UDC 621.654
DOI: http://dx.doi.org/10.20535/2521-1943.2018.82.126859

Flow control valve with the polymer envelope as control organ

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Received: 26 January 2018 / Accepted: 16 February 2018

Abstract. *The existing hydraulic devices, with design based on the usage of "spool-and-sleevecylinder", have disadvantages such as low speed reaction and reliability, due to high sensitivity to the pollution in working fluid and non-workability of the construction. The aim of the research is to substantiate, on the base of mathematical modeling and experimental studies the application in the construction of fluid control valve the control organ, made of the polymer material in the form of the envelope. The influence of geometric shell parameters on the quality of the control process is investigated. The conditions and directions of the most effective use of the regulator are established. The results obtained are engineering basis for the creation of the efficient construction of fluid control valve with polymer control organ of the envelope form with the enhanced technical characteristics.*

Keywords: flow control valve, polymer control organ, regulation accuracy, speed, workability of the construction

Introduction

Hydraulic equipment, intended to control and distribute the working fluid in hydraulic drives, are used in the drives, is conventionally based on the application of mainly spool-type devices [1,2]. Availability of the accurate mated surfaces complicates the design of the hydraulic devices, the technology of their manufacturing and repair as well as decreases their reliability due to their sensitivity to the pollution of the working fluid [3]. Numerous cases of the failures of technological machines hydraulic drives as a result of the increased losses, jamming of plungers and spools, seal failures of the reverse valves. Particular damage such failures cause in case of the shutdown of the mechanisms, performing seasonal work as it happens in agricultural equipment, operating limited period of time during calendar year but very intensively, practically continuously. Eliminate or considerably decrease the above-mentioned drawbacks allows the application of the control devices with the elastic and polymer shutoff and control valves [4, 5, 6].

The analysis of scientific-engineering publications and patent materials shows that there exists rather wide range of structures where elastic, mainly rubber, elements are used. At the same time, the lack of methods of calculation of static and dynamic characteristics of hydraulic equipment with the elastic polymer shutoff is serious obstacle for the large-scale usage of the promising hydraulic devices.

Problem setup. To widen the area of application of the hydraulic and pneumatic systems it is necessary to perform engineering and research studies, aimed at simplification of the equipment construction in the context of replacement, where it is possible, of precision elements, for instance, spool-and-sleeve, by simpler non-conventional units without sacrificing the necessary operating characteristics.

Therefore, the aim of the given research is to design the flow control valve with the polymer envelope as control organ and its comprehensive study concerning the provision of high operation characteristics.

Flow control valves with the polymer control organ

Analysis of scientific and engineering sources shows the interest of foreign and Ukrainian researchers and engineers to use polymer envelopes and elastic elements in shut-off, control and actuating units for hydraulic and pneumatic devices. The elements in toroidal and cylindrical envelope forms are widely used nowadays. Regulation principle is based on local deformation of shutoff and control organ 3 in the process of changing the working window size of the regulator for the passage of working fluid. Similar is the construction of the fluid control valve in Fig 16 where toroidal regulating organ 3 is also used but the regulation principle is formed on the base of macro deformation, i.e., deformation of the regulating organ in radial direction, in the peripheral zone for the formation with the collar of the

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housing1 the regulator's working window. In such construction, unlike the previous one, the combination of permanent 4 and changeable throttling elements is used, it provides more efficient regulation process.

The constructions of the regulators, considered above, contain the genera disadvantage, negatively influencing the quality of regulation process – this disadvantage is the force of friction between the regulating organ the housing. This drawback is missing in the constructions [6,7,8] where the envelope is used as the regulation organ (see Fig 1 c,d,e). Regulation principle in such constructions is also based on "macro deformation" of the regulating organ in the radial direction In the construction [7] (Fig. 1g), the combined principle of regulation is used, that is, deformation simultaneously in the two aforementioned directions. In this paper attention will be paid to the study, in more detail, of the design presented in Fig. 1d, which in the opinion of the authors is the most promising.

