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PRESSURE OSCILLATIONS IN TRANSIENT PROCESSES OF HYDRAULIC SYSTEMS WITH VARIABLE DISPLACEMENT PUMPS

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Abstract. *In aviation hydraulic drive of high power as a power supply the axial-piston variable displacement pumps became wide spreaded. The pump operational modes with air isolation and cavitation are accompanied by increased noise, delivery reduction and intensive pressure oscillations. The negative results of such phenomena are hydraulic elements erosion, pipeline fatigue failure, working fluid viscosity reduction and its contamination by wear products. The mechanism of cavitation rising in axial-piston pumps is considered, and factors which influence the cavitation rising and working fluid aeration are specified. The features of transient processes in aircraft hydraulic systems with variable displacement pumps are considered. It has been showed that as the pump delivery changes from its minimum to maximum great pressure oscillations in the aircraft pressure pipeline of the hydraulic system takes place, and have a negative influence on the pump service life. The recommendations concerning such pressure oscillation reduction are given.*

Keywords: aircraft; cavitation; hydraulic system; pressure oscillations; pressure pipeline; pump delivery; variable displacement pump; working fluid.

1. Introduction

The world trend in the transport aircraft centralized hydraulic systems (HS) development is wide usage of variable displacement pumps which provide required pressure in the HS pressure pipeline at different flight modes [1], [2] ,[3].

The gained experience of aircraft operation which have centralized HS with variable displacement pumps, points out to the possibility of weakly damped pressure oscillations rising in the pressure pipeline at a transient modes of HS operation. Such pressure oscillations significantly increase the load on the bearings and elements of pumping assembly unit and greatly reduce its service life. Especially, such negative effects inherent to aircraft Ту-134А and Як-42 hydraulic systems. The axial-piston variable displacement pumps of НП-34М and НП-72МВ- type respectively are used in these airplanes [4]. The rising of such typical operational malfunctions in the hydraulic systems of these aircraft as pressure reduction at the pump inlet or pressure drop in the gas chamber of pneumatic accumulator increases oscillations of transient processes.

2. Analysis of researches and publications

Most of volumetric pumps create the volumetric pulsation with frequency which depends on number of pumping elements and rotor shaft revolutions. Pulsation amplitude depends on the pump design. The volumetric pulsation is the source of force that provokes appearance of forced oscillations [5].

The hydro- pneumosystems dynamic characteristics significantly depend on other parameters. In particular, the viscosity and compressibility of the systems working medium are referred to them. The-se two parameters are functions of the working medium state and their physical and chemical properties, which depend on temperature and pressure. For liquid they depend also on quantity of undissolved air it contains [6]. Influence of these parameters, in particular their mathematical formulation, have not been studied yet. The viscosity can vary in range of 1:10 and compression occurs in greater limits especially for double phase liquids. So it is evident that mentioned above properties considerably influence the dynamic characteristics of hydraulic and pneumatic systems.

The volumetric pumps are characterized by disproportionality of the liquid delivery. The delivery pulsations are not strictly harmonic, but the first harmony expansion into Furrier series gives us sufficiently accurate result at the hydro-systems dynamics studying. These oscillations are transferred along pressure pipeline to the separate system devices in the form of input signal. When oscillations frequency of liquid coincides with natural frequencies of pipelines, governors, actuators and other devices the reso-

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nance can occur. The resonance provokes great vibrations and noise in hydro-system. That is why, during the hydro-system designing it is necessary to eliminate conditions the resonance is possible to occur. Most often pipelines dimensions are determined taking into account design features so changing of these dimensions are not often reasonable [7].

For hydro-systems vibration level reduction it is necessary to choose correlations during design between capacity and inertial resistance in pressure pipeline that consists of the pump, safety valve, filter, distributor, hydro-engine pressure chamber, etc [8]. Moreover, the pipeline that connects these elements is small enough, so we can consider this chain to be a system with concentrated parameters. A pipeline that goes to actuators can have considerable length, that is why, for system solution in this case it is necessary to take into account appeared here wave processes [9].

The purpose of the work

The purpose of the work is to develop recommendations to prevent significant pressure pulsations in the pressure pipeline of the aircraft hydraulic systems in transient modes of the pump operation.

