## Секція 5
## Загальні питання промислової гідравліки і пневматики, енергозбереження, екології

## Секція 6
## Інноваційні, інвестиційні та освітні аспекти розвитку промислової гідравліки та пневматики

## ПЛЕНАРНЕ ЗАСІДАННЯ

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**Strutynskiy V.B.,**
**Doctor of Technical Sciences, Professor**
**Potiienko P.O.**
National Technical University of Ukraine
«Igor Sikorsky KPI»

# IMPROVING THE ACCURACY OF PRECISION HYDRAULIC AUTOMATION DEVICES BY IMPLEMENTING FUZZY STOCHASTIC OSCILLATIONS OF THE SPOOL VALVE

Precision pressure differential control devices are used in the hydraulic automation systems of special equipment. They have spool regulators integrated into the system, which ensures stabilization of the pressure differential over a wide range of flow rates and operating parameters, in particular, temperature changes. Improving the control accuracy of such devices is a pressing scientific and technical problem. As a rule, the accuracy of pressure differential control of known regulators in dynamic modes does not exceed 10–15% [1]. This significantly reduces the efficiency of hydraulic automation systems. Various means of increasing the accuracy of spool pressure regulators are used [2]. The most effective measures are those aimed at reducing friction and hydrodynamic forces in spools [3]. As a result of information research, it has been established that there are currently no methods for significantly improving the accuracy of pressure differential regulators by implementing fuzzy stoch **Skvorchevsky** astic oscillatory movements of the spool.

The aim of the research is to improve the accuracy of pressure differential regulators by implementing fuzzy stochastic oscillatory movements of the spool. To achieve this goal, the following tasks were set and solved: a theoretical justification was provided for the possibility of improving the dynamic accuracy of precision hydraulic units by implementing fuzzy stochastic oscillatory movements of the spool valve; based on theoretical and experimental studies, an innovative hydraulic automation device was implemented that implements fuzzy stochastic oscillations of the spool; the effectiveness of the developed technical solution was confirmed by mathematical modeling. Experimental design and theoretical methods [4] were used in the research process.

The theoretical justification for improving the accuracy of precision hydraulic automation devices takes into account that they operate in harsh dynamic conditions. Samples of special equipment that use precision devices are complex hydraulic units. Experimental studies of devices as part of a hydraulic unit and measured values of the resulting pressure drop p (see Fig. 2b) confirm the presence of significant changes in pressure drop over time. This is unacceptable from the point of view of reliable operation of the hydraulic unit.

In a linear formulation, the relationship between the output Yi(t) and input Xj(t) parameters of the hydraulic automation device is presented as a set of linear differential equations:

$$a_{in}\frac{d^nY_i}{dt^n}+\ldots+a_{i1}\frac{dY_i}{dt}+a_{i0}Y_i=\sum_{j=1}^{\mu}\left(b_{j0}X_j+b_{j1}\frac{dX_j}{dt}+\ldots+b_{jm}\frac{d^mX_j}{dt^m}\right) \quad (1)$$

where $i = 1, 2, ..., \upsilon$.

Equation (1) includes $\mu$ coefficients $b_{j0}, b_{j1}, ..., b_{jm}$ and $\nu$ coefficients $a_{i0}, a_{i1}, ..., a_{in}$.

In mathematical modeling, each pair of input–output parameters is considered separately, resulting in ($\mu$-$\nu$) operator mathematical models of the form:

$$Y_i(s) = W_{ij}(S)X_j(S), \quad i = 1, 2, ..., \nu, \quad j = 1, 2, ..., \mu, \quad (2)$$

$W_{ij}(S)=\dfrac{b_{j0}+b_{j1}S+\ldots+b_{jm}S^m}{a_{in}S^n+\ldots+^n a_{i1}S+a_{i0}}$ – transfer function from the j-th input parameter to the i-th output parameter.

In mathematical modeling of a hydraulic automation device, the frequency characteristics of a dynamic system corresponding to its transfer function are used. The transfer function $W_{ij}(S)$ by formal substitution – $S \to j\omega$ ($\omega$ – frequency, $j=\sqrt{-1}$ – imaginary unit) is converted into frequency form:

$$W_{ij}(j\omega)=\frac{b_{j0}+jb_{j1}\omega+\ldots+j^mb_{jm}\omega^m}{j^na_{in}\omega^n+\ldots+ja_{i1}\omega+a_{i0}}$$

which is a complex-significant function of the real argument (frequency) $\omega$.

A hydraulic automation device, whose input receives a stationary ergodic input parameter with spectral density $S_{xj}(w)$, also has a stationary ergodic random parameter with spectral density at its output:

$$S_{yi}(\omega) = |W_{ij}(j\omega)|^2 \bullet S_{xj}(\omega), \quad (3)$$

$|W_{ij}(j\omega)|^2$ – square of the frequency transfer function modulus.