The study of the efficiency of the polymer shell as a lock-regulating body of the flow control valve was considered by the authors in [9], in which the dependences of its deformation under the influence of pressure drop in the regulation process are determined. It is also noted that the deformation of the shell should be limited to the area of elasticity. The results of this work were used in the development of a mathematical model of the regulator, which is presented in this paper.

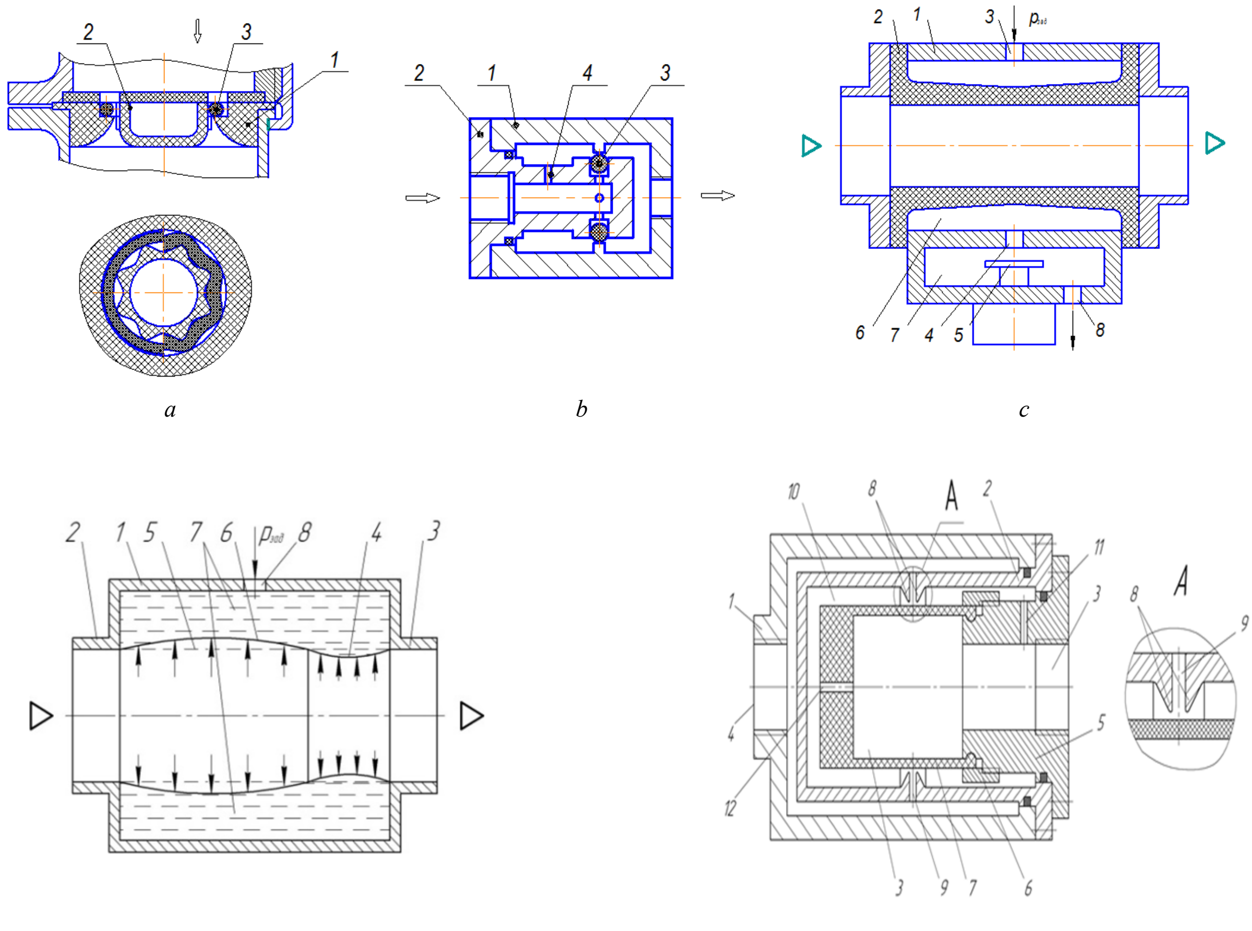


Fig. 1. Constructions of expenditure regulators: a, b - regulators with toroidal ESO [4, 5]; c, d, e - regulators with a shell ESO [6, 7, 8]

