electrostatic interaction. Such structures "align" the friction surface by reducing the arithmetic mean deviation of the profile points Ra and increasing the average pitch of the inequalities along the midline of the profile Sm.

The results of the Fourier analysis, which allow us to state that the use of a fullerene composition leads to a decrease in the main stress vector in both steel and bronze triboelements in accordance with the vector of the sliding direction. When using the fullerene composition, the level of anisotropy of the subblocks of the structure increases significantly, almost 2 times, which indicates the transition of the tribosystem to a new, higher level of self-organization.

After chemical analysis of the friction surfaces using a fullerene composition, it was found that on the friction surface there is a structure with a high carbon content. This result confirms the working hypothesis that it is a "crosslinked" structure of micelles, where the nucleus of the micelle is a molecule, or several molecules of fullerene, to which are attached molecules of oleic acid solvent. This conclusion is confirmed by the increase in the percentage of carbon C = 24,3…29,2 %, while reducing the percentage of oxygen from 18,4 % to 7,4 %. The latter chemical elements remain almost unchanged. This result allows us to conclude that a structure is formed on the friction surface, which contains the chemical element carbon, the ratio of which significantly exceeds other chemical elements..

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Modeling of Working Processes of an Adjustable APN Type PVC 1.85 Taking Into Account Parametric Oscillations

The paper presents the calculation results of the two mathematical models of the variable displacement axial piston pumps PVC 1.85. In the first mathematical model of the pistons averaged force was used, the application point of which corresponds to the offset of the swash plate's swivel axis. In the second mathematical model the parametric change of the pistons consolidated force magnitude and the coordinates of its application point was taken into account.
variable displacement axial piston pump, flow rate characteristics, the swash plate swivel axis, moment of pistons consolidated force, pressure pulsation

Statement of the problem. Energy saving and the increasing of the economic efficiency are the fundamental trends in the development of modern multipurpose mobile machines, including agricultural, constructional, road-building, etc. This is done with the help of energy supply activation to the working parts' driving units, productivity and operating speeds enhancement, extension of machines' technological capabilities, minimization of the number and the power of the drive engines. These tasks are most efficiently solved by using hydraulic power for the operating units' drives [1].

Analysis of recent research and publications. Currently, the load-sensitive LS-hydraulic systems are widely used in order to improve the efficiency of the hydraulic systems and mobile machines, in process of using of the hydraulic drives of the working parts. These hydraulic systems are capable for a flexible providing of the working fluid to the several executive hydraulic engines according to their needs with a single pump [2, 3]. In the most cases, the level of the technical characteristics of the LS-hydraulic systems is determined by the quality indicators of the hydraulic equipment components, first of all, by the variable displacement pumps that provide the appropriate supply of the working fluid to each hydraulic motors of the LS-hydraulic system. Variable displacement axial piston pumps are frequently used, as pumping units of the LS-hydraulic systems. In this case, adjustable axial rotary piston pumps with a swash plate enjoy the priority usage [1]. The pumps of this design are relatively simple compared to the other types of the pumps, while the range of the control of the working fluid supply fully satisfies the consumers.

These factors determine the interest of the world leading firms such as Bosch Rexroth, Danfoss, Parker Hannifin, Eaton and others to develop the production and improve the design of the pumps of this type [4-6]. Currently, the enterprises of Ukraine pay the considerable attention to the development in this area. PrJSCHydrosila APM has achieved the most notable results. The company pays considerable attention to the reducing of the level of the volumetric and mechanical losses, the reducing of the ripple of the flow rate and pressure, the improving of the quality of the static and dynamic characteristics [7].

At present time, the manufacturers of the hydraulic machines of this type pay the considerable attention to the increasing of the nominal pressure, the expanding of the working temperature range, the improving of the quality of the static and dynamic characteristics. Successful solution of these problems requires many efforts in such scientific fields as the material science, the developing of the design and the engineering technologies of the implementing hydraulic machines, the future developing of a scientific approach in the selection of the parameters of the hydraulic machines. Therefore, the development of the scientifically based methods for the selecting of the rational values of the variable displacement axial piston pumps parameters is a task of a current interest.

Statement of the problem. The purpose of this work is to study the static characteristics of the variable displacement axial piston pump PVC 1 type and to develop the methods to improve the pump.

