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Parametrical identification of destructive processes in avionic hydraulic drives

K e y - w o r d s

Fluid power transmission, positiv-displacement hydraulic pump, delivery of a pump, volume efficiency of a pump, hydraulic motor, distribution valve, hydrostatic (forcing) pressure, pressure characteristic of hydraulic pump, hydraulic intensifier, volume flow (rate), opinion of technical state (technical condition assessment), structural parameter.

S ł o w a k l u c z o w e

Napęd hydrostatyczny, wyporowa pompa hydrauliczna, wydajność pompy, sprawność objętościowa pompy, silnik hydrauliczny, zawór rozdzielczy, ciśnienie tłoczenia, charakterystyka ciśnieniowa pompy hydraulicznej, wzmacniacz hydrauliczny, natężenie przepływu, ocena stanu technicznego, parametr strukturalny.

S u m m a r y

The paper contains identification of destructive processes that affect avionic hydraulic drive and its subassemblies and analyses impact of such processes onto values of defining parameters that characterize internal structure and performance of drives. Hydraulic precision pairs of hydraulic drives have been defined and described along with their operation conditions and mechanisms contributing to wear and tear of such pairs. A close look is taken to physical phenomena that underlie wear processes in hydraulic drives and lead to progressive destruction of hydraulic drives. Due consideration is paid to major effects that bring about to alteration of parameters that characterize structures and performance of hydraulic pumps, hydraulic tracking devices as well as distributing and control units. The performed analysis consisted in subdivision of the examined phenomenon (destruction of hydraulic drives) into elementary processes with no regard to mutual relationships among them. Such an approach has made it possible to find links between wearing processes (destruction) and deterioration of characteristic parameters that define structure and

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performance of drives. Finally, the conclusion was made that there exists correlation between wear of hydraulic precision pairs in hydraulic drives and deviation of their structural and performance parameters from their rated values.

1. Introduction

Any avionic hydraulic drive is a sophisticated technical system that contains hydraulic fluid as one of its structural components. The hydraulic fluid in the circulating system is a pressurized elastic agent that links together all the other components of the system. It plays the role of a power transmission carrier and simultaneously lubricates all the moving parts that frequently are subject to significant unit pressures or exhibit high relative velocities.

Avionic hydraulic drives are composed of hydraulic power systems and hydraulic circuits that are responsible for a single operation of a multi-functional drive, e.g. lowering the undercarriage, actuation of wing mechanisms or other aircraft steering systems. They comprise a hydraulic pump as the major component of the drive as well as other components and subassemblies, such as hydraulic tracking devices, hydraulic manifolds and control valves (the valves that control flow direction and flow intensity of the hydraulic fluid and its pressure) as well as hydraulic servomotors that transmit driving power to various actuators (power consumers).

During the exploitation process every avionic hydraulic drive and its individual components and subassemblies are subject to the impact of a wide spectrum of various factors that affect technical condition thereof. The effect of operation factors onto technical condition of a hydraulic drive leads to deviations of its parameters from their rated values that results from natural wear of the system components. Operation parameters may vary within a wide range and the influence of such variations onto technical condition of avionic hydraulic drives is usually of stochastic nature [1, 2]. Consequently, random disturbances of the exploitation process of hydraulic drives may occur that are manifested by occurrence of temporary faults, e.g. jamming or unstable operation of the drive or its subassemblies as well as worsening of its dynamic characteristics. Therefore identification of destructive processes is a crucial factor that makes it possible to evaluate stochastic disturbances in the process of hydraulic drive operation.

As a result of permanent effect of destructive processes onto components of a hydraulic drive the parameters that characterize its structure and performance capabilities begin to alter at increasing rates. Hence, investigation for physical features of such processes and finding out applicable analytic descriptions of such alterations is the issue of high importance. Therefore there arises a need to describe operating conditions of the avionic hydraulic drive and physical mechanisms that contribute to wear of its components as well as to identify the processes of the drive destruction along with assessment of the impact of such processes onto values of parameters that characterize structures and functional performance of drives and individual components thereof.

2. Hydraulic precision pairs of hydraulic drives and operation conditions thereof

The study [3] presents functional and structural decomposition of a hydraulic drive along with description of its hierarchical structure. That enabled identification of parameters that characterize the drive structure and operation performance of both the entire drive and its components or subassemblies. Furthermore, a set of measurable parameters was defined for a drive (hydraulic system), a module (hydraulic circuit) and a block (hydraulic unit). Physical parameters that result from information circulation between modules of a system and between blocks within a module represented a set of characteristic factors for the entire structure and performance of individual modules and blocks.

In [4] it was proved that the process of surface wear of matching pairs, such as cylinder – piston (plunger), block of cylinders – distributor disk, valve seat – distributor slide, cylinder sleeve – piston, is the major phenomenon that degrades parameter of a hydraulic positive-displacement pump or a hydraulic distributing and control valve. Consequently, wear of the matching pairs in the self-aligning block of cylinders and the mechanism of the distributing disk or pairs of pistons and cylinders directly affects the parameters of hydraulic positive-displacement pumps, i.e. pump delivery at the defined working pressure and pump volumetric efficiency. Surface wear of matching components in hydraulic distributing and control valves, for instance piston – cylinder, valve seat – distributor slide, plunger – sleeve, leads directly to internal leakages inside the valve and eventually depreciates dynamic parameters of the hydraulic drive.

Analysis of information disclosed in [3] and [4] allows to make the conclusion that wear of the hydraulic node in the predominant factor that affects alteration of basic operational characteristics for the hydraulic drive and the hydraulic node in contact points of matching and cooperating components of the block (hydraulic unit), e.g. piston – cylinder, valve seat – distributor slide, slide – sleeve. Hydraulic nodes (slide, piston, plunger and manifold pairs) represent hydraulic precise pairs that comprise two matching and cooperating components, namely a piston (plunger, slide, poppet, piston rod) and a cylinder (sleeve, casing, housing block) whereas hydraulic fluid (hydraulic oil) is the third structural component of such pairs.

The term of a hydraulic precision pair is understood as a moving couple of components (a kinematic tribological node) with various design and purpose that has components (two or more) with cylindrical or flat working surfaces, machined with high accuracy and furnished with purposefully finished upper coating of high smoothness. Every hydraulic precision pair is featured by very tough clearance that guarantees appropriate tightness with no sealing rings, glands, etc. The characteristic operation attribute of any precision pair is collaboration of its components during plane or rotary to-and-from motions in the environment of working fluid that penetrates into very small clearance between moving components. Components of hydraulic pairs are machined with the accuracy that is up to the second class at least whereas the roughness parameters for matching surfaces must be as follows: arithmetic average of the absolute deviations from the mean surface level $R_a \leq 0{,}63$ μm, average surface roughness $R_z \leq 3{,}2$ μm. Radial clearance, depending on the component dimensions and its destination ranges from 2 μm to several dozen of micrometers, usual clearance of hydraulic precision pairs is from 10 μm to 25 μm.