3. Results of investigation

Specialized experimental investigations were done at the hydro-gas systems department of the National aviation university to develop recommendations to prevent significant pressure oscillations in the pressure pipeline hydraulic system of the aircraft Як-42 in transient modes of pump НП-72МВ operation.

Pump НП-72МВ (Fig. 1) is a rotary pump with axial cylinders arrangement and spatial kinematics [4]. The pump has a tilted block of cylinders 3, which is rotated by the driving shaft. The pistons of the cylinder block move relative to their case. The distribution of the working fluid is carried out through crescent slots of the valve plate and orifices of the cylinder block. In the cylinder dead points the orifices are overlapped by bottom and top cross-pieces that are situated between the control slots. The pump delivery is regulated by changing the angle α of the cylinder block inclination.

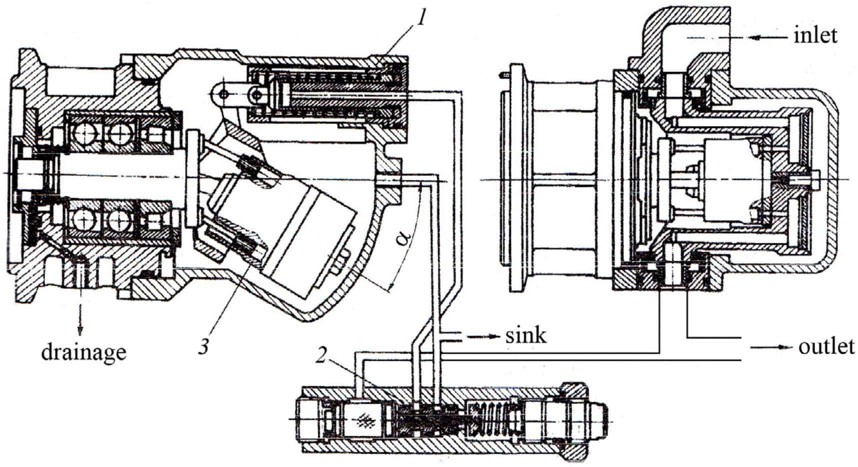

Fig. 1. Design scheme of hydraulic pump НП-72МВ: *1* – cylinder of the delivery governor; *2* – valve of the delivery governor; *3* – block of cylinders

The delivery governor regulates the pump delivery depending upon the mode of the aircraft hydraulic system operation. In the static modes of operation (Fig. 2) the pump delivery is equal to fluid flow rate on consumers operation Q_{com} and total leakage compensation Q_{leak} [9]:

$$Q_p(p) = Q_{com} + Q_{leak}.$$

If consumers are non-operated, the pump delivery approaches to minimum. If at the moment a consumer with a high required flow rate starts to operate (for example, landing gear system), than delivery governor changes pump delivery for maximum. Nowadays, the strict demand is estimated on the speed of operation of the aviation pump delivery governor. Time of changing of the variable displacement pump level from minimum to maximum one should not be greater than 0,04 sec, and time of reducing the pump delivery from nominal to minimum value should not be greater than 0,02 sec. The transition process that accompanies such change of the pump operational modes has an oscillatory mode [10].

Experimental investigations have shown that the parameters of transient processes in the pump are significantly depended on technical condition of both the aircraft hydraulic system and the pump itself [Germany].

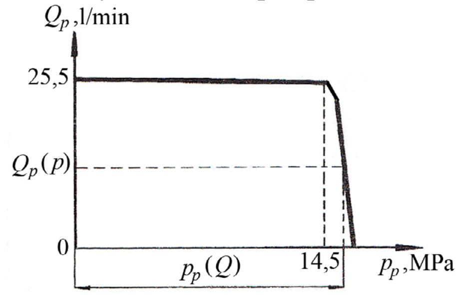

Fig. 2. Dependence of the pump НП-72МВ delivery on the pipeline pressure

To improve the operational conditions of pump НП-72МВ in Як-42 aircraft hydraulic system the hydraulic tank pressurization is provided (at normal conditions p^{pr}_{tank}= 0,19…0,21MPa). However, during flight the pressurization can vary. It is caused by different HS operational modes and different flight altitudes. As altitude increases the pressurization is reduced because the pressure regulator provides constant pressure drop relative to the atmospheric pressure. In addition, the reduction of pressurization is observed when the liquid level in the tank sharply decreases due to landing gear extinction, since the filling of the hydraulic tank air chamber goes with some delay.