Main material. One of the most important characteristics of the variable displacement axial piston pumps used in the construction of the LS-hydraulic actuators is the relationship between the pump flow rate and the load (pressure) at the pump output. According to the modern requirements, the change in the pump flow rate during the increasing of the pressure from zero to the nominal value should not exceed ± 4 % of the nominal flow rate.

PVC 1 series pumps are available in several sizes from PVC 1.18 with a displacement of 18 cm^3 to PVC 1.85 with a displacement of 85 cm^3. Along with it, pumps of all sizes are equipped with the LS-regulators of the PVN 45 type, with different diameters of the control hydraulic cylinders.

According to the design scheme (Fig. 1), the pump consists of the cylinder block 1 in which the pistons 2 are installed, a swash plate 3, a drive shaft 7. The pistons have a spherical heads, which engage in the slippers 8 which fit against the sliding surface of the swash plate. The pump flow control system consists of the LS-regulator 4, which includes two spool valves – a control valve and a shut-off valve; a hydraulic cylinder 5, a tilting of the swash plate 3, and a spring 6 for pressing the swash plate.
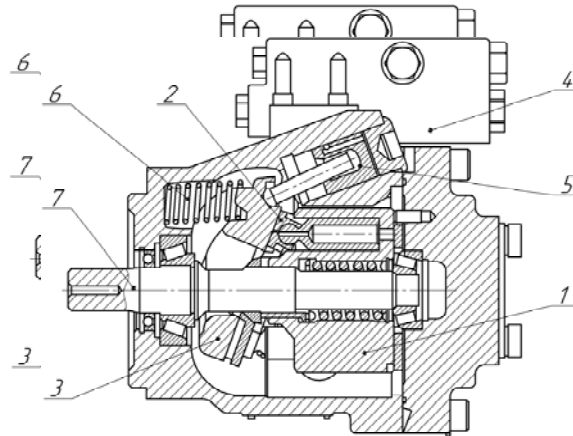
Figure 1 – The design of the variable displacement axial piston pump PVC 1.85
Source: developed by the author [7]

The design feature of the pump is the location of the swash plate is the offset ε of the swash plate swivel axis relatively to the cylinder block rotation axis (offset), shown on a calculating scheme (Fig. 2), which is used in the research. As a result, the pistons exercise a force on the swash plate, aimed to turn the swash plate in the direction of increasing of the inclination angle φ from the vertical axis and increasing of the pump flow rate appropriately.

On the basis of the calculating scheme (Fig. 2), a mathematical model was drawn up describing the work process of the pump as part of the LS-hydro power drive, with taking into the account the signal from the hydraulic motor to the LS-regulator [8]. The significant influence of the spool pairs clearance of the LS-regulator on static characteristics quality of the pump unit had been shown and was taken into the account by the manufacturer, and the arrangements to stabilize the radial clearance in spool pairs between 0,004 mm and 0,006 mm were implemented.
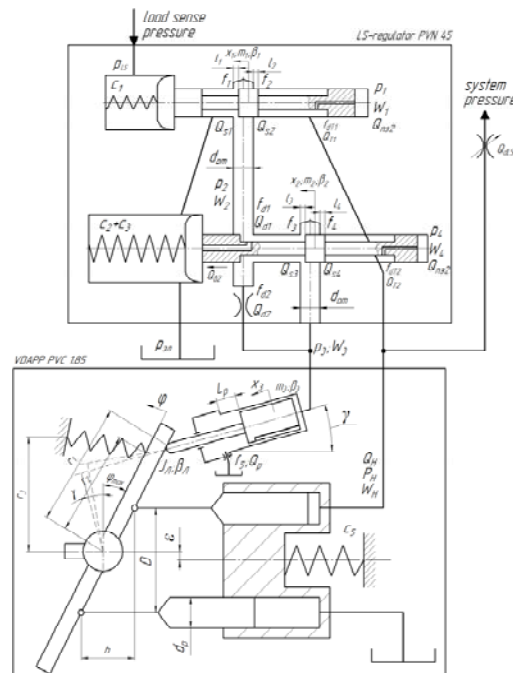

Figure 2 – The calculating scheme of the variable displacement axial piston pump PVC 1.85
Sourse: obtained by authors

At the same time, it is important to clarify the nature of the pump parameters' influence on its static characteristics. It should be noted, that there is no method for the choosing of the offset value, based on the results of the pump static characteristics research. The offset value significantly influences the operation of the pump flow rate control mechanism, determining the torque value, which action is directed on increasing the swash plate inclination angle γ and the pump flow rate respectively. As it was already noted, the decreasing of the flow rate is provided by the action of the control hydraulic cylinder piston 5 (Fig. 1) on the swash plate 3.