In spite of large diversity of structural forms and variety of application areas, the author of this study has classified hydraulic precise pairs according to the criterion of loads and kinematic features of movements. Use of such classification reveals mutual interrelationships between kinematic parameters of movements within a precision pair and possible disorders of its components. Such a criterion enables subdivision of precision pairs into five classes:

The first class comprises hydraulic precision pairs that are used in control systems, where a cylindrical slider (spool) performs continuous to-and-from movements relatively to a cylinder (sleeve) and is actuated by variable pressure of hydraulic fluid or return spring. Thus, the first class can comprise pressure reduction and relief valves, fixed pressure valves, differential valves, sliders for pump delivery regulators, hydraulic moderators, etc. Hydraulic precision pairs rated to the first class are featured by the following qualities:

1) permanent advance and reverse (to-and-from) movements of a slider (spool) relatively to a cylinder is performed due to pressure of hydraulic fluid and action of a reverse spring,
2) the slider (spool) transmits variable axial loads (forces) exerted from the both sides caused alternatively by the pressure of hydraulic fluid or the return spring,
3) structural clearance and plays along with variable axial loads of the slider (spool) result in its misalignment in relation to the cylinder, which leads to significant local loads at places where the matching surfaces actually contact one another,
4) high vulnerability of the slider (spool) to axial oscillations (caused by hydraulic fluid pressure pulsation) is conducive to sticking the matching surfaces at places of actual contact,
5) relative velocity of the slide (spool) slipping relatively to the cylinder and acceleration of the moving part depend on delivery of the hydraulic fluid that flows to the hydraulic precision pair, stiffness of the return spring and own weight of the slider (spool),

6) significant sensitivity to presence of solid particles in the hydraulic fluid that increase friction between components of the pair, slider (spool) seizure or leakage of the precision pair,
7) malfunctioning of a precision pair is chiefly caused by increase of friction forces between matching surface of cooperating components.

Hydraulic precision pairs that are applied to distributing manifolds where a cylindrical slider (spool) performs linear and periodical to-and-from movements related to the cylinder with rather small displacements are rated to the second class. Movements of the slider (spool) are enforced due to actuation by a one-sided manual or solenoid control system. Therefore the second class can comprise sliding pairs in hydraulic amplifiers, distributing manifolds and hydraulic converters. Hydraulic precision pairs rated to the second class are featured by the following qualities:

1) movements of the slider (spool) never depend on delivery of the hydraulic fluid that inflows to the hydraulic precision pair,
2) during periodical stops of the slider in its movements related to the cylinder the hydraulic fluids flows continuously via clearances of the hydraulic pair components,
3) relative velocity of the slider (spool) in relation to the cylinder as well as the slide acceleration depend on the value of a control signal,
4) the slider accepts no one-sided axial forces due to the hydraulic fluid pressure as the fluid is delivered to distributing channels (manifold) in the sleeve (cylinder) walls,
5) the slider (spool) never performs oscillations alongside the axial direction when pulsations of hydraulic pressure occur (no sticking /seizure of matching surfaces at places of actual contact thereof),
6) no unbalanced hydrostatic forces occur that would press the slider (spool) to the sleeve walls and lead to mechanical jamming of the slider,
7) significant sensitivity to presence of solid particles in the hydraulic fluid that increase friction within the mechanism or jamming the slider,
8) malfunctioning of a second-class precision pair may occur when stability of friction forces is disturbed or components of the hydraulic pair are excessively worn.

The third class incorporates hydraulic precision pairs that are used in distributing manifolds where a flat slider performs linear and periodical advancing and reversing movements (axial or rotary ones) in relation to the housing of the hydraulic unit with small displacements. Movements of the slider are enforced due to actuation by a one-sided manual or solenoid control system. The third class shall include slider pairs in hydraulic amplifiers and distributing valves with distributing disks. Hydraulic precision pairs rated to the third class are featured by the following qualities:

1) movements of the slider never depend on delivery of the hydraulic fluid that inflows to the hydraulic precision pair,

2) the slider is depressed to the housing by the spring effort and pressure of the hydraulic fluid,
3) during periodical stops of the slider in its movements related to the cylinder the hydraulic fluids flows continuously via clearances of the hydraulic pair components,
4) relative velocity of the slider in relation to the cylinder as well as the slide acceleration depend on the value of a control signal,
5) the slider accepts no axial loads due to the hydraulic fluid pressure as the fluid is delivered to distributing channels (manifold) in the housing of the unit,
6) the slider (spool) never performs oscillations alongside the axial direction when pulsations of hydraulic pressure occur (no sticking /seizure of matching surfaces at places of actual contact thereof),
7) significant sensitivity to presence of solid particles in the hydraulic fluid that increase friction within the mechanism,
8) malfunctioning of a third-class precision pair may occur when stability of friction forces is disturbed or components of the hydraulic pair are excessively worn.

Plunger-type and piston-type hydraulic precision pairs that are used in pumps or rotary hydraulic servomotors can be rated to the fourth class. Hydraulic precision pairs rated to the fourth class are featured by the following qualities:

1) continuous to-and-from movements of plungers or pistons in relation to the cylinder, with the stroke length from several millimetres to several centimetres and with velocity that is multiplication of the rotation speed of the lifting system (driving shaft),
2) high values of radial forces between a plunger (piston) and internal surface of cylinders,
3) high contact loads to the face area of a plunger and area of a control component,
4) operation under conditions of complex superposition of acting loads and mutual displacement of matching friction surfaces with relative slip thereof with rapidly decreasing velocity of slipping, corresponding to rotation angle of the rotor,
5) significant sensitivity to presence of solid particles in the hydraulic fluid that increase friction within the pair plunger – cylinder and may cause possible jamming of the plunger,
6) malfunctioning of plunger-type and piston-type precision pairs may result from the progressive process of wear of matching surfaces in kinematic friction nodes as well as from damages to face areas of plungers.

