pulse-width modulation mode to ensure the accuracy of the whole system operation. Reducing the quantity of electropneumatic valves the contradiction appears between ACCS speed and the accuracy of its operation.

Kharkiv National Automobile and Highway University (KhNAHU) proposes the design of the ACCS actuator for the robotic transmission with only two control electropneumatic valves. They ensure the good accuracy of their operation. The required speed of ACCS is guaranteed due to the acceleration valve in the design of its actuator. It is possible to eliminate the contradiction between ACCS speed and accuracy due to the special design of the acceleration valve [2–6]. The operation quality of the above-mentioned acceleration valve depends on both its design parameters and the parameters of electropneumatic valve control pulses that the electronic control unit (ECU) of ACCS generates. This fact stipulates the necessity of rationalization of the control mode implemented by means of the ECU algorithm.

The choice of the way to control the electropneumatic valves of the automated clutch control system

The research of the ACCS operation is carried out with the help of the test unit (fig. 1). The choice of an optimal control mode is made on the basis of the range of experimental research of the developed ACCS design (fig. 2, 3), when a control signal is first delivered to the electropneumatic valves continuously and then in the form of the pulse-width modulation (PWM). Besides, pulse-width modulation parameters are changed for the purpose of determining the most favourable values of electropneumatic valve open time.

The oscillograms illustrated the transitions in the ACCS actuator, use the following symbols: X_{rod} – the transition of an actuator rod, mm; p_c – the pressure in a power chamber, MPa; p_{av} – the pressure in an acceleration valve control chamber, MPa; t_{pulse} – the time of an electropneumatic valve being under pressure, s; ΔX – the inertial transition of an ACCS actuator rod, mm; a_1, b_1 – the position of an ACCS actuator rod during electropneumatic valve closing; a_2, b_2 – the stable position of an ACCS actuator rod after electropneumatic valve closing.

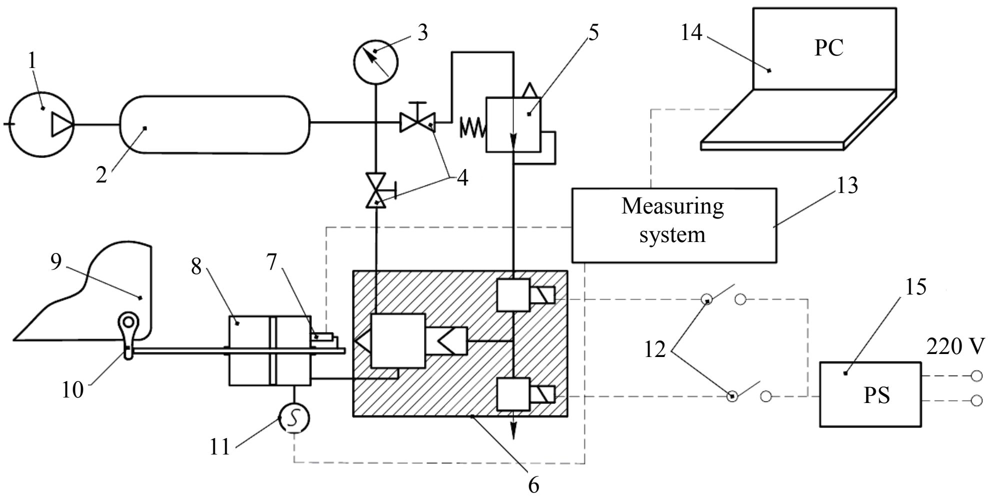

Fig. 1. Block diagram of a test unit: 1 – compressor; 2 – receiver; 3 – gauge; 4 – valve; 5 – pressure regulator; 6 – pressure control unit; 7 – rod displacement sensor; 8 – power cylinder; 9 – vehicle powertrain; 10 – clutch fork; 11 – pressure sensor; 12 – switch; 13 – measuring system; 14 – PC; 15 – power supply unit