The Fig. 3 shows the static characteristics that represent the dependences of the pump flow rate on the outlet pressure p_{LS} of the LS throttle, connected to the input of the corresponding hydropower drive, calculated for the pump PVC 1.85 with the displacement of 85 cm^3 and the nominal pressure $p_{nom} = 210$ bar under the condition of the using of the LS- throttle in accordance with: the pump shaft rotational speed $n = 1500$ rpm, the volume of the hydraulic line connecting the pump output to the LS throttle $W = 40$ cm^3, the hole diameter in the LS throttle $d_{LS} = 6$ mm, the initial swash plate inclination angle $\varphi = 18°$, spools diameter $d_s = 7$ mm, the spool pairs radial clearance $\delta = 0,004$ mm, the moment of the inertia reduced to the pump shaft $I = 13,6$ kg·m^2, the overlapping of the working windows of the LS-regulator spools $l_2 = l_4 = 1,4$ mm, the diameter of the control hydraulic cylinder $d_c = 24,72$ mm, the working fluid viscosity $v = 19,3$ cSt, which corresponds to the viscosity of the hydraulic oil HM 46 at the temperature of 60°C.

(a) Spools clearance $\delta = 4$ μm   (b) Spools clearance $\delta = 16$ μm
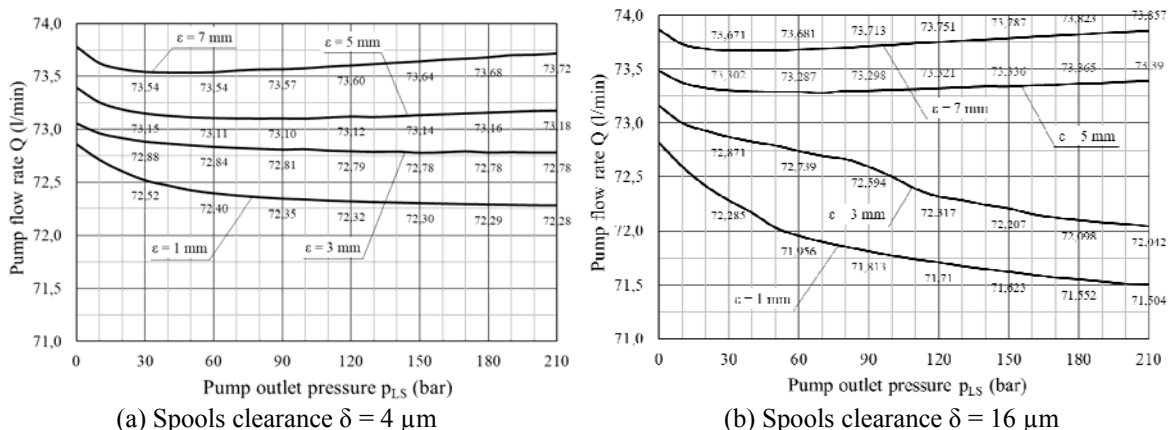
Figure 3 – The static characteristics curves of the pump PVC 1.85 for different offset values
Sourse: obtained by authors

The static characteristics have been calculated at the various offset ε values that were equal to 1 mm, 3 mm, 5 mm and 7 mm respectively.

The value of the offset ε significantly changes the nature of the pistons force action to the swash plate [9]. The value of the arising moment, that is aimed to increase the swash plate inclination angle, rises accordingly to the offset ε value increasing. In the process of this static characteristic calculating we have assumed that the consolidated action force of the cylinder block pistons was constant and applied at the offset ε level.

The starting point of the static characteristics at the pressure value $p_{LS} = 0$ bar corresponds to the work of the executive hydraulic motor without a load. At the same time, the LS-hydraulic power drive operational principle provides the 20 bar of a pressure difference in the LS-throttle. The difference between the pump flow rate values at the initial pressure is correspondingly determined by the different force effects exerted by the pistons of the cylinder block acting on the swash plate; by the various torques aimed to increase the pump flow rate at the different offset ε values.