The fifth class includes hydraulic precision pairs that are used for control systems, where a cylindrical slider (spool) simultaneously performs booth to-and-from movements along the axial direction and rotates with the speed that can reach up to several thousands rpm. That class can comprise slider-type hydraulic precision pairs in rotation speed regulators. These hydraulic precision pairs are featured by the following qualities:

1) the slider transfers two-sided variable axial loads (forces) caused by pressure of the hydraulic fluid, action of the return spring and centrifugal forces from the regulator weights,
2) high slipping velocities during operation of the hydraulic precision pair,
3) high sensitivity of the slider to oscillation along the axial direction (caused by pulsations of the hydraulic fluid) is conducive to sticking /jamming of matching surfaces at places of actual contacts,
4) relative slipping velocity of the slider in relation to the cylinder as well as its acceleration depend on the delivery value of the hydraulic fluid that flows to the hydraulic precision pair, stiffness of the return spring and centrifugal forces of the regulator weights,
5) high sensitivity to presence of solid particles in the hydraulic fluid that increase friction within the pair and may cause possible jamming of the slider,
6) malfunctioning of the precision pair may be chiefly caused by increase of friction forces between matching working surfaces.

Analysis of the above characteristics of hydraulic precision pairs shows their susceptibility to presence of solid particles in the hydraulic fluid that bring about to increase of friction within the pair and to jamming of moving parts of the pair or leakage of the coupling, whereas malfunctioning of such pairs is connected with disturbed balance of friction forces or excessive wear of components. The operation practice shows [7, 8, 9, 10, 11] that a great number of hydraulic drive failures was caused by temporary malfunctioning that were exhibited by jamming, unstable operation and progressive decrease of volumetric efficiency during the operation time. Temporary malfunctioning of hydraulic units are chiefly caused by increase (in relation to normal operation conditions) of friction forces within the hydraulic precision pair or excessive wear of its components that may lead to undesired leakages of the hydraulic fluid via clearances between components of the pair. Increase of clearances and enormous damages on the hydraulic unit surface results in formation of critical clearances (leakage paths), which is accompanied by variations in flow of the hydraulic fluid. Such variations that exceed limits as defined for a specific hydraulic unit can bring about to deterioration of dynamical characteristics and operation stability of the driven actuator. In turn, enormous leakages in components of hydraulic drives reduce stiffness of actuators and increase the response time that results in deviations of speed adjustment of servomechanisms.

Therefore the conclusion can be made that the destruction degree of a hydraulic precision pair in a hydraulic drive during its operation depends on occurrence of contamination in the system. Contamination is understood as an undesired foreign body or energy that may adversely affect operation, durability or reliability of a hydraulic drive operation.

Contamination, when present in an avionic hydraulic drive, is a result of the following disturbances: slower movements of driven actuators or complete lack of motion thereof, positioning errors and vibrations, deviations of speed adjustment systems, different velocities of driven actuators depending on movement directions, rapid jerks of driven actuators in spite of infinite (stepless) changes of control signals, decrease of the system stiffness and movement velocity of driven actuators due to leakages that may even increase in time.

3. Identification of destructive processes in hydraulic drives and their impact on deterioration of parameters that define drive structure and performance

As it was mentioned above, processes of surface wear within hydraulic precision pairs should be considered as the major phenomenon that leads to deterioration of operational quality of hydraulic pumps, hydraulic tracking devices and hydraulic manifolds /distributing and pressure control valves. In general, mineral contaminations, when present in a hydrostatic drive, result in excessive surface wear of precise pairs due to presence of solid particles in the hydraulic fluid. Eventually, abrasive and erosive wear of matching surfaces occurs.

Abrasive wear is the most serious problem related to the issues of fluid systems as it leads to the highest expenditures. Any two components of a hydraulic precision pair that are in mutual relative motion are subject to abrasive wear. The abrasive wear process starts when the protecting film of hydraulic fluid is damaged, i.e. when solid particles of mineral contaminants penetrate between matching surfaces of a precision pair.

Author of this paper co-participated in the investigation programme that was aimed at determination of the impact of material contamination caused by presence of solid particles in the hydraulic fluid onto deterioration of characteristic parameters that define structure and performance of hydrostatic drives and their components. The investigations employed the method of colmatation, i.e. various hydrostatic subassemblies (hydraulic pumps, hydraulic tracking devices, hydraulic distributing and control valves, hydraulic servomotors) were examined during operation with fluids of various purity classes. After a specific time of those subassemblies operation the essential structural and performance characteristics were measured and their corresponding curves were plotted. Then the assessment could be made how far the material contamination affects structural and performance parameters, i.e. how much these parameters differ when purity class of hydraulic fluids is subject to changes. The operation practice shows that concentration and size distribution of contaminants in the hydraulic fluid of avionic hydrostatic drives corresponds to 8÷11 purity classes to the standard of NAS 1638 [7, 9, 11, 13, 14 ,15, 16]. The major part of contaminants is represented by sharp-edged particles of metallic and silicon oxides [4], which was confirmed by measurements that were taken in the Air Force Institute of Technology (ITWL) with use of the DR-III ferrograph and MOA emission spectrometer. It is why test contaminants for workshop investigations of hydraulic drive subassemblies were selected in accordance with real operating conditions. For the workshop tests the following testing powders were used: natural sand to the standards MIL-E-5007B and BS:1701, silicon dust to MIL-E-5504A, aluminium oxides with trade names Aloxite 50 and Aloxite 225 to BS:2831. The test arrangements were composed of three basic parts: generation (supply), impedance (control) and measurements. The supplying part incorporated appliances that could build up energy of the hydraulic fluid. The impedance part comprised devices that controlled distribution of the fluid energy into different parts. The measuring part was made up of all the applicable gauges and instruments, such as flowmeters (flow intensity), manometers (pressure), torquemeters (torque at driving shafts), measuring instruments for linear and angular displacements, thermometers (temperature of the hydraulic fluid), granulometers (purity class of the hydraulic fluid).

The own experience of the author allows to state that material contamination is extremely harmful to valve gears and piston units of hydraulic pumps and is the reason for rapid devastation of those parts. Consequently, pump delivery and volumetric efficiency dramatically decrease. To find the exact relationship the plunger-type hydraulic pumps from the combat aircrafts *Su-22* i *MiG-21* were examined in the Air Force Institute of Technology (ITWL) [5, 7, 9, 10]. Fig. 1 presents results of such examinations in the form of the characteristic curves where variations in volumetric efficiency of the axial piston pump NP-34M-1T are shown for operation with pure and contaminated fluids. The examination results exhibit that contamination of the hydraulic fluid by very fine particles with the size below 10μm results in no significant variations in volumetric efficiency of the pump whereas contaminants of the size up to 20 μm bring about to only slight decrease of that parameter. However, when particle sizes range from 15 μm to 50 μm the pump volumetric efficiency after 200 hours of operation drops down to 65% of the initial value.