The internal parameters of the hydraulic automation device, which have vaguely defined stochastic oscillations of the spool, change randomly. To determine them, a set of random numbers is used, which implements the Monte Carlo method [1].

It is assumed that changes in the coefficients of mathematical model (1) are functions of a set of k independent random variables. $g_1^*, g_2^*,..., g_k^*$. with normal distribution laws. Accordingly, the internal parameters of the mathematical model of the hydraulic automation device will be determined by functional dependencies:

$$a_{i0}^* = a_{i0}(g_1^*, g_2^*, ..., g_k^*), \qquad b_{j0}^* = b_{j0}(g_1^*, g_2^*, ..., g_k^*),$$

$$a_{in}^* = a_{in}(g_1^*, g_2^*, ..., g_k^*), \qquad b_{jm}^* = b_{jm}(g_1^*, g_2^*, ..., g_k^*).$$

These formulas yield an infinite number of implementations:

$(l = 1, 2, ..., L \to 8)$
values of the model coefficients.

In this case, the differential equations of the relationship between the input and output parameters of the device will take the following form:

$$a_{inl}\frac{d^nY_{il}}{dt^n}+\ldots+a_{i1l}\frac{dY_{il}}{dt}+a_{i0l}Y_{il}=\sum_{j=1}^{\mu}b_{i0l}X_j+b_{j1l}\frac{d^nX_j}{dt}+\ldots+b_{jml}\frac{d^mX_j}{dt^m}$$

$$i = 1, 2, ..., \omega, \quad l = 1, 2, ..., L \to 8. \quad (4)$$

In equation (4), the index l denotes l and the realization of a set of random variables that determine the coefficients of the mathematical model. Moreover, the values of the coefficients of equation (4) do not depend on time, and the realization of the output parameter $Y_{il}$ is a deterministic function of time. Equation (4) is a generalization of equation (1). For equation

(4), operator dependencies (2) and (3) also apply. Accordingly

$$\overline{S}_Y(\omega) = \frac{1}{L}\sum_{l=1}^{L}\left|W_{ijl}(j\omega)\right|^2 S_{\dot{x}}(\omega)$$

otherwise

$$\overline{S}_Y(\omega) = \overline{\left|W_{ij}(j\omega)\right|^2} \cdot S_{\dot{x}}(\omega) \qquad (5)$$

$$\overline{\left|W_{ij}(j\omega)\right|^2} = \frac{1}{L}\sum_{l=1}^{L}\left|W_{ijl}(j\omega)\right|^2$$

The criterion for the efficiency of a hydraulic automation device with vaguely defined stochastic spool oscillations is a reduction in the calculated spectral output density (5) compared to its value (3). It has been established that by changing the coefficients $b_{j0}$, $b_{j1}$, ..., $b_{jm}$ та $ai_0$, $a_{i1}$, ..., $a_{in}$ The hydroautomatic device can ensure a reduction in the calculated spectral density (5) by an order of magnitude compared to the value (3).

Based on theoretical and experimental research, an innovative hydraulic automation device has been developed that implements fuzzy stochastic oscillatory movements of the spool (Figure 1).

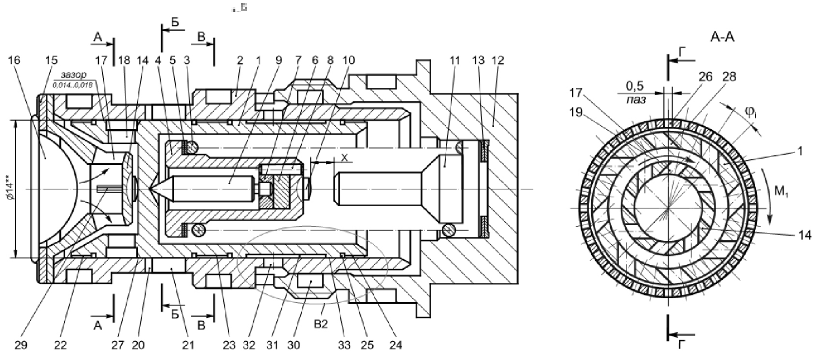


*Figure 1 – Hydraulic automation device that implements stochastic oscillatory movements of the spool*

The device includes a spool 1 located in the opening of the sleeve. Spring 3 is installed in cup 4. Cup 4 has a support insert 6 and a radial bearing 7 in its inner part, which are fixed with pin 8.