The maximum value of the pump flow rate Q = 73,78 l/min has been obtained at the offset ε = 7 mm. The minimum value of the pump flow rate Q = 72,86 l/min corresponds to the offset ε = 1 mm. Mismatch of the pump flow rates at the pointed offsets reaches 1,25 %. Wherein the static characteristics have been calculated for the offsets ε equal to 5 mm and 7 mm were practically stable over the entire range of the pressure variation. Along with it, at the offsets ε equal to 1 mm and 3 mm, the pump flow rate decreases as the pressure p_{LS} increases at the output of the LS-throttle. At the pump outlet nominal pressure, the pump flow rate decreasing at the offset ε = 1 mm reaches 2 % compared to the pump flow value at the offset ε = 7 mm. Note, that this result has been obtained when there was a minimum clearance in the spool pairs of the LS-regulator, equal to δ = 0,004 mm.

In the case of the increasing of the LS-regulator spool pairs radial clearance to δ = 0,016 mm, which is close to the existing technical conditions for the spool pairs production, the static characteristics have the form shown in the Fig. 3, b. In this case, at the offset ε values equal to 5 mm and 7 mm, the pump flow rate is stable over the entire range of the pressure variation p_{LS}. Along with it, at the offset ε = 1 mm, the drop in the pump flow rate at the nominal pressure at the outlet of the pump reaches 3,5 %, which approaches to the maximum permissible values.

Analysis of the pump flow control system operation revealed the peculiarities of the force effect of the cylinder block pistons to the swash plate during the pump flow rate changing process. The parametric dependence of the clamp by the consolidate force of the cylinder block pistons of the swash plate was studied by Bashta and al. [9]. The refined nature of this relationship was studied in article [10](Fig. 4). The authors have also identified the variable position of the application point of the consolidate force of the swash plate clamping, which changes during the cylinder block rotation. As a result, the value of the moment oscillation amplitude of the swash plate reversal in the direction of the pump flow rate increasing, caused by the action of the pistons consolidate force, for the pump PVC 1.85 reaches 325 N·m. It has been shown that the minimum and maximum reversal moment values of the swash plate substantially depend on the offset ε value. At the offset ε< 5 mm, negative values of the consolidated force moment may appear, that are directed towards the decreasing of the swash plate inclination angle, i.e. the reverse of the swash plate is replaced by its obverse (Fig. 4) [9].
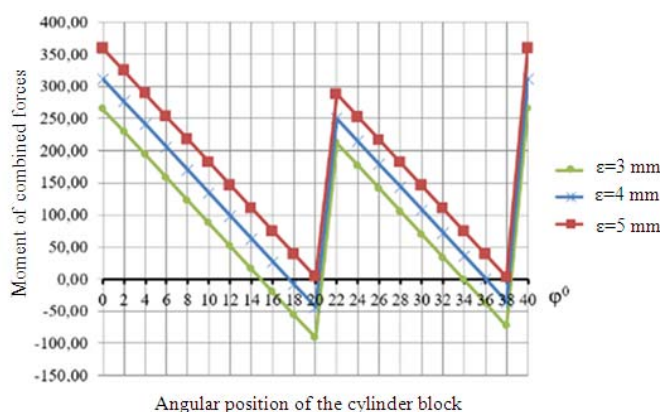

Figure 4 – Correlation between angular position of the cylinder block and the consolidate force moment that works on the swash plate

Sourse: obtained by authors

In the pump PVC 1.85 static characteristics calculations (Fig. 3), the averaged value of the piston consolidated force moment on the swash plate has been taken into the account, the application point of which according to [9] was also constant and was at the offset level. It is as well obvious that significant amplitude fluctuations in the moment of pistons reduced force

(the fluctuations frequency is 450 Hz at a cylinder block nominal speed $n = 1500$ rpm) cause corresponding swash plate oscillations. Along with it, as it is shown in Fig. 4, at the small offset ε values, a periodic moment change of the piston consolidated force on the swash plate causes the opposite effect. The indicated moment changes the sign and thus coincides in the direction with the moment created by the control hydraulic cylinder, which can cause the opposite effect. This fact makes it necessary to study the influence of the parametric dependence of the moment of the pistons consolidated force action on the swash plate on the cylinder block angular position on this type pumps characteristics.