In Fig. 3 experimental dependences of the pump delivery and pressure pulsations in the aircraft pressure pipeline on the pressurization in the hydraulic tank at nominal frequency of the pump driving shaft rotation ($n = 4000$ rpm) and different pressure in the aircraft pressure pipeline are shown.

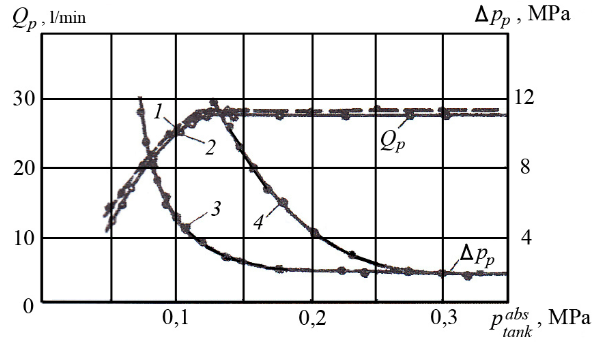

Fig. 3. Dependence of the pump НП-72МВ delivery and pressure pulsations in the aircraft pressure pipeline on the hydraulic tank pressurization: *1* – p_p = 10 MPa; *2* – p_p = =15 MPa; 3 – steady mode; 4 – transient mode

Experiments have confirmed that the pressurization in the aircraft hydraulic tank influences the pressure value at the pump inlet and significantly effects its operation. The initial decreasing of the pump delivery starts at $p^{abs}_{pr} < 0{,}125$ MPa. The sharp decreasing of the pump delivery at $p_p = 15$ MPa starts at $p^{abs}_{pr} = 0{,}10$ MPa that corresponds to the atmospheric pressure at the sea level. Total delivery breakdown due to considerable pressure oscillations and pump vibrations which indicate the cavitation mode of the pump operation in the hydraulic tank at pressure $p^{abs}_{pr} = 0{,}06$ MPa takes place. Experimental investigations have shown that for normal pump operation in the aircraft Як-42 hydraulic system the pressurization in the hydraulic tank shall not be less than 0,15 MPa.

During the aircraft running the considerable pressure oscillations in the aircraft HS in transient modes of pump operation were admitted. As an example, the oscillogram of pressure oscillation in the aircraft pressure pipeline at the moment of landing gear retraction process completion is shown in Fig. 4. The frequency of the oscillations is equal to 12,5 Hz.

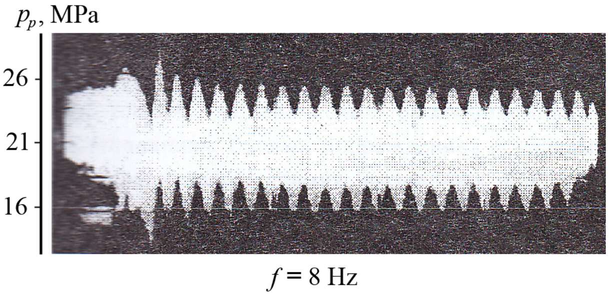

Fig. 4. The oscillogram of pressure oscillations in the Як-42 pressure pipeline after the pump НП-72МВ at the moment of completion of landing gear retraction

An effective way of pressure oscillations reduction in transient modes of operation of the hydraulic system with variable displacement pump is to establish a special pressure oscillation dampers of capacitative type [8]. Calculation of such oscillation damper is reduced to the added volume V_{ad} determination based on the required degree of pressure oscillations damping in the frequency range typical for specific aircraft hydraulic system.

For added volume V_{ad} of pressure oscillation damper determination the technique developed by V.P.Shoryn was used [8].

Dynamic performances of damper will be determined by impedance Z_p, a module of which depends on the added volume of the chamber and decreases monotonically while the frequency of oscillation is growing up:

$$Z_p = -j\frac{\rho a^2}{\omega V_{ad}},$$

where $j=\sqrt{-1}$ – imaginary unit; ρ – liquid density; a – velocity of oscillation propagation in liquid (speed of sound); $\omega = 2\pi f$ – angular frequency; f – frequency of oscillation.