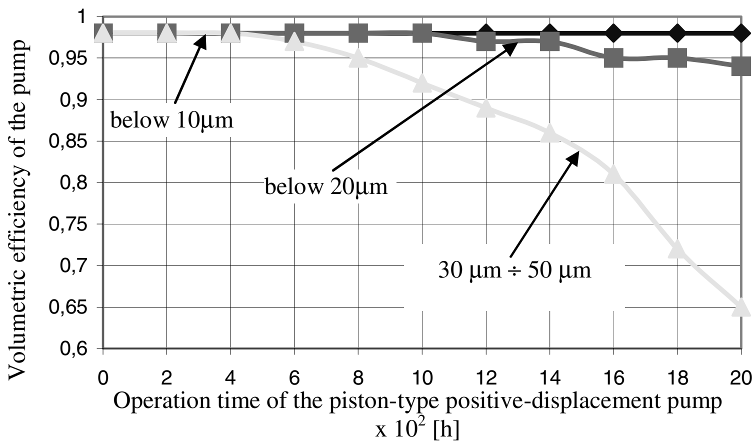

Fig. 1. Variations in volumetric efficiency of the axial piston pump NP-34M-1T as a function of operation time with hydraulic oil of various purity classes

Rys. 1. Zależność zmian sprawności objętościowej osiowej pompy tłoczkowej typu NP-34M-1T w funkcji czasu pracy z olejem hydraulicznym o różnym poziomie czystości

Results of workshop tests for two hydraulic pumps NP-34M-1T will be presented below. The pumps were operated with hydraulic fluids of different purity degrees where the hydraulic pump NP-34M-1T with its number N409W953 was operated with hydraulic oil with purity degree of 6÷7 to NAS 1638 and the pump with its number N501D823 used hydraulic oil with the purity degree of 11 to NAS 1638. Hydraulic parameters of the pump No N501D823 were measured after 760 hours of operation. Fig. 2 presents the pressure characteristic curves that were taken for these pumps, i.e. flow intensity θ_t downstream the hydraulic pump as a function of pumping pressure p_t, for rotation speeds of the pump shaft n_1 = 4000 rpm, n_2 = 2000 rpm and n_3 = 500 rpm with sucking pressure p_s = 0.22 MPa. The lower limit for intensity of hydraulic flow enforced by that pump at zero pressure is 35 dm^3/min, which means that in no case the flow can be less. The above characteristic curve confirms that the hydraulic pump that had operated with the hydraulic fluid of the 11[th] purity class to NAS 1638 could achieve the limit value for the enforced flow intensity. Fig. 3 presents the velocity characteristic for the same pumps (i.e. flow intensity θ_t downstream the pressurized l

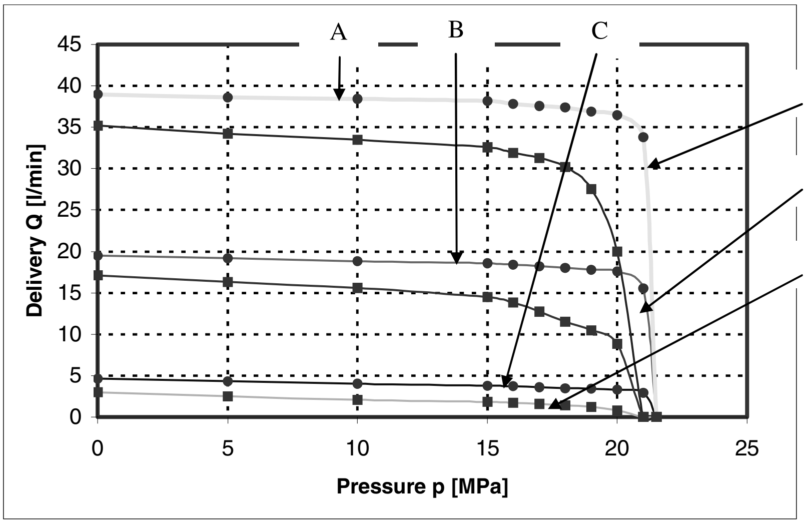

Fig. 2. Pressure characteristic curves of positive-displacement, multi-piston hydraulic pumps with angular positioning of the block of cylinders
A – pump no N409W953 at n_1 = 4000 rpm; B – pump no N409W953 at n_2 = 2000 rpm; C – pump no N409W953 at n_3 = 500 rpm; D – pump no N501D823 at n = 4000 rpm; E – pump no N501D823 at n_2 = 2000 rpm; F – pump no N501D823 at n_3 = 500 rpm
Rys. 2. Charakterystyki ciśnieniowe wyporowych, wielotłoczkowych pomp hydraulicznych, z kątowym usytuowaniem bloku cylindrowego
A – pompa nr N409W953 przy n = 4000 obr/min; B – pompa nr N409W953 przy n = 2000 obr/min; C – pompa nr N409W953 przy n = 500 obr/min; D – pompa nr N501D823 przy n = 4000 obr/min; E – pompa nr N501D823 przy n = 2000 obr/min; F – pompa nr N501D823 przy n = 500 obr/min

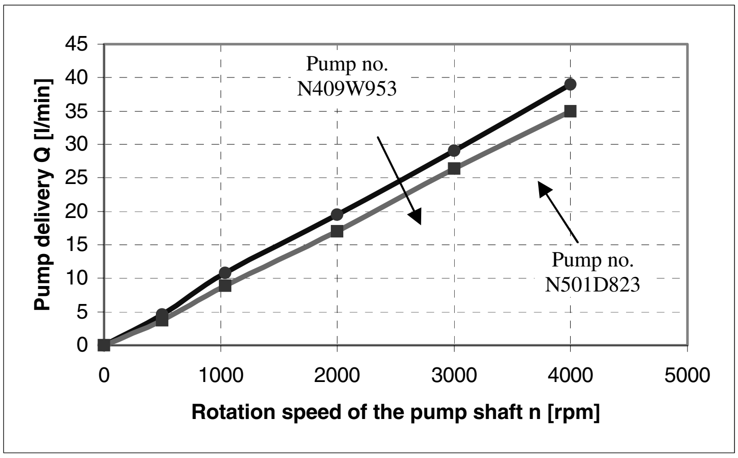

Fig. 3. Velocity characteristic for positive-displacement, multi-piston hydraulic pumps with angular positioning of the block of cylinders
Rys. 3. Charakterystyka prędkościowa wyporowych, wielotłoczkowych pomp hydraulicznych, z kątowym usytuowaniem bloku cylindrowego

ine vs. rotation speed of the pump shaft) whereas the characteristic curve for flow intensity in the cooling circuit of the mentioned pumps (i.e. flow intensity θ_c in the circulation contour of the pump vs. forcing pressure p_t) is disclosed on Fig. 4. The performed investigations revealed that flow intensity in the cooling circuit of the pump (internal leakages inside the hydraulic pump) are much higher for the pump that was operated with the hydraulic fluid with purity class of 11 to NAS 1638. Fig 5 presents the characteristic curve for zero flow (i.e. maximum delivery pressure $p_{t\,max}$ as a function of hydraulic fluid temperature). Analysis of hydraulic characteristic curves for the pumps NP-34M-1T shows that presence of solid particles in hydraulic fluid significantly influents on worsening of structural and performance parameters of the pumps. Exploitation of the hydraulic pump in the environment of the hydraulic fluid with purity class of 11 to NAS 1638 resulted in the situation where rated parameters that depict structure and performance of the pump reached their limit values (the non-operational state) after a much shorter time period than in case of the same hydraulic pump yet operated in the environment of hydraulic oil with purity class of 5 ÷ 7 to NAS 1638.