Mathematical model of fluid control valve with the polymer regulating organ of the envelope form

Fluid control valve with control body in the form of envelope - as an object of mathematical study can be represented by the calculation model, which is depicted on (fig. 2). Fluid regulation process performed by this structure is realized by the combination of two, serially connected throttles, permanent *6* and changeable *7*. The flow Q_1 into inner volume W_1 of the envelope, passes across the permanent throttle *6*, volume, hosed between cylinder and envelope W_2 and across changeable throttle *7*, created in the form of the annular gap *8* between the external surface of the control polymer element *4* and circular collars *8* at the internal cylindrical surfaces of the pieces *2* and *3* into the output channel.

To provide the uniformity of the control organ of the hydraulic technological machine operation it is necessary to maintain the consumption value Q_3 constant. This can be performed by means of changeable throttle *7* that maintains constant pressure differential as a result of the change of the passage area of the working window cross-section due to the deformation of the control element (Fig.2). The dynamics of the flow control valve with the polymer control element is described by the system of differential equations (1), under such assumptions:

– the coefficient of flow through the working window of the regulator is constant

– volume of the polymer control element is unchangeable;

– polymer control element – is lineally elastic body;

– the area of the end surface in the equation of the balance of forces, acting on the control organ, is not taken into account;

– the area of working window of the changeable throttle is connected with the displacement of the control element by the linear dependence.

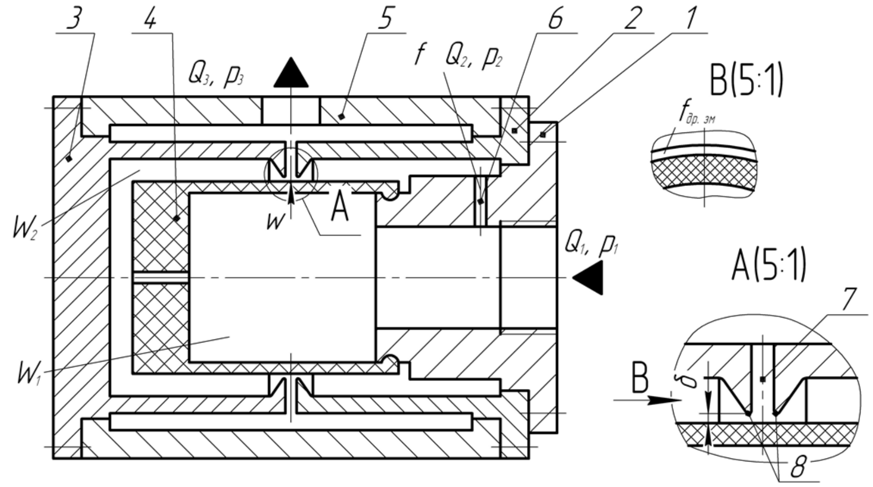


Fig. 2. Calculation scheme of the fluid control valve with the polymer regulating element

$$\begin{cases} m\dfrac{d^2x}{dt^2}+\dfrac{\tilde{n}_{\ddot{e}}\cdot\rho\cdot f_{env}}{2}\dfrac{dx}{dt}+\dfrac{p\cdot\pi\cdot d\cdot l}{e^{\beta x}(C_1\cos\beta x+C_2\sin\beta x)+e^{-\beta x}(C_3\cos\beta x+C_4\sin\beta x)+f(x)}x= \\ = f_{env}\cdot\eth_1+f_{env}\cdot\eth_2+f_{env}\cdot\eth_3; \\ Q_1=\mu\cdot\dfrac{\pi\cdot d^2_{\text{perm throt}}}{4}\sqrt{\dfrac{2}{\rho}\left(p_1-p_2\right)}+k\dfrac{\pi\cdot d^2_{env}}{4}\cdot l_{env}\dfrac{dp}{dt}+\pi\cdot d_{env}\cdot l_{env}\dfrac{dx}{dt}; \\ Q_2=\mu\cdot\dfrac{\pi\cdot d^2_{\text{housing}}}{4}-\dfrac{\pi d^2_{env}}{4}\sqrt{\dfrac{2}{\rho}\left(p_2-p_3\right)}-k\dfrac{\pi\cdot d^2_{\text{housing}}}{4}\cdot l_{\text{housing}}-\dfrac{\pi\cdot d^2_{env}}{4}\cdot l_{env}\dfrac{dp}{dt}-\pi\cdot d_{env}\cdot l_{env}\dfrac{dx}{dt}. \end{cases} \qquad (1)$$