The formula of the added volume V_{ad} that provides pressure oscillation damping to designed one under the worst operational conditions of the HS is given below. The argument value of oscillation reflection coefficient $\varphi_\Sigma(\omega) = -\pi/2$,

$$V_{ad} \geq \sup\left[\frac{\rho a^2(\eta+1)\left|Y_\Sigma(\omega)\right|}{\omega}\right]_{\omega\in[\omega_1,\ \omega_2]}.$$

In this formula η – given value of oscillation damping coefficient; $Y_\Sigma(\omega)$ – total conductivity of hydraulic circuit.

$Y_\Sigma(\omega)$ can be estimated by formula:

$$Y_\Sigma(\omega) = \frac{Y_{int}+Y_{inp}}{e^{j\varphi_\Sigma(\omega)}};\quad Y_{int} = \frac{1}{Z_{int}};\quad Y_{inp} = \frac{1}{Z_{inp}},$$

where Y_{int} – internal conductivity of source of oscillation; Y_{inp} – input conductivity of hydraulic circuit: $\omega_1 = 2\pi f_1$; $\omega_2 = 2\pi f_2$.

For the aircraft Як-42 HS $f_1 = 5$ Hz; $f_2 = 15$ Hz.

If pulsation damper is located at some distance from the oscillation source, it is necessary to provide the condition for the increasing of oscillation amplitude in the area of «pump – oscillation damper» throughout the considered range of frequencies ($f_1 = 5$ Hz; $f_2 = 15$ Hz), so

$$V_{ad} > \sup\left[\frac{a}{\omega}\left(S+\rho a\left|Y_p(\omega)\right|\right)\right]_{\omega\in[\omega_1,\ \omega_2]},$$

where S – pipeline cross-sectional area at the «pump – oscillation damper» sector.

Taking into account mentioned above formulas the optimal volume of pulsation damper for aircraft Як-42 has been determined. The value V_{ad} was equaled to 210 cm^3. However, taking into account the real stiffness of pulsation damper walls the added volume V_{ad} should be increased by 20% [8]. So for the effective pressure oscillation damping in the aircraft Як-42 hydraulic system the oscillation damper of volume 250 cm^3 is required.

The special experimental investigations of the aircraft Як-42 HS operation were conducted on the semi-fullscale stand in order to confirm the obtained results. The operation of landing gear «retraction – extension» system was simulated by special electromagnetic valve. The transient processes recordings in the system were conducted by means of oscilloscope. Similar investigations were conducted by means of a real aircraft hydraulic system. Measurements of pressure pulsation in the HS after pump НП-72 МВ were carried out by means of the sensor ЛХ-601, which signal was recorded on the screen of oscilloscope С8-12.

It was proved that installation of an appropriate pulsation damper significantly reduces pressure oscillations in the HS (Fig. 5).

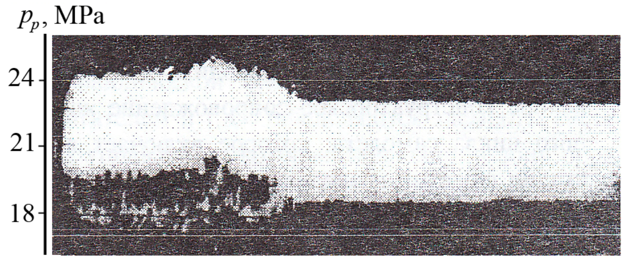

Fig. 5. Oscillogram of pressure oscillations after the pump НП-72 МВ in pressure pipeline of the aircraft Як-42 HS at the moment of landing gear retraction completed (the additional pulsation damper is installed after the pump).

Experimental investigations have also shown that the parameters of the aircraft HS transient processes essentially depend on the technical conditions of pneumo-hydraulic accumulator, which is installed in the HS pressure pipeline. Weakly damped pressure oscillations with amplitude 4…6 MPa can occur in the aircraft HS due to pneumo-hydraulic accumulator gas chamber pressure drop.