The static characteristics of the PVC 1.85 pump have been calculated using the mathematical model, described in article [8], taking into account the parametric dependence of the moment of the pistons consolidate force to the swash plate on the cylinder block angular position, described in [10].

The Fig. 5 shows the static characteristics of the pump PVC 1.85, calculated with the regard on the parametric dependence of the piston consolidated force moment on the swash plate on the angular position of the cylinder block at different offset values.

The Fig. 5, a, shows the static characteristics have been calculated with the offset ε equal to 1 mm, 3 mm, 5mm and 7 mm. The parameters of the considered pump correspond to those pointed above for the Fig. 3. The radial clearance in the spool pairs is 0,004 mm.

It has been shown above that regarding the pistons consolidated force moment on the swash plate in the form of average value for a given value of the radial clearance, the static characteristics have significant stability. Along with it, consideration of the parametric dependence of the pistons consolidated force moment causes significant differences in the pump PVC 1.85 static characteristics.

(a) Spools clearance $\delta = 4$ μm   (b) Spools clearance $\delta = 16$ μm
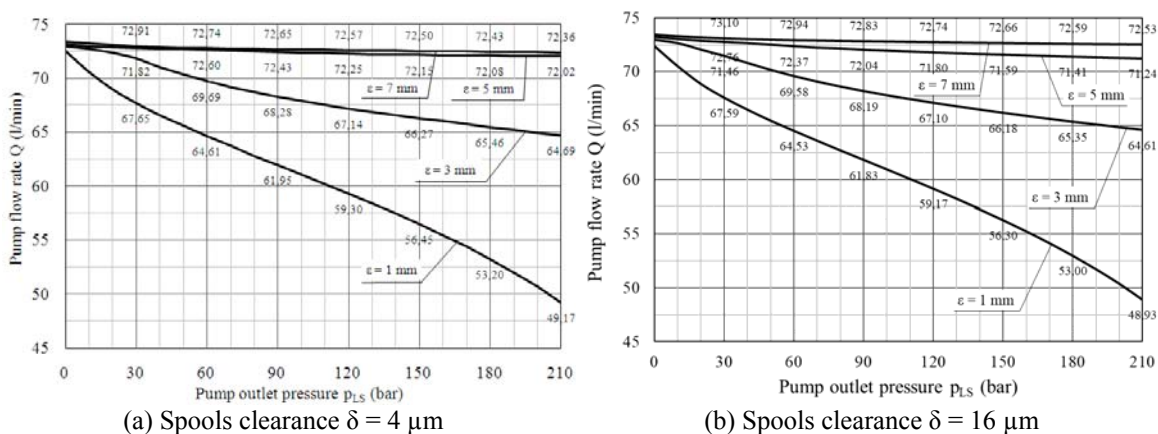
Figure 5 – The static characteristics curves of the pump PVC 1.85 for different offset values, with the regard of the moment pulsation of the pistons consolidate force

Sourse: obtained by authors

At the offset ε values equal to 5 mm and 7 mm, the flow rate reduction does not exceed 1,5 % with the pressure p_{LS} increasing from the minimum value to the nominal one. At the same time, the significant pump flow rate reduction occurs when the pump outlet pressure increases at the offset 1 mm and 3 mm. In the case, when the offset $\varepsilon = 3$ mm, the pump flow reduction reaches 11,3 %, and at the offset $\varepsilon = 1$ mm the decreasing of the pump flow reaches 32,7 %. These values of the pump flow rate reducing indicate to non-compliance with pump specifications at the assigned offset values. Taking this into the account, the manufacturer of these pumps stopped using the previously assigned offset equal to 4 mm and set the offset equal to 5 mm into the swash plate design.

The Fig. 5, b, shows the static characteristics of the pump PVC 1.85, calculated with regard on the parametric dependence of the pistons consolidated force moment on the swash plate with the offset ε values 1 mm, 3 mm, 5 mm and 7 mm. In this case, it has been assumed that the radial clearances in the LS-regulator were $\delta = 0{,}016$ mm. The remaining pump parameters have the values as defined above.

The static characteristics of the pump PVC 1.85 in this case have changed slightly. The smallest change in the pump flow rate with the pressure p_{LS} increasing corresponds to the offset ε value equal 7 mm. The pump flow rate drop does not exceed 0,6 %. At the offset ε value equal 5 mm, the flow rate reduction is at 1,6 % while the output pressure is increased to the nominal value ($p_{LS} = 210$ bar). In the both cases, the static characteristics level indicates their insignificant deterioration compared with the static characteristics shown in the Fig. 5, a, at the spool pairs radial clearance $\delta = 0{,}004$ mm.