where p_1 p_2 p_3 – are pressures in the input, intermediate and input cavities of the regulator, correspondingly; Q_1 Q_2 – are expenses in the intermediate and output cavities of the regulator correspondingly; m – is the mass of the control element; d_{env}, l_{env}, f_{env} – external diameter, length and total area of the control element correspondingly; K – is the compression ratio; m – is the orifice coefficient; $d_{throt\ perm}$ – is the diameter of the permanent throttle; $d_{throt\ house}$ – is the diameter of chartable throttle window; C_f – is the drag coefficie; P – is the density of the fluid.

The process of the formation of changeable throttle area of the considered regulator differs fundamentally from the similar devices, where area change of such element is provided by the motion of the spool (axial or annular) or by the valve, at the same time, motion of the latter is obstructed by the forces of dry and liquid friction, characterized by the corresponding damping coefficients. In the consumption regulator with the polymer control element the formation of the changeable working window takes place due to the deformation of the envelope, that is why, the above-mentioned forces of resistance (friction) are missing but other forces, preventing the deformation of the envelope, take place. First of all, these are mechanical characteristics, namely, the rigidity of the envelope in the radial direction, that depends on the material and the shape of envelope, as well the forces of deformation resistance of the envelope, which cause the filling of the cavity with the working fluid.

Thus, it is necessary to determine the damping coefficient, that characterizes the force of the fluid resistance in the intermediate chamber, caused by the deformation of the polymer control element. In general, the force of resistance, emerging during the relative motion of the body in the fluid consists of the resultant frictional forces, directed along the tangent line to the surface of the body and pressure force, which is the result of pressures differential at the external and internal surfaces of the body. The action of the fluid on the body in general case can be reduced to the vector; that is applied to a certain point, called pressure centre. The vector acting on the solid body, is presented in the form of head resistance force, directed along the vector of the flow rate

$$\beta = \frac{C_f \cdot \rho \cdot f_{env}}{2}, \qquad (2)$$

where C_f – is the drag factor; P - is the fluid density; f_{env} - is total area of the control element.

The experimental studies proved the adequacy of the taken assumptions. It is determined that in case of control element deformation rate change the non-linear change of the phase shift was revealed. The reduction of the fluid control valve intermediate cavity volume leads to the increase of deformation resistance and causes this delay. To present this phenomenon in the mathematical model the empiric component, shown in Fig. 3, is introduced. By means of Data Fit 8 software on the base at the regression analysis the empiric dependence (4) with the reliability of 99,9% is determined:

$$F_1 = \frac{v}{2{,}1575 + 0{,}0917 \cdot v - 0{,}85 \cdot v^2}, \qquad (3)$$

$$\beta = \frac{\tilde{n}_f \cdot \rho \cdot f_{env}}{2} v^2 + \frac{v}{2{,}1575 + 0{,}0917 \cdot v - 0{,}85 \cdot v^2}. \qquad (4)$$

The impact of the intermediate cavity volume of the fluid control valve on the deformation rate was determined (see Fig. 3).With the increase of the intermediate cavity volume the deformation rate and damping coefficient decrease proportionally.