Besides, the hydraulic system oscillations reduction can be achieved by the increasing of pump internal working fluid flows. The V.I. Zahrebelny's [11] investigations show that the effective mean of pressure oscillation reduction is the special check valve installation which allows the certain amount of working fluid flow from high pressure line into drainage. It artificially increases internal working fluid flows and the minimum pump delivery at non-operated consumers and improves the pump cooling. The negative result of this method of pressure oscillation reduction in the aircraft HS pressure pipeline is decreasing of the pump volumetric efficiency.

4. Conclusions

The pressurization in the aircraft hydraulic tank influences the pressure value at the pump inlet and significantly effects its dynamical operation. Experimental investigations have shown that for normal pump operation in the aircraft Як-42 hydraulic system the pressurization in the hydraulic tank shall not be less than 0,15 MPa.

An effective way of dynamic pressure oscillations reduction in transient modes of operation performance of the hydraulic system with variable displacement pump is to establish a special pressure oscillation dampers of capacitative type.

The cavitation in the pumps on certain stage of operation can develop on one’s own and against background of air isolation. Without air isolation the cavitation develops due to insufficiently input pressure at which the liquid separation from the pistons occurs. The greater speed of piston movement the bigger the input pressure is required in order to ensure operation without cavitation. The air isolation begins at pressure less or equal input pressure which corresponds to cavitation threshold.

For cavitation performance of axial-piston pump the three segments presence is typical. In the first segment at sufficiently pressures p_{inp} the pump delivery does not depend on input pressure. In the second segment the pump delivery gradually decreases due to air isolation and cavitation process starting. On the third segment the pump delivery sharply decreases due to processes intensification.

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Г. Й. Зайончковський[1], В.С. Бутько[2], Т.В. Тарасенко[3]. Коливання тиску в перехідних процесах гідравлічних систем з насосами змінної подачі
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У авіаційному гідроприводі великої потужності в якості джерел живлення отримали розповсюдження аксіально-поршневі насоси регульованої подачі. Режими роботи насоса, за яких відбувається виділення повітря і кавітація, супроводжуються підвищеним шумом, зниженням подачі, інтенсивними коливаннями тиску. Негативні наслідки цих явищ – ерозія деталей, втомне руйнування трубопроводів, зниження в'язкості робочої рідини, її забруднення продуктами зносу. У статті розглянуто механізм виникнення кавітації в аксіально-поршневих насосах, визначені фактори, що впливають на виникнення кавітації та аерації робочої рідини в цих насосах. Також розглянуто особливості перехідних процесів в гідросистемі літака. Показано, що при зміні подачі насоса з мінімальної до максимальної можливі значні коливання тиску в напірній магістралі гідросистеми літака, які негативно впливають на ресурс насоса. Даються рекомендації щодо зменшення таких коливань тиску.
Ключові слова: гідравлічна система; кавітація; коливання тиску; літак; напірна магістраль; насос регульованої подачі; подача насоса; робоча рідина.

Г. Й. Зайончковський[1], В.С. Бутько[2], Т.В. Тарасенко[3]. Колебания давления в переходных процесах гидравлических систем с насосами переменной подачи
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В авиационном гидроприводе большой мощности в качестве источников питания получили распространение аксиально-поршневые насосы регулируемой подачи. Режимы работы насоса, при которых происходит выделение воздуха и кавитация, сопровождаются повышенным шумом, снижением подачи, интенсивными колебаниями давления. Отрицательные последствия этих явлений – эрозия деталей, усталостное разрушение трубопроводов, снижение вязкости рабочей жидкости, ее загрязнение продуктами износа. В статье рассмотрен механизм возникновения кавитации в аксиально-поршневых насосах, определены факторы, влияющие на возникновение кавитации и аэрации рабочей жидкости в аксиально-поршневых насосах. Также рассмотрены особенности переходных процессов в гидросистеме самолета. Показано, что при изменении подачи насоса с минимальной до максимальной возможны значительные колебания давления в напорной магистрали гидросистемы самолета, которые отрицательно влияют на ресурс насоса. Даются рекомендации по уменьшению таких колебаний давления.
Ключевые слова: гидравлическая система; кавитация; колебания давления; напорная магистраль; насос регулируемой подачи; подача насоса; рабочая жидкость; самолет.

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