It should be noted that in this case, the nature of the static characteristics that have been calculated at the offset values equal to 1 mm and 3 mm, closely coincides with those shown in the Fig. 5, a, and the differences between them do not exceed 1,5 %. The static characteristic quality of the pump PVC 1.85 at the offset ε value 1 mm and 3 mm, with this combination of parameters, does not meet the regulatory requirements, which determines the inoperability of the pump in this case.

The consideration of the parametric dependence of the pistons consolidated force on the swash plate has showed a significant effect of the offset ε value on the calculation results of the static characteristics of PVC 1.85 pumps. There is a significant discrepancy between the results of the static characteristics calculation, considering the moment of the pistons consolidated force on the swash plate, averaged over the value and independent of the cylinder block rotation angle, and regarding this moment in the form of a parametric dependence. This difference allows noting the need to use the characteristics of variable displacement axial piston pump methods taking into account their features as accurately as possible in the characteristics calculations. The results of the of static characteristics calculation are corresponding to the existing experience in this size pumps production at PrJSCHydrosila APM (Kropyvnytskyi, Ukraine).

The research results show that the pump flow rate stability is enhanced when offset value increases according to the corresponding static characteristics in the entire operating outlet pressure range. In this case, a high stability of the pump flow rate should be expected at the offset values 5 mm and 7 mm. It should be noted, that increasing of the offset from 5 mm to 7 mm does not give a significant effect, since the calculated accuracy values of the static characteristics are actually close to the ideal values in this case. Along with it, it should be noted, that the increasing of the offset leads to the increasing of the pressure in the cavity of the servo-piston.

The Fig. 6 shows the oscillograms of the pressure fluctuations in the control cylinder cavity, have been calculated for the different offset ε values.
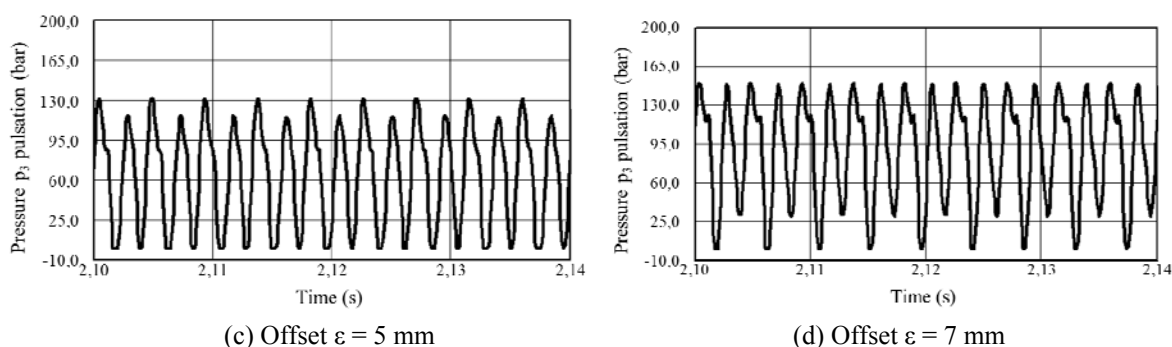

(a) Offset $\varepsilon = 1$ mm	(b) Offset $\varepsilon = 3$ mm

(c) Offset ε = 5 mm   (d) Offset ε = 7 mm
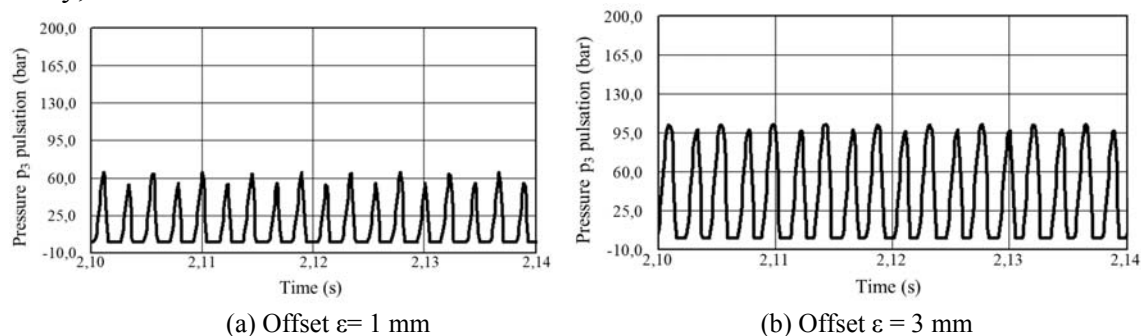
Figure 6 – Pulsations of the pressure p_3 in the control cylinder cavity
Sourse: obtained by authors