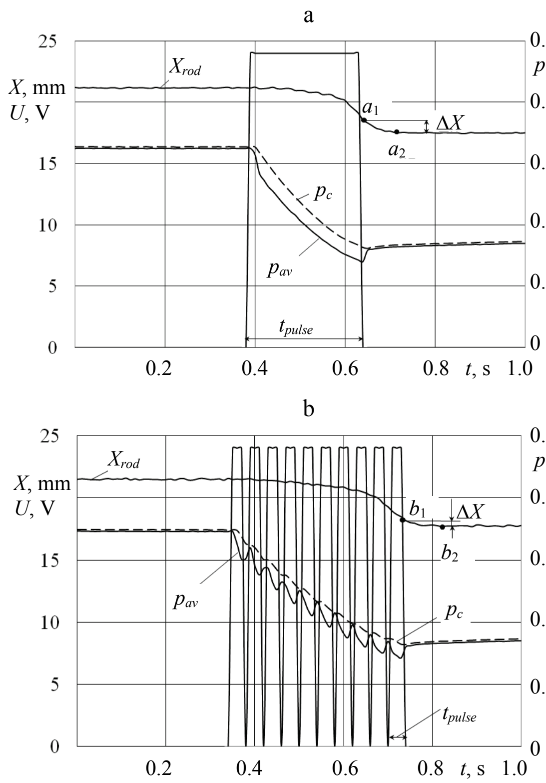

Fig. 2. ACCS actuator operation:
a – voltage delivery as a continuous signal;
b – voltage delivery as a PWM

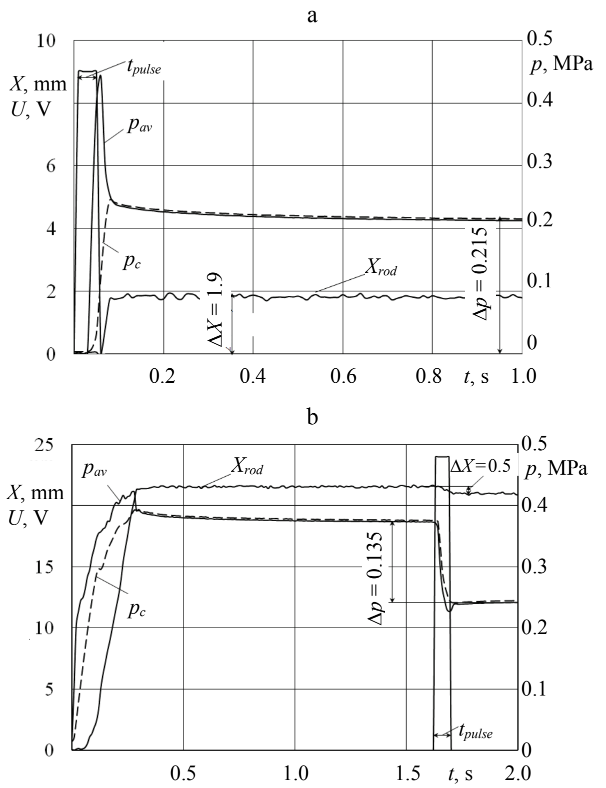

Fig. 3. Process of overcoming hysteresis in the ACCS actuator:
a – clutch disengagement; b – clutch engagement

We will present the example of the most significant examples of ACCS operation in different modes. In the case of voltage delivery to the electropneumatic valve as a continuous signal with duration t_{pulse} = 0.25 s (fig. 2a) there is a considerable inertial transition of the actuator rod.

According to the oscillogram (fig. 2a) the case of actuator rod stopping at the point a_1 seems to be ideal, directly during electropneumatic valve closing. However, experiment results show that after valve closing the rod continues moving at the distance ΔX that makes about 45 % from a rod transition for the nonce. Concerning a general rod stroke distance ΔX makes about 10 %. In this case it is necessary to establish the dead space of an appropriate size for switching off the vibrational nature of a rod movement. The dead space which corresponds to the value 10 % (2.2 mm) is unacceptable in terms of a positioning accuracy.

In the case of usage for the PWM electropneumatic valve control (fig. 2b) there is a small increase in the duration of an actuator rod transition process, but at the same time its more accurate positioning should be marked as well.

After stopping a voltage delivery to the electropneumatic valve at point b1 there is an inertial rod movement to point b_2, the length of transition makes up near 10 % of the rod transition. The total time of the electropneumatic valve operation in the given case equals $\Sigma t_{pulse} = 0.4$ s. Concerning the general rod stroke transition ΔX is about 2.7 %.

The analysis of the conducted research [7] has confirmed the appropriateness of PWM usage for the electropneumatic valves control. The further development of an ACCS control algorithm is closely connected to the choice of pulse-width modulation optimal parameters. It is known that [8–10], a large quantity of used moving rubber packings increase the friction by parts movement causing the appearance of a considerable hysteresis loop in drive static characteristics and worsening its sensibility. As there are moving rubber packings in the design of the ACCS developed actuator, it is necessary to determine the level of a hysteresis influence on the ACCS operation before the development of a control system operation algorithm.