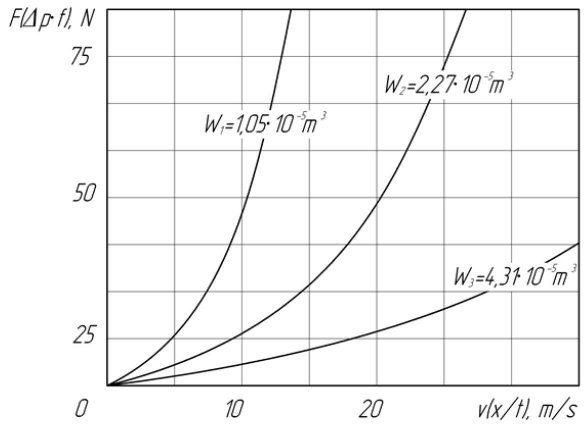


Fig. 3. Dependence of the damping force on the rate of polymer control element deformation

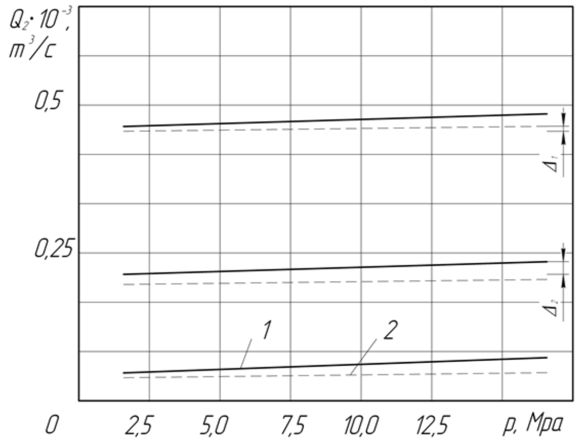


Fig. 4. Static characteristic of fluid control valve: 1 – G55; 2 fluid control valve with the polymer control element

The given system of differential equations (1) was solved in the MATLAB-Simulink-software environment. As a result of study the static characteristic (Fig 4) of the fluid control valve with the polymer control element was obtained, using this characteristic the range of pressure differential can be determined at which the changeable throttle will adequately respond to the disturbance (*Ap=0,1…1 MPa for Q=0,5·10-3 m³/s*). The analysis of the static characteristics showed that the accuracy of flow stabilization across the fluid control valve with the polymer control organ is 10% lower as compared with the serial analog *G55-2*.

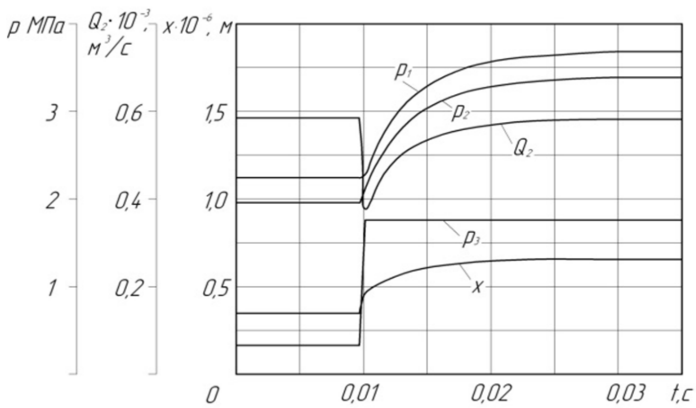


Fig. 5. Transient process in the fluid control valve with the polymer control element (reaction on «stage» disturbing signal)

The range of geometric parameters of the control element of the fluid control valve were determined (Fig. 2). For instance, for the fluid control valve with nominal flow $Q=0.5\ 10\ m^3/s$ the diameter of the control element $d=0.022\ m$ with the wall thickness $h=1.5\ 10$ is optimal. With the increase of the wall thickness of the control element accuracy of flow stabilization increases by *3.5%* and regulation time increases by *6%*. The analysis of the transient processes, obtained as a result of simulation mathematical modeling (see example in Fig 5) shows that the fluid control valve has the increased speed and stability characteristic (transient process has smooth aperiodic character and lasts not more than *0,01s*.The form of the transient process shows that the component of the second order (response rate of the envelope) in the balance of forces equation, acting on the envelope, practically does not influence its character, that is why in the engineering calculation this component is not taken into account.