Hydraulic tracking devices, referred to also as hydraulic amplifiers, represent the type of equipment that is extremely vulnerable to contamination. It is why hydraulic amplifiers BU-250 [11, 12] dismounted from control system of combat aircrafts *Su-22* were subject to workshop examinations in the Air Force Institute of Technology (ITWL). Similarly to plunger pumps, the BU-250 amplifiers were operated with hydraulic oil with various purity classes. The hydraulic amplifier with the number H035380096 was operated in the environment of hydraulic oil with purity class 5÷7 to NAS 1638 whereas the hydraulic amplifier

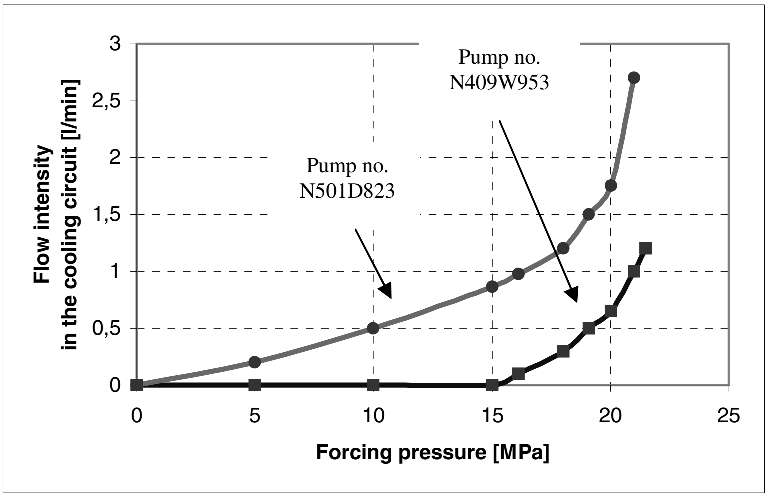

Fig. 4. Characteristic curve for flow intensity of the hydraulic fluid in the circulation contour of positive-displacement, multi-piston hydraulic pumps with angular positioning of the block of cylinders
Rys. 4. Charakterystyka natężenia przepływu cieczy roboczej w obiegu cyrkulacji wyporowych, wielotłoczkowych pomp hydraulicznych, z kątowym usytuowaniem bloku cylindrowego

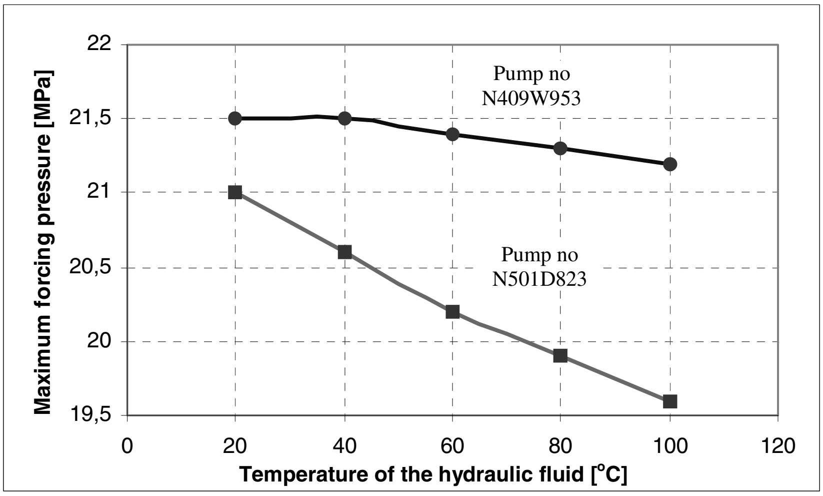

Fig. 5. Characteristic curves for zero pressure of positive-displacement, multi-piston hydraulic pumps with angular positioning of the block of cylinders
Rys. 5. Charakterystyki zerowego ciśnienia wyporowych, wielotłoczkowych pomp hydraulicznych, z kątowym usytuowaniem bloku cylindrowego

no H093350159 used hydraulic oil hydraulic oil with purity class 10 to NAS 1638. Examination of hydraulic amplifiers BU-250 consisted in taking measurements and making assessment of the following parameters: dislocation of separating plates and friction forces thereof, movement velocity of the actuating stem and internal leakages. Measurements for maximum dislocation of separating plates were taken by means of the indirect method, i.e. by measurements of control lever displacement with depressurized hydraulic system. Friction forces of separating plates were evaluated by measuring the force that must be applied to the control lever of separating plates to achieve full dislocation (stroke) of the plates. Velocity measurements were carried out with no external loads and for full displacement of separating plates whereas a step function was applied to the mechanism input. Finally, internal leakages within the amplifier were evaluated on the basis of the oil volume that flows via the short circuit of the amplifier (leakage via its separating valve) during a defined period of time. After having compared the measurement results with rated parameters of the amplifier the observation was made that the measured parameters were below permissible limits. However, such parameters of hydraulic amplifiers as the dead zone, friction forces of separating plates and internal leakages were much worse for the amplifier that was operated in the environment of the hydraulic oil with purity class of 10 to NAS 1638 than in case of the amplifier that used hydraulic oil with purity class of 5÷7 to NAS 1638.