The results of the experimental research have shown (fig. 3) that filling the power cylinder the pressure burst in the rod end up to 0.215 MPa causes the rod movement to the value less than 2 mm which can be compared with the choice of clearance in the drive (fig. 3a). There is a similar effect by emptying the rod end of the power cylinder. A pressure reduction by 0.135 MPa causes the rod movement to less than 1 mm (fig. 3b).

As a result of the experimental data of the analysis which was carried out we can make a conclusion that to ensure ACCS qualitative maintenance characteristics such as good tracking action and high speed, the use of the pulse-width modulation by the electropneumatic valves control is inevitable.

The presence of hysteresis in the actuator emphasizes the need of using different parameters of PWM depending on a drive operating mode. The choice of PWM optimal parameters can be made on the basis of the results of the experimental research or the mathematical modelling of electropneumatic clutch drive operation.

Taking into account experimental research results, it was decided to divide clutch engagement and disengagement processes into two phases with PWM different parameters (fig. 4).

PWM parameters in phase 1 (F_1) and phase 3 (F_3) (fig. 4) are chosen taking into account the need for overcoming hysteresis in operation by clutch engagement and disengagement respectively. It is suggested to calculate pulse on-time impulst1 in phase 1 (F_1) depending on a rod current position, pulse on-time impulst3 – depending on a clutch pedal movement speed. In phases 1 and 3 it is suggested to exercise control on a pulses on-time change, pauses on-time pauset1 and pauset3 are chosen minimal from the view of electropneumatic valves technical specifications.

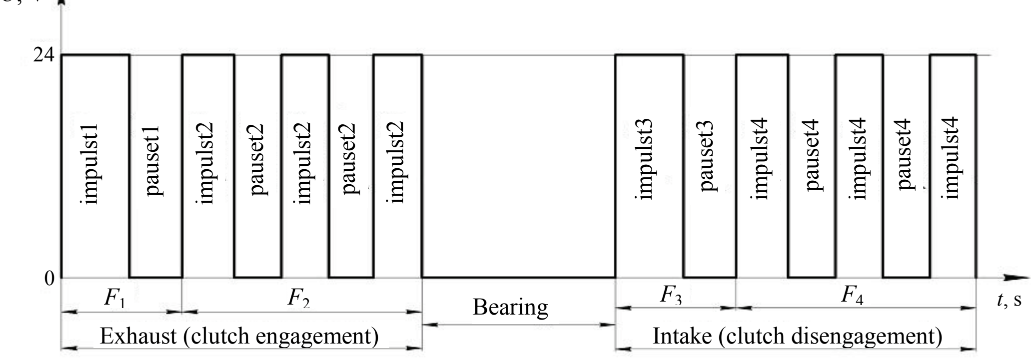

Fig. 4. Phases of an ACCS control system operation: impulst1 – pulse on-time in phase 1 of a clutch engagement process; pauset1 – pause on-time in phase 1 of a clutch engagement process; impulst2 – pulse on-time in phase 2 of a clutch engagement process; pauset2 – pulse on-time in phase 2 of a clutch engagement process; impulst3 – pulse on-time in phase3 of a clutch disengagement process; pauset3 – pause on-time in phase 3 of a clutch disengagement process; impulst4 – pulse on-time in phase 4 of a clutch disengagement process; pauset4 – pause on-time in phase 4 of a clutch disengagement process

Phases 2 (F_2) and 4 (F_4) (fig. 4) are necessary for actuator rod positioning respectively. It is proposed to calculate pulse on-time impulst2 not only depending on the clutch pedal movement speed, but also to set time pauset2 minimal. During the clutch disengagement process impulst4 is suggested to set minimal but to control by means of a pause on-time change pauset4 depending on the pedal movement speed.

Taking into account the literary review and the analysis of experimental studies performed before, the operation of the ACCS control system was built on the basis of the three-position algorithm, presented in fig. 5.

Fig. 5 demonstrate the following accepted symbols: U_{FB} – a signal from the rod position sensor (feedback sensor); U_{RS} – a signal from the pedal position sensor (reference signal sensor); p – a parameter that provides guaranteed pressure drop from the rod end of the power cylinder with the clutch pedal fully released in the case of using a normally closed exhaust valve; δ_1, δ_2 – the limits of the upper and lower null zones of the rod position sensor respectively; EK_1 – inlet electropneumatic valve; EK_2 – exhaust electropneumatic valve; t_{off} – temporal value of taking the initial position of the pedal; t_i – current time value.