Experimental test stand for the flow control valve with the polymer envelope as control organ

Experimental studies of the fluid control valve were performed at a special stand (Fig. 6, 7), that corresponds to the calculation scheme. The main components of the stand are executive part, consisting of the hydraulic cylinder *C*, regulating valve *R1*, spring S_{sp}, that performs the function of the mechanical positional load for the hydraulic cylinder and distribution valve *R2* for the simulation of the hydraulic load. Pump station consists of the feed pump *FP*, main ump of changeable working volume *P1* and pressure-relief valve *PV1*. Hydraulic motor *HM* and the tachometer *T* is intended for the measurement of the hydraulic fluid consumption. Measuring-registration equipment with the analog –to –digital adaptor 1406 and the computer was used. Test sample is used with the set of pressure sensors and displacement sensors.

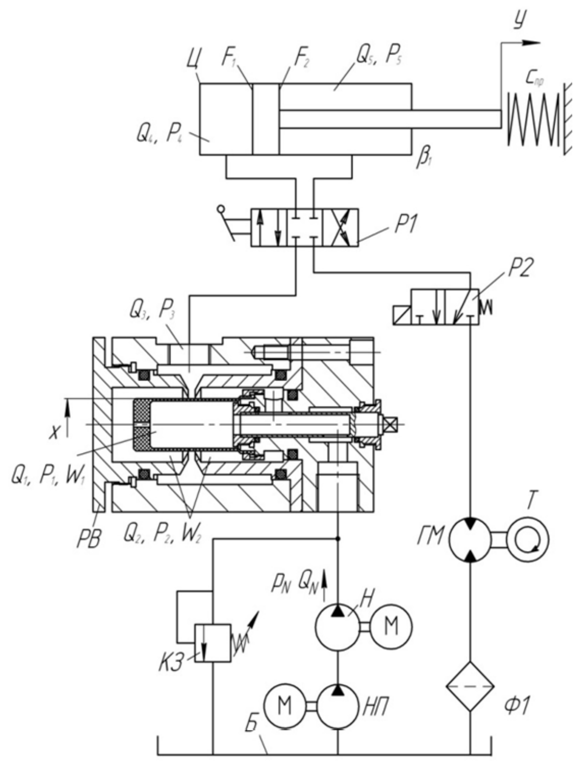
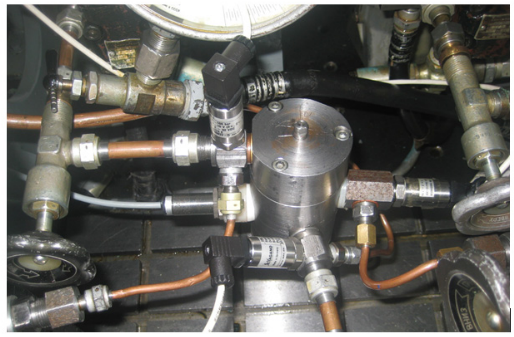
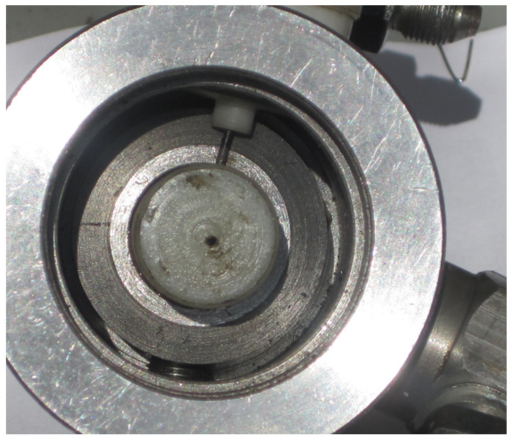


Fig. 6. Hydraulic circuit of the stand for the experimental research of fluid control valve operation characteristics with the polymer control element of the envelope form



a



b

Fig. 7. General view of the test sample of the valve (a) and wiring diagram of the sensor for envelop deformation measurement (b)

Construction composition of the stand for experimental research enables to obtain static and dynamic characteristics of the studied fluid control valve due to the available pump station with the regulated consumption and blocks for the creaction of static and dynamic load on the object of the research.