Table 1. Results for examination of the BU-250 hydraulic amplifiers with their number H035380096 and H093350159 operated on boards of combat aircrafts
Tabela 1. Wyniki badań wzmacniaczy hydraulicznych BU-250 o nr H035380096 i H093350159 eksploatowanych na samolotach wojskowych

Checked parameter	Unit.	Parameter limit	Measured parameter value for the amplifier with number	
			H0353800096	H093350159
Dislocation of separating plates	mm	$3^{+0.5}$	3.1	3.4
Dead zone of the amplifier	mm	≤ 0.4	0.25	0.35
Friction force of separating plates	kG	≤ 2.1	0.8	4.8
Movement velocity of the actuating stem	mm/s	55 ÷ 65	58	65
Internal leakages: neutral position of the piston	cm^3/min	≤ 350	135	285
retracted position of the piston			140	315
advanced position of the piston			135	295

Material contamination in systems for accurate adjustments of small flows, e.g. at small opening of control valves, contributes to clogging of gaps that are formed by hydraulic precision pairs of valves. The practical experience shows that flow of fluids via small cross-sections decreases when the operation time goes by and tends to total disappearance. Research of the Air Force Institute of Technology (ITWL) with co-participation of the author confirmed the assumption that leakages via small gaps vary in time as if clogging of gaps by solid particles had occurred. The experiment consisted in allowing the hydraulic fluid to flow via a rectangular gap with variable dimensions whilst the fluid had been pre-filtered to remove particles larger than 12 µm. Sizes of particles that could pass via the gap was determined by means of the automatic counter of particles type PMT-3120 manufactured by Praktikel-Mestechnik GmbH. The test arrangement incorporated a special head with replaceable inserts that enables stepwise change of the gap dimension. The full set of inserts made it possible to form rectangular gaps that were 5 mm wide while their heights were of 35.4 µm, 25.3 µm, 20.2 µm, 15.4 µm and 10.6 µm. During the experiment the hydraulic oil OO H-515 passed the upstream filter with filtering capacity of 5 ÷ 12 µm placed at the inlet of the gap whereas the differential pressure across the filter was Δp = 5 MPa. The experiment comprised measurements of flow delivery downstream the head.

Fig. 6 presents how the flow intensity via the rectangular gaps depends on the overall time of oil flow. The investigations showed that flow intensity via gaps with the heights exceeding 20 µm did not vary in time yet for gaps smaller than 15 µm the flow intensity decreased. No literature sources that are available to the author bring theoretical explanation of the gap clogging phenomenon, which makes it impossible to interpret the obtained experimental results. However, the attempt to construe the sophisticated effect associated with the influence of contamination onto flow intensity via micro-gaps can be made with use of general theory of colmatation processes in gaps.

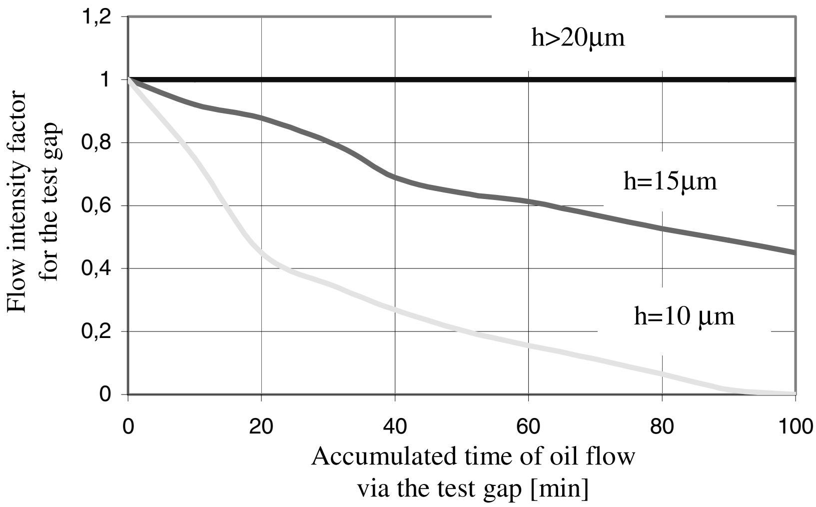

Fig. 6. Flow intensity factor for rectangular test gaps with the width of 5 mm and variable height of 35 µm, 25 µm, 20 µm, 15 µm and 10 µm as a function of the accumulated flow time
Rys. 6. Zależność współczynnika wydatku przepływu przez szczeliny prostokątne szerokości 5 mm i wysokości 35 µm, 25 µm, 20 µm, 15 µm i 10 µm w funkcji czasu przepływu

Solid particles that move with significant velocity attack surfaces of hydraulic precision pairs and may bring about to abrasive erosion of their edges. The abrasive wear occurs chiefly due to excessive tensions on the metal surfaces caused by forces that arise when particles attack the surfaces. Therefore abrasive erosion involves two predominant wear mechanisms [6]. The first one consists in cutting due to forces that act in parallel to the surface "bombed" by abrasive particles, the second one assumes deformation caused by component force that is perpendicular to the surface. Particle bombardment causes generation of multiple pressure pulses on the exposed surface with very short duration and limited area of the pulse impact. The reference literature available to the author presents no theoretical deliberations or practical advices related to the problem of abrasive wear in pressurized fluid systems. Thus it was assumed that dimensions, hardness and velocity of bombarding particles are the major factors that contribute o erosive wear of precise pair components. The author, along with a team of the employees from the Air Force Institute of Technology (ITWL), carried out a series of experiments with use of various test arrangements and with the purpose to find out how the process of abrasive wear depends on sizes and velocities of bombarding particles. The workshop investigation dedicated to the influence of particle sizes onto abrasive wear used the hydraulic fluid contaminated by the following test powders: alundum with sizes of particles 5÷10 µm, 5÷20 µm, 10÷30 µm, 10÷40 µm and 25÷50 µm and aluminium oxide Aloxite 50 and Aloxite 225 to the standard BS:2831 with various sizes of grains (from 0 to 50 µm).

The experiment consisted in allowing the hydraulic fluid contaminated with alundum (hard particles) or aluminium oxide (soft particles) to flow through the GA-185 valve with its closed position. The fluid velocity was 75 m/s and the experiment lasted 25 hours. After passing the hydraulic valve the fluid was collected in a special tank where sedimentation of contaminations took place. After having the experiment terminated and having the liquid stilled the sediments were drained via a special opening in the tank bottom onto a filter paper. The filter paper was dried and then weighted. Results of investigations on dependence of erosive wear on size of contamination particles are presented graphically on Fig. 7. Based on the performed research one can conclude that erosive wear very strongly depends on sizes of particles that are transferred by the hydraulic fluid. Increase of contamination weight for the flow of fluids with alundum contamination with particle sizes from 5 to 10 µm is five times less than in case of flow with alundum particles sized of 25÷50 µm. Flow of hydraulic fluid with alumnum contamination resulted in five times faster gain of contamination weight as compared to reciprocal flow of fluid with aluminium oxide.