At the initial moment of time the ECU receives data from the pedal position sensor U_{RS} and the rod position sensor U_{FB}, as well as data whether the first round of computing this branch of the algorithm takes place. The algorithm has four main branches [8–14].

The first branch of the algorithm operation describes the case when the system is at rest (fig. 5). The ECU verifies whether the clutch control actuator is in its original position ($U_{RS} = 0$). If the signal from the pedal position sensor indicates that it is in the starting position, this may be a sign of two operational modes: the system has not come out of the resting or the operator has acted on the pedal and brought it to its original position.

This is verified by means of the condition $P = 1$ (dimensionless quantity). If the condition is fulfilled the operator has acted on the control actuator and returned it to its original position, then we have the first round of the algorithm computing. To exclude the availability of residual pressure in the actuator dead space, the ECU supplies the voltage to EK_2 for 3 seconds and ensures that there is no residual pressure. At every next step of computing the condition $p = 1$ is not fulfilled and the ECU brings the system to the rest, there is no voltage on both electro-pneumatic valves.

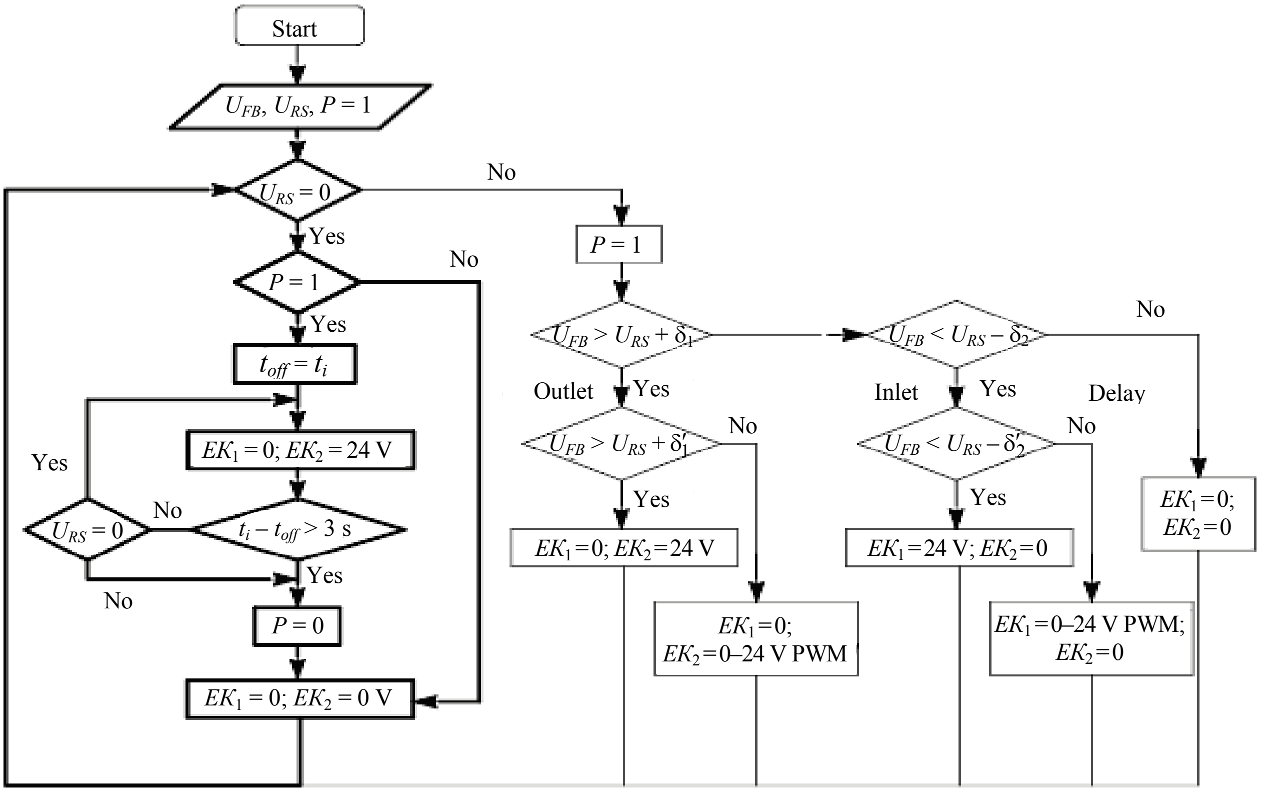

Fig. 5. Operational algorithm of automated control system

The second branch is the algorithm operation in the case when the rod of the actuator has travelled more than was specified by the operator (fig. 6a).