The oscillogram in the Fig. 6, a, corresponds to the pressure fluctuations in the control hydraulic cylinder cavity at the offset ε value equal 1 mm. The pressure oscillations in the control hydraulic cylinder cavity have a frequency of 450 Hz, which corresponds to the frequency of the moment oscillations of the pistons consolidated force on the swash plate. The maximum pressure does not exceed 66,2 bar. However, it should be noted, that there is a pressure periodic drop in the control hydraulic cylinder cavity to the zero value in this case. In the used model, it has been taken into account that the working fluid does not work in the tension. Thus, the appearance of the zero pressure values may indicate the appearance of a vacuum in the cylinder cavity, which may cause the development of the cavitation processes.

Fig. 6, b, shows an oscillogram of the pressure fluctuations in the control hydraulic cylinder cavity, calculated with the offset ε value 3 mm. The increasing of the offset value causes the increasing of the maximum pressure in the cylinder cavity to 102,6 bar. The frequency of the pressure fluctuations remained unchanged and corresponding to the frequency of the oscillations of the moment of the pistons consolidated force to the swash plate. However, in this case, there is a periodic pressure drop to the zero value, which may mean the possibility of cavitation. The value of the average pressureis 51,3 bar.

With the offset ε equal to 5 mm, the average value of the pressure fluctuations in the control hydraulic cylinder cavity increases to 66 bar (Fig. 6, c). However, there is no pressure drop to the zero value, which indicates the elimination of the possibility of the cavitation processes during the control hydraulic cylinder operation.

Increasing of the offset ε value up to 7 mm, the average value of the pressure oscillations in the control hydraulic cylinder cavity (Fig. 6, d) increases to 75 bar. In this case, the maximum pressure also increases to 150 bar. Thus, increasing of the offset ε of the swash plate swivel axis to 7 mm does not cause a noticeable increasing of the static characteristics quality. Along with it, pressure increasing in the control hydraulic cylinder cavity causes the increasing of the volumetric losses during the operation of the LS regulator. It should be noted, that in the modern analogues of the PVC 1.85 pump, the volumetric losses in the pump supply control system should not exceed 2,5 – 3,5 l/min.

Conclusions. The simulation results indicate a significant effect of the variable displacement axial piston pumps PVC 1.85 parameters, such as the clearance in the spool pairs of the LS-regulator and the swash plate swivel axis offset corresponding to the cylinder block rotation axis on the static characteristics quality that determine the dependence of the working fluid supply on the pump outlet pressure.

The manufacture specifications for the spool pairs set the permissible values at which the clearance in the pairs can exceed 0,02 mm. In this work, the effect of these clearance dimensions on the stability of the static characteristics has been examined. The requirements for these clearance values do not allow fluctuations beyond ± 4%. It is recommended to set

the allowable clearance in the spool pairs in the range of 0,004-0,006 mm with a purpose to ensure the stability of the pump flow rate.

This research investigates the influence of the offset value of the swash plate swivel axis corresponding to the cylinder block rotation axis on the stability of the pump flow rate. The static characteristics of the pump have been calculated with the offset values of the swash plate swivel axis equal to 1 mm, 3 mm, 5 mm and 7 mm. The offset value incrementing of the swash plate swivel axis increased the stability of the pump flow rate, depending on the executive hydraulic actuator load. At the offset of the swash plate swivel axis corresponding to the cylinder block rotation axis equal to 5 mm and 7 mm, the deviation of the pump flow rate from the given one does not exceed 1,5 %. Along with it, as the offset value decreases to 1 mm and 3 mm, in the case of the pump PVC 1.85, the quality of the static characteristics deteriorates. The deviation of the pump static characteristics from the set values increases with the decreasing of the offset of the swash plate swivel axis and with the offset of 1 mm it can amount up to 30 %, which indicates the unsuitability of this design solution.