Workshop tests to investigate the effect of the velocity of bombarding particles onto erosive wear used the hydraulic fluid contaminated by test powders: alumnum with gain sizes from 5 to 20 µm and aluminium oxide Aloxite 50 and

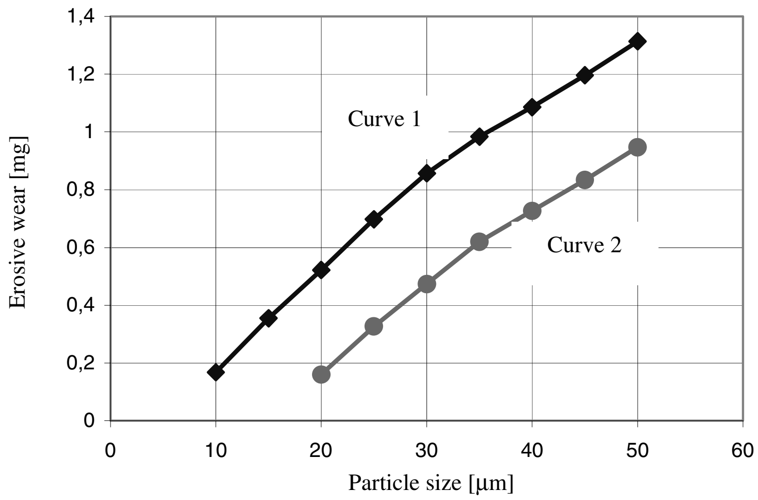

Fig. 7. Dependence of erosive wear on size and hardness of contamination particles
Curve 1 – flow of hydraulic fluid contaminated by alundum,
Curve 2 – flow of hydraulic fluid contaminated by aluminium oxide
Rys. 7. Zależność zużycia erozyjnego od rozmiarów i twardości cząstek
Krzywa 1 – przepływ cieczy roboczej zanieczyszczonej elektrokorundem
Krzywa 2 – przepływ cieczy roboczej zanieczyszczonej tlenkiem aluminium

Aloxite 225 with grains sized of 10÷25 µm. The experiment consisted in allowing the hydraulic fluid contaminated with test powders to flow through the GA-185 valve at various velocities with closed position of the valve. The total duration of the experiment was 25 hours. After passing the hydraulic valve the fluid was collected in a special tank where sedimentation of contaminations took place. After having the experiment terminated and having the liquid stilled the sediments were drained via a special opening in the tank bottom onto a filter paper. The filter paper was dried and then weighted. Results of investigations on dependence of erosive wear on velocity of bombarding particles are presented graphically on Fig. 8. Based on the performed research one can conclude that erosive wear significantly depends on velocity of bombarding particles. Flow of hydraulic fluid with alumnum contamination resulted in much higher gain of contamination weight as compared to reciprocal flow of fluid with aluminium oxide.

Fig. 9 graphically exhibits variations of relative intensity of the hydraulic fluid flow Q_{wz} through the control valve as a function of time with differential pressure drop Δp = 10 MPa. Velocity of the contaminated hydraulic fluid flow via the valve was ca. 35 m/s where the curve 1 corresponds to grain size below 15 µn and the curve 2 to grain size above 50 µm. The term of relative intensity of hydraulic flow Q_{wz} is understood as a ratio of momentary flow intensity Q_r to theoretical flow Q_t. Increase of Q_{wz} is the evidence of the growth of hydraulic flow via the valve and, therefore, increased abrasive wear of a hydraulic precision pair of the valve material. After 35 hours of the hydraulic fluid flow via the valve he overall internal leakages increased by about 12%.

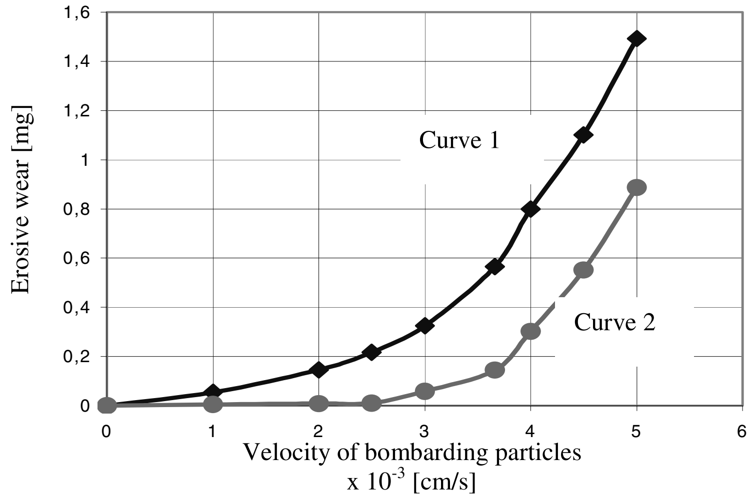

Fig. 8. Dependence of erosive wear on velocity and hardness of bombarding particles
Curve 1 – flow of hydraulic fluid contaminated by alundum,
Curve 2 – flow of hydraulic fluid contaminated by aluminium oxide
Rys. 8. Zależność zużycia erozyjnego od prędkości uderzających cząstek i ich twardości
Krzywa 1 – przepływ cieczy roboczej zanieczyszczonej elektrokorundem
Krzywa 2 – przepływ cieczy roboczej zanieczyszczonej tlenkiem aluminium

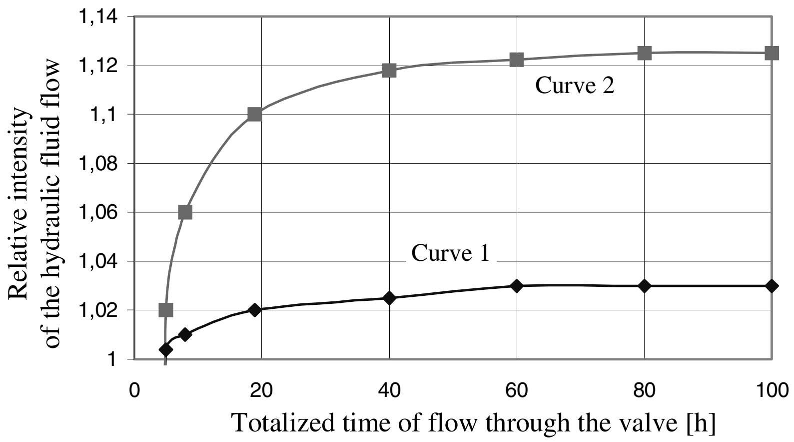

Fig. 9. Variations of relative intensity of the hydraulic fluid flow Q_{wz} through the control valve as a function of time Curve 1 – flow of hydraulic fluid with contaminating particles of the size below 15 µm, Curve 2 – flow of hydraulic fluid with contaminating particles of the size above 50 µm
Rys. 9. Zmiana natężenia względnego przepływu Q_{wz} przez zawór sterujący w zależności od czasu
Krzywa 1 – przepływ cieczy zawierającej zanieczyszczenia poniżej 15 µm
Krzywa 2 – przepływ cieczy zawierającej zanieczyszczenia powyżej 50 µm