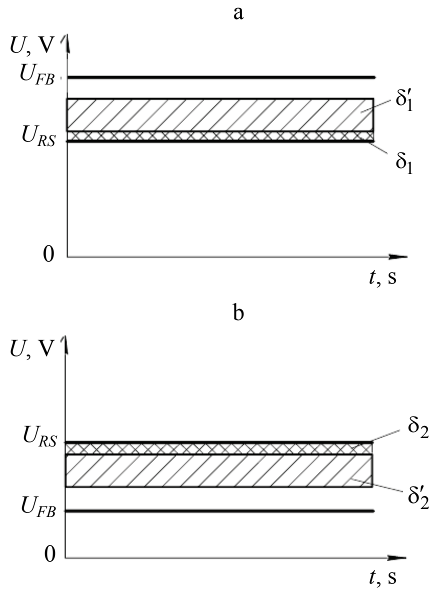

Fig. 6. Position of actuator rod:
a – rod travels more than specified;
b – rod travels less than specified

If the condition when the rod is in its original position ($U_{RS} = 0$) is not fulfilled, the ECU concludes that the operator has acted on the actuator and introduces a new setting $P = 1$, that will provide the first round of computing this branch of the algorithm. Then the ECU defines the current state of the actuator rod in relation to the position specified by the operator. If the signal from the feedback sensor is larger than from the pedal position sensor, taking into account the upper null zone ($U_{FB} > U_{RS} + \delta_1$), the ECU concludes that the system has reacted to the operator's impact but has crossed the position specified by him. The next step of the ECU is determining to what extent the rod is far from the specified position, checking if the condition $U_{FB} > U_{RS} + \delta'_1$ is fulfilled. If the condition is fulfilled, the ECU supplies the voltage as a continuous signal to EK_2 to return the rod into the specified position, if not – in the PWM mode.

The third branch of the algorithm describes the case when the actuator rod has not reached the position specified by the operator (fig. 6b).

When working out the second branch of the algorithm if the condition $U_{FB} > U_{RS} + \delta_1$ is not fulfilled the condition $U_{FB} < U_{RS} - \delta_2$. If it is fulfilled, the ECU concludes that the system has reacted onto the operator's act, but the rod has not reached the specified position. The next step of the ECU is determining how far the rod is from the specified position checking the fulfilment of the condition $U_{FB} > U_{RS} - \delta'_2$. If the condition is fulfilled, the ECU supplies the voltage as a continuous signal to EK_1 to return the rod into the specified position, if not – in the PWM mode.

The fourth branch describes the case when the actuator rod has taken up the position according to the specified pedal position. If none of the conditions $U_{FB} > U_{RS} + \delta_1$ and $U_{FB} < U_{RS} - \delta_2$ is fulfilled, the ECU concludes that the rod has reached the position specified by the operator. The system is at rest before the change U_{RS}, there is no voltage on both electro-pneumatic valves.

During the operation of the algorithm the ECU conducts a constant scanning of pedal position and rod position sensors at the set frequency. Making a comparison of these signals directly to each other is not possible either in analogue or in digital forms. This is due to such two factors:

– a range of the signal change from the feedback sensor during the total travel of the actuator differs in 2.5–3 times from the signal coming from the pedal position sensor;

– a range of the signal change from the feedback sensor while in operation constantly shifts, due to the wear of the clutch friction facings.

Correct comparison of two signals is possible only in percentage terms. It is suggested to perform the determination of the current range limits of the feedback sensor operation in the calibration mode. This mode is activated automatically at each loading of the ECU. When the driver presses the clutch pedal for the first time, the system memorizes two extreme points of the voltage range from the feedback sensor and then interprets them as a maximum and a minimum.

The required parameters of the null zone δ_1 and δ_2 are chosen in terms of ensuring steady operation of the system and the required precision of ACCS operation.

For the correct operation of the automated control system ACCS it is necessary to ensure a high degree of signal reliability and smoothness of the pedal position and the actuator rod incoming from the sensors to the ECU. When using sensors without high protection, noise can be made by any accidental event such as an electric discharge. In this case the signal can acquire a deliberately impossible false meaning. In order to exclude the influence of this false value on the operation of the control system, it is necessary to elimina te it from the data array incoming in the ECU. The easiest and the most convenient way to do this is to use a filter.