As a result of the experimental research carried out, the obtained oscillograms of the transient processes (see the sample in Fig 8) proved basic operation characteristics of the fluid control valve with the polymer control organ that were declared as a result of mathematical simulation modeling, namely, fast operation speed and the quality of the transient processes al satisfactory static characteristics.

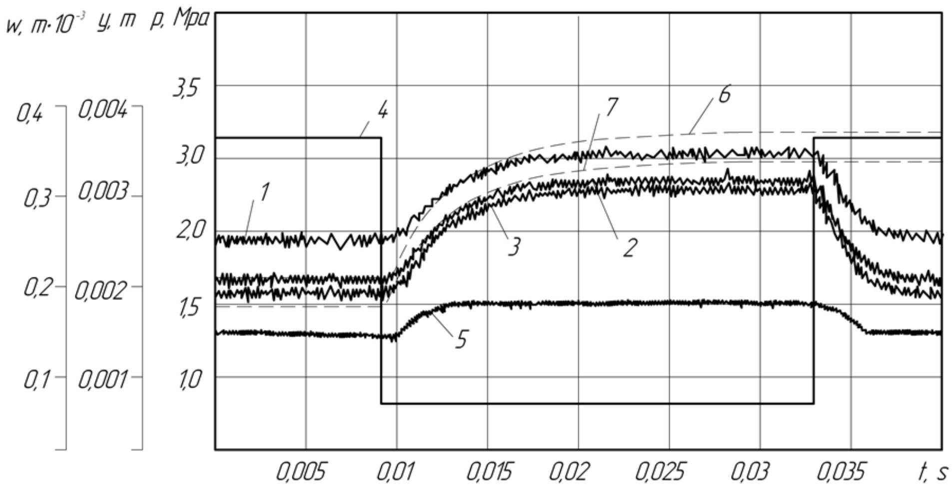


Fig. 8. Transient process in fluid control valve, determined experimentally:
1, 2, 3 – pressure in the input, intermediate and output cavities of the valve , correspondingly; 4 –form of disturbance action signal; 5 – displacement of the generating envelope; 6, 7 – pressure in the intermediate and output cavities of the valve, determined by means of mathematical modeling

Conclusions

It is shown that the fluid control valve with the controlling element of the envelope form of polymer material, according to the proposed scheme by the authors, provides satisfactory technical specifications: the accuracy of the flow stabilization has been improved by *3.5%* compared to the serial analogue G55-2, and the transition time has been reduced by *60%*. The analytical calculations of deformation dependences of the shell on the pressure of the working fluid have determined the operating range of the control body *0.1 ... 1.0 Mpa*. The basic geometric parameters of the control element at the flow rate $Q = 0,5 \cdot 10\text{-}3\ m^3/s$ are defined. The diameter $d = 0,022\ m$ with wall thickness $h = 1,5 \cdot 10^{-3}\ m$.

The reliability of the results obtained by analytical and mathematical modeling is confirmed by experimental research. In the case of development of design documentation in accordance with the applicable standards, such a regulator can be implemented in real production.

Регулятор витрати з полімерним керуючим органом оболонкової форми

В.П. Пурдик, О.Л. Брицький

Анотація. *Існуючі регулюючі гідроагрегати, конструкція яких базується на використанні золотникової пари мають ряд недоліків – це невисока швидкодія, недостатня надійність внаслідок підвищеної чутливості до забруднення робочої рідини та не технологічність конструкції. Мета роботи – обґрунтування на основі математичного моделювання та експериментальних досліджень використання в конструкції регулятора витрати керуючого органа із полімерного матеріалу у вигляді оболонки. Досліджено вплив геометричних параметрів оболонки на якість процесу керування. Встановлено умови та напрямки найбільш ефективного використання регулятора. Отримані результати представляють інженерну основу для створення ефективної конструкції регулятора витрати з полімерним керуючим органом оболонкової форми з підвищеними технічними характеристиками.*