Another type of contamination-induced wear is the erosion caused by cavitations. In case of cavitation erosion the damages of matching surfaces of cooperating precision pairs or other components of a hydraulic drive are caused by implosions of bubbles in the flowing stream of the hydraulic fluid. Very high pressure that is associated with implosion of vapour bubbles leads to deformations, damages and erosion of material surfaces. Shock waves or micro streams that exert very strong impact onto the material and cause very high deforming velocities. Consequently, not only surfaces of hydraulic precise pairs are damaged but new hard particles are seized and captured by the hydraulic fluid to the circulation system. The author carried out research work to identify the phenomena that are associated with the cavitation process. During the experiments the effect of cavitation was artificially induced at the inlet of the NP-73 plunger-type hydraulic pump by lowering of the supplying pressure below the minimum permissible value. Then the automatic particle counter PMT-3120 manufactured by Praktikel-Mestechnik GmbH was connected to both the high pressure circuit and the circulation (cooling) contour of the pump. The tests involved checking of particle number increase and growth of their sizes, both in the high pressure circuit and the circulation contour of the pump. Investigation results have proved that the rates of the particle growth in number and sizes in the circulation contour are subject to variations depending on the deterioration stage of both the valve-gear mechanism and the piston unit of the hydraulic pump. Until 5 hours and 30 minutes of the test duration no increase of particle number and size was observed but after 32 hours and 15 minutes of the test both number and sizes of the particles began to grow at significant rates. In particular, the rates of the particles number increase were extremely high. After 65 hours of the test the process of particle number and sizes growth started to slow down and after 87 hours and 45 minutes of the tests the respective rates of particle numbers and particle sizes stabilized at the constant level. Finally, after 127 hours of operation since the test had begun the pump failed to deliver pressure (pistons were jammed in the block of cylinders). Thus, the investigation results make it possible to distinguish four stages of the pump deterioration: (i) incubation, when no increase of particle number and size thereof is observed, (ii) accumulation, when rates of particle number increase and size growth are higher and higher, (iii) weakening, with decrease of the rates for both number and sizes increase for contaminating particles and (iv) stabilization, when rates of particle number and size growth is kept at the constant level. Fig. 10 shows pressure values that were delivered by the NP-73 pump to the high pressure line during examination. Cavitation effect at the pump inlet brings about to pressure pulsation in the high pressure line and amplitudes of that pulsation are really high. Examination of the pump allowed also to find out that there were some periods of the pump operation when the effect of cavitation did not occur in spite of lowering its supplying pressure below the minimum permissible level. The lack of cavitation is manifested by disappearing of cavitation noise that is normally heard from the hydraulic drive. Pressure drops during the tests were caused by jamming of pistons within the block of cylinders or total damage thereof (breaks of piston rods).

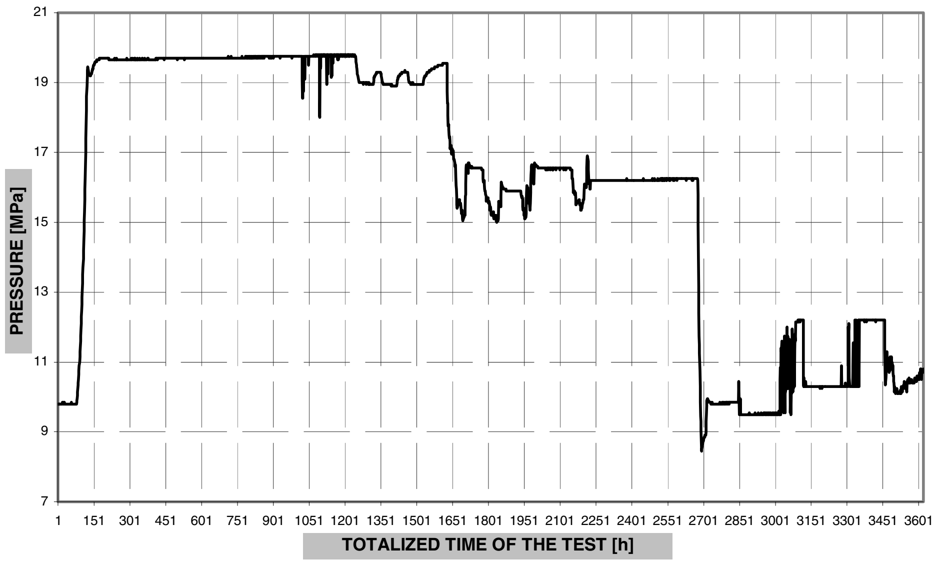

Fig. 10. Characteristic curves for pressure delivered by the plunger-type pump NP-73 to the high pressure line during cavitation trials
Rys. 10. Przebiegi ciśnienia wytwarzanego przez nurnikową pompę NP-73 w linii wysokiego ciśnienia podczas prób kawitacyjnych

5. Conclusions

According to the author's opinion, the major phenomena that contribute to worsening of operational parameters of hydraulic pumps, hydraulic tracking devices, hydraulic manifolds and distributing and control valves include processes of surface wear within internal hydraulic precision pairs of such equipment. Normal wear of hydraulic drive components is a result of prolonged operation of a drive, so it represents a superposition of various elementary wear processes. Major factors that result in destruction of hydraulic precision pairs must comprise processes of abrasive and erosive wear. Usually, under specific conditions for operation of a hydraulic drive one process should be regarded as the predominant one that contributes to the total wear in the highest degree. The author claims that friction wear is the prevailing factor for the wearing process of the hydraulic precision pairs as it proceeds at the highest rates.

The performed analysis made it possible to reveal relationships between the processes of material wear (the destructive process) and deterioration of characteristic parameters that define structures and performance of hydraulic drives. There is apparent correlation between wear of hydraulic precision pairs and deviation of drive structural and performance parameters from their rated values. Wear of collaborating components of matching pairs in a self-aligning node and a distributing disk directly affects output parameters of hydraulic positive-displacement pumps, i.e. pump delivery and its volumetric efficiency. Wear of mutually co-operating components of such pairs as piston – cylinder or valve seat - distributor valve directly affects internal leakages of a hydraulic unit. Alteration of flow intensity and exceeding their permissible limits depreciates dynamic characteristics and operation stability of driven actuators. Increase of leakages in subassemblies of hydraulic drives reduces rigidity (response time) and speed of actuator movements and leads to deviations in speed adjusting and control modules for servomotors. Material contamination in systems for accurate adjustment of small flows, e.g. at small openings of control valves brings about to clogging of gaps formed by components of hydraulic precision pairs.

The crucial precondition for reliable operation of hydraulic precision pairs in hydraulic units, such as hydraulic pumps, hydraulic tracking devices, manifold and control units of both slide (spool) and piston design is maintaining low friction forces on the matching surfaces and good tightness. Durability of hydraulic precision