A rod 9 is placed in the cavity of the glass 4, which has a cylindrical shank that enters the bearing 7. The shank has a spherical end 9 that interacts with the support insert 6. The left edge of the rod interacts with a conical recess made in the center of the spool 1. The cup 4 has a spherical support protrusion 10 on its right end. This shoulder limits the stroke of the spool x. The right edge of the spring 3 rests on the bushing 11, and the spring is centered on the bushing by its inner diameter. The bushing 11 is installed in the opening of the cover 12. Washers 13 are installed between the bushing 11 and the cover 12.

The movement of spool 1 to the left is limited by stop 14, which has a spherical protrusion that interacts with the end face of the spool. Stop 14 is fixed by sleeve 2. Washer 15 is installed between stop 14 and filter 16. Stop 14 has a system of holes 17, which serves as a guide device for creating a vortex motion of the fluid at the inlet to the holes 18 of spool 1.

The holes 17 in the stop 14 swirl the flow of fluid passing into the spool cavity (shown by arrow 19). The flow of fluid passing through the holes 18 of the spool 1 creates a torque M1 on the spool, which causes the spool to turn (rotate) in the direction of the torque M1.

To facilitate rotation, three groups of grooves are made on the surface of spool 1. Group 22 of grooves is directly adjacent to the left end of the spool. The central group of grooves 23 is located in the middle part of the spool, and group 24 of grooves is located near the right end of the spool. Grooves 25 are made to relieve the spool from the action of transverse pressure forces on its surface.

The grooves on the surface of the spool form a system of hydrodynamic bearings that facilitate the rotation of the spool. In addition, the grooves provide drainage in the main parts of the gap between the spool and the sleeve. This is especially important for a spool that has high-frequency axial oscillations of insignificant amplitude. Axial oscillations are provided by small grooves 27 on the throttle edge of the spool. Grooves 27 are made on the end face of the spool using a special electrode.

Grooves 27 are arranged randomly . The distances between the grooves are selected using a random number generator with a normal distribution law. When the spool 1 rotates, the grooves 27 located on the throttle edge of the spool pass in the vicinity of the throttle groove 20 made in the sleeve 2. This causes random pulse changes in the fluid flow rate. This leads to a stochastic pulse axial load on the spool. Random values of the distances between the grooves provide a system of random pulses of axial load on the spool. The spectral density of random loads is selected from the condition of overlapping the range of natural frequencies of the spool. Under the action of random loads, statistical resonance occurs and the spool performs stochastic axial oscillations at frequencies close to the resonance frequencies. For the fluid to exit the cavity of the cover 12, a groove 31 is made on the surface of the spool 1, and holes 32 are made in the sleeve 2.

The device design provides for damping of the spool's axial vibrations. The spool's vibrations are damped by a throttle in the form of a belt 33 on the spool surface. The effectiveness of the developed innovative hydraulic automation device has been confirmed by mathematical modeling.

The characteristic of the device is a parabola whose coefficients have random variations:

$$\Delta p = R_1 Q_1 + R_T Q_1 \left| Q_1 \right| \tag{6}$$

$R_Л$ – linear hydraulic resistance of the device's hydraulic line; $R_T$ – quadratic hydraulic resistance of the hydraulic line.

Linear hydraulic resistance is determined by the following relationship:

$$R_{Ë} = \frac{150}{\pi} \rho \sum_{i=1}^{n_1} \frac{\ell_i}{d_i^4} + \delta R_{Ë} \tag{7}$$

ρ – density of liquid; $\ell_i$, $d_i$ – length and equivalent diameter of a pipeline with laminar fluid flow; $n_i$ – number of consecutively connected pipelines; $\delta R_Л$ – random component of linear resistance determined according to the Monte Carlo method.

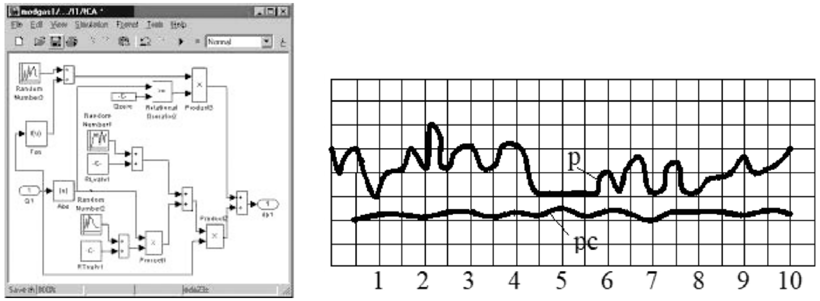
Quadratic hydraulic resistance is determined by the following relationship:

$$R_T = \frac{8\rho}{\pi^2} \sum_{j=1}^{n_T} \frac{\lambda_j \ell_j}{d_j^5} + \frac{\rho}{2} \sum_{K=1}^{n_M} \frac{\xi_K}{S_K^2} + \delta R_T + \frac{\rho}{2} \frac{\xi_\partial}{s_\partial^2} \tag{8}$$

The first sum on the right corresponds to hydraulic losses along the length of the pipeline, and the second sum corresponds to local pressure losses in the spool.

In formula (8), it is indicated that: $\ell_i$, $d_i$ – length and equivalent diameter of a pipeline with turbulent fluid flow ; $s_k$ – cross-sectional area of local hydraulic resistance; $\zeta_k$ – coefficient (of к-numbers) of local hydraulic resistance; $n_T$ – number of consecutively connected pipelines with turbulent fluid flow; $n_M$ – number of local hydraulic resistances; λ – hydraulic resistance coefficient of the j-th pipeline (Darcy coefficient); $\delta R_1$ – the random component of quadratic resistance is determined according to the Monte Carlo method; $\zeta_\delta$ – hydraulic resistance coefficient of the spool throttle opening; $s_\delta$ – the cross-sectional area of the throttle opening, which is a random variable.

A mathematical model of the static characteristics of the device has been developed (Fig. 2a).



a b

*Figure 2 – Structural mathematical model of the static characteristics of the unit (a) and simulation results (b)*

The model has means for calculating random characteristic parameters. The model input is fluid flow rate $Q_1$ through the device, and the pressure difference at the outlet dp1.

Blocks RLvalve and RTvalve models are used to input deterministic components of linear (laminar) and quadratic (turbulent) drag. Random components of these parameters are specified in Random Number blocks numbered 1 and 2. In the vicinity of zero flow values ( $Q_1 \approx 0$ ) The device characteristics differ from parabolic ones. Nonlinear characteristics in the vicinity of low flow rates are modeled using a block Fcn, and the random component using the Random Number 3 block. As a result of modeling, the device characteristics pc are determined (Figure 2b).

Conclusions

1. As a result of the theoretical analysis of the dynamic properties of precision hydraulic automation devices, it has been established that the vaguely defined stochastic oscillations of the spool reduce the spectral density of the output pressure drop by 2–5 times.

2. It has been proven that the necessary values of fuzzy parameters that implement optimal stochastic axial oscillations of the spool can be achieved by design measures, in particular, by making microgrooves on the working edge of the spool, randomly located around the periphery of the spool edge. It is rational to make grooves with a distance between them distributed according to a normal law.

3. Mathematical modeling of a hydraulic automation device in which vaguely defined stochastic oscillations of the spool are implemented confirmed a significant increase in the accuracy of the device. The presence of oscillations reduces pressure drop control errors by 4–8 times compared to the basic version of the device.

4. As a direction for further research, it is recommended to investigate the possibility of using stochastic spool valve oscillations to compensate for the negative impact of pump pressure pulsations on the characteristics of the hydraulic unit as a whole.

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**Кондусь В.Ю., канд. техн. наук**
Сумський державний університет

# УЗАГАЛЬНЕНА МАТЕМАТИЧНА МОДЕЛЬ ФОРМУВАННЯ НАПОРУ У ВІЛЬНОВИХРОВИХ НАСОСАХ ДЛЯ ОДНО- ТА БАГАТОФАЗНИХ СЕРЕДОВИЩ

Вільновихрові насоси використовуються для перекачування складних середовищ із твердими, волокнистими та газовими включеннями, тому стандартні підходи до розрахунку напірних характеристик не забезпечують достатньої точності. У роботі представлено узагальнену математичну модель формування напору, яка охоплює як однофазні режими, так і транспортування багатофазних сумішей зі змінною концентрацією включень [1].

Модель ґрунтується на розділенні енергетичного обміну в насосі на три механізми: лопатевий внесок, вихровий внесок та сумарні гідравлічні втрати. Лопатевий внесок описує безпосередню передачу енергії через міжлопатеві канали робочого колеса, де розглядається реальний трикутник швидкостей і вплив ковзання потоку. Вихровий внесок визначається тороподібною циркуляцією рідини у вільній камері, де потік має двозонну структуру: область твердотільного обертання поблизу робочого колеса та область потенційного вихору у периферійній зоні. Узгодження цих зон забезпечує визначення енергії вихору, що перетворюється у напір [2].

Гідравлічні втрати поділено на три складові: втрати на вході, втрати на виході з робочого колеса та втрати змішування в зоні взаємодії лопатевого й вихрового потоків. Останні є найбільш значущими для вільновихрових насосів, оскільки саме тут формуються інтенсивні турбулентні пульсації та дисипація енергії.

Для однофазних рідин модель дозволяє визначати напір як суму лопатевого і вихрового внесків з урахуванням втрат, що забезпечує базову характеристику насоса.

Для багатофазних робочих середовищ модель узагальнено на три підходи залежно від концентрації включень:

1. Однорідне реальне середовище (вміст домішок <1%), де вводяться ефективні густина та в’язкість без врахування ковзання фаз.