Ключові слова: *регулятор витрати, полімерний керуючий орган, точність регулювання, швидкодія, технологічність конструкції.*

Регулятор расхода с полимерным управляющим органом оболочковой формы

В.П. Пурдик, О.Л. Брицкий

Аннотация. *Существующие регулирующие гидроагрегаты, конструкция которых базируется на использовании золотниковой пары, имеют ряд недостатков - это невысокое быстродействие, недостаточная надежность вследствие повышенной чувствительности к загрязнению рабочей жидкости и не технологичность конструкции. Цель работы - обоснование на основе математического моделирования и экспериментальных исследований использования в конструкции* *регулятора расхода управляющего органа с полимерного материала в виде оболочки. Исследовано влияние геометрических параметров оболочки на качество процесса управления. Установлены условия и направления наиболее эффективного использования регулятора. Полученные результаты представляют инженерную основу для создания эффективной конструкции регулятора расхода с полимерным управляющим органом оболочечной формы с повышенными техническими характеристиками.*

Ключевые слова: *регулятор расхода, полимерный управляющий орган, точность регулирования, быстродействие, технологичность конструкции.*

References

1. Kozlov L.G., Lozinsky D.O., Kovalchuk VA, Dzis Yu.V. Features of hydrodistributor designs for hydrosystems sensitive to loading / Industrial hydraulics and pneumatics. - 2009. – no.1. - P. 80-84.
2. Lurie Z. Ya., Chekmasova IA The mathematical model of the throttle hydraulic unit with flow controller // Bulletin of the National Technical University of Ukraine "Kiev Polytechnic Institute". Mechanical engineering. - Sumy: Sumy State University. - 2002. – no. 42. - Vol. 1.- P. 178-183.
3. Burennikov Y. Mechatronic hydraulic drive with regulator, based on artificial neural networks / Y. Burennikov, L. Kozlov, V. Pyliavets, O. Piontkevych // IOP Conf. Series : Materials Science and Engineering, 2017. – 2017. -Vol. 209 (012071). – P. 8. – doi :10.1088/1757-899X/209/1/012071
4. Patent № 3847176 FRG Ruckschlagventil mit hulsenformigen elastischen Ver-Schlupstuk / Volf-Diter Keppel. 03.08.74 Kl. 47g I 15/14.
5. A.s. №752240 (SSSR). Regulaytor rashoda / Purdyk V.P., V.B. Petrov, V.V.Syrkin. – Opubl. v B.I., 1980, №28.
6. Patent №7118086 USA. PNCH VALVE WITH INLET AND OUTLET PORTS / Anthony R. Borglum, Cedar Falls, IA (US); John C. Estapa, Lynnville, IA (US); Corey W. Cerwinske, Waverly, IL (US); Richard P. Borglum, Janesville, IA (US); Perry R. Anderson, Scottsdale, AZ (US) Mar. 4, 2005 FI6K 7/04.
7. Bityukov V.K., Gavrilov A.N. Regulyator rashoda pryamotochnyy. // Pologitelnoe reshenie po zayavke №4923934/24(027077) ot 28.01.1992.
8. Patent №43347 Ukrainy MPK8 G05D7/00 Regulyator vytrety / Purdyk V.P., Brytskyi O.L.; Zayavnyk ta patentovlasnuk Vinnytskiy nats. teh. universytet.– №u200903011; zayav. 30.03.2009.; opubl. 10.08.2009, Byul. №15.
9. Purdyk V.P., Brytskyi O.L. Eksperymentalne doslidgenya robochogo organu regulaytora vytraty z polimernogo materialu. Naukovi pratsi VNTU, 2012, no. 4. – P. 65 – 67.
10. Purdyk V.P., Brytskyi O.L., Matemetychne modelyuvanya regulyatora vytratype z robochym organom z polimernogo materialu./– Promyslova gidravlika ta pnevmatyka. No.1(39) 2013. – P. 75–77.