In the process of modeling of the variable displacement axial piston pump operation a comparative studying of the static characteristics, calculated by the different models describing the mechanism of the pistons consolidated force action formation to a swash plate, has been performed. In this research the authors used the models of the averaged forces of pistons, the point of application of which corresponds to the established offset of the swash plate swivel axis. In the second case, the authors consider a parametric changing of the magnitude of the pistons consolidated force and the coordinates of its application point. The comparison of the calculation results indicates a significant difference. So, if the offset values of the swash plate swivel axis are in the range of 5-7 mm, the results of the static characteristics calculations, considering different models of the action of the pistons consolidated force, was hardly distinguishable, then for the small values of the swash plate swivel axis offsets the differences were significant. For the offset of the swivel axis of 1 mm the pump flow rate deviation is about 3,5 % in the first model. Along with it, for the calculation taking into account the parametric changing of the pistons consolidated force the deviation of the static characteristic from the given one, approaches to the value of 30 % and it is close enough to the actual characteristics of the pump. According to this, the authors consider relevant to take into account the changes of the parametric dependences of the pump parameters when performing calculations on the choice of the variable displacement axial piston pumps parameters.

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Моделювання робочих процесів регульованого АПН типу PVC 1.85 з урахуванням параметричних коливань

В роботі представлені результати розрахунку двох математичних моделей регульованого аксіального роторно-поршневого насоса PVC 1.85. У перші математичні моделі використовувалося усереднене усилення поршнів, точка прикладання якого відповідає зсуву осі повороту похилого диска. У другі математичні моделі враховувалися параметричні зміни величини зведеної сили поршнів і координати точки її застосування.

Порівняння результатів розрахунку в двох моделях показали їх істотне розходження. Так, якщо при зсувах осі повороту похилого диска на 5-7 мм результати розрахунку статичних характеристик з урахуванням різних моделей дії зведеної сили мало відрізняються, то для малих значень зміщення осі повороту похилого диска відмінності значні. Якщо для зміщення осі повороту в 1 мм по першій моделі

отримуємо похибку подачі насоса близько 3,5 %, то для розрахунку з урахуванням параметричної зміни зведеної сили поршнів відхилення статичної характеристики від заданої наближається до 30 %, що досить близько до реальних характеристик насоса. Тому, доцільно при виконанні розрахунків по вибору параметрів регульованих аксіальних роторно-поршневих насосів враховувати параметричні залежності зміни параметрів насоса.

Результати моделювання свідчать про істотний вплив таких параметрів регульованих аксіальних роторно-поршневих насосів типу PVC 1.85, як зазори в золотникових парах LS – регулятора і зміщення осі нахилу похилого диска щодо осі обертання блоку циліндрів на якість статичних характеристик, що визначають залежність подачі робочої рідини від тиску на виході насоса.

Технічними умовами на виготовлення золотникових пар встановлені допуски, при яких зазори в парах можуть перевищувати 0,02 мм. Виконано дослідження впливу величини зазначених зазорів на стабільність статичних характеристик. Рекомендовано для забезпечення стабільності подачі насоса встановити допустимі зазори в золотникових парах в межах 0,004-0,006 мм.

Досліджено вплив величини зміщення осі повороту похилого диска щодо осі обертання блоку циліндрів на стабільність подачі насоса. Проаналізовані статичні характеристики насоса розраховані при величинах зсуву осі повороту похилого диска на 1 мм, 3 мм, 5 мм і 7 мм. Встановлено, що збільшення зсуву осі повороту похилого диска підвищує стабільність подачі насоса в залежності від навантаження виконавчого гідродвигуна. При зсувах осі повороту похилого диска щодо осі обертання блоку циліндрів на 5 мм і 7 мм відхилення величини подачі насоса від заданої не перевищує 1,5 %. У той же час при зменшенні величини зміщення до значень 1 мм і 3 мм істотно в разі використання насоса PVC 1.85 погіршується якість статичних характеристик. Відхилення статичних характеристик насоса від заданих зростає при зменшенні зміщення осі повороту похилого диска і при зміщенні на 1 мм може досягати 30 %, що свідчить про непридатність даного конструктивного рішення.

регульований аксіальний роторно-поршневий насос, статична характеристика, вісь повороту похилого диска, момент зведеної сили тиску поршнів, коливання тиску