There are two types of filter forms: hardware and software. Hardware filters are implemented on the elements of integrated circuits, while the digital ones – using programs executed by the processor or microcontroller. The advantage of software filters prior to hardware ones is the ease of implementation, configuration and change. Application of a software filter does not result in increasing the price of the ECU as a whole because it does not require additional components.

Many types of digital software filters are known. The median filter providing a high degree of protection against erroneous values while not slowing down the ECU was selected for implementing in the developed automated control system ACCS.

Median filtering is a method of nonlinear signal processing, developed by J. Tuckey in 1971.

The principle of filtering

The median of the numerical sequence x_1, x_2, ..., x_n, when n is odd, is the average term of the series obtained by arranging this sequence in increasing (or decreasing) order [15].

The central value is substituted by the obtained average value in the window for the processed signal. Thereby the median filter belongs to nonlinear filters replacing anomalous points and spikes by the median values regardless of their peak values. It is steady and capable of removing even spikes enormously large by value.

The median filtering algorithm excludes isolated spikes, both negative and positive, that are on the edge of the ranked list from the signals effectively. Taking into consideration the list ranking the median filters suppress some noise and interference with the length less than half the window. A permanent point is a sequence (in a one-dimensional case) or an array (in a two-dimensional case) that do not change with median filtering. Due to this feature, median filters with optimally selected number of elements can store preserved edges of objects, obstacles and small dimensional details without changes. Under similar conditions, linear filtering algorithms inevitably smooth out the sharp edges and forms of objects.

Different strategies of implementing a median filter for noise suppression are possible. One of them recommends starting with a median filter, whose window covers three elements of the input data array. If the signal attenuation is insignificant, the filter window is expanded to five elements.

This is done as long as median filtering starts to do more harm than good. Another possibility is to implement a cascade median filtering of the signal using a fixed or variable window width. In general those areas having been constant after a single filter treatment are not changed after reprocessing. The areas where the pulse signal duration is less than half the width of the window will be changed after each processing cycle.

Advantages of median filters:

– a simple filter structure;

– a filter does not change step and powder functions;

– a filter suppresses single impulse interference and accidental noise spikes.

Disadvantages of median filters:

– median filtering is nonlinear because the median of the sum of two random sequences does not equal the sum of their medians, that in some cases can complicate the mathematical analysis of signals;

– a filter causes the flattening of vertices of triangular functions;

– delays in one reading with continuously increasing input values.

An example of signal processing by five points:

$x[7] = x_i; x_{i–1}; x_{i–2}; x_{i–3}; x_{i–4}; x_{i–5}; x_{i–6}$ – an input data array obtained directly from the sensor;

$XFm[5] = XFm_{i–2}$; $XFm_{i–3}$; $XFm_{i–4}$; $XFm_{i–5}$; $XFm_{i–6}$ – a data array for the median filter.

Median filtering can be recursive and nonrecursive. Non-recursive filtering processes only input array data

$$XFm_{i-4} = mediana(x_{i-2}; x_{i-3}; x_{i-4}; x_{i-5}; x_{i-6}). \quad (1)$$

Recursive filtration processes both input and filtered array data at the same time

$$XFm_{i-4} = \\ = mediana(XFm_{i-2}; XFm_{i-3}; x_{i-4}; x_{i-5}; x_{i-6}). \quad (2)$$

A data array for derivative of rod travel

$$\frac{\Delta XFm}{\Delta t}[3] = XFm_4;\ XFm_{i-5};\ x_{i-6}. \qquad (3)$$

Five-point differentiation with simultaneous using the filter

$$\frac{\Delta XF_{i-4}}{\Delta t} = \frac{\left(XFm_{i-2} - XFm_{i-6}\right) + \left(XFm_{i-3} - XFm_{i-5}\right)}{5\left(t_i - t_{i-1}\right)}, \qquad (4)$$

where i – a quantization step.

The displacement of the derivative relative to the real time will be four steps of quantization, for a predicted sampling rate of 200 Hz this will be approximately 0.02 s.

CONCLUSIONS

1. It has been proved that the two modes for controlling the electropneumatic valves to ensure an actuator rod rapid movement and its accurate positioning are necessary.

2. The use of electropneumatic valves with reaction time of 0.03 s enables us to achieve a rod positioning accuracy of 0.59 mm, this rate allows to reduce the control system dead space by 2.7 %.

3. Rapid rod movement from the spot is possible due to the control pulse delivery to the magnetic coil for 0.07 s.

4. Unlike existing commercial clutch control systems, this system enables to perform the functions using only two electropneumatic valves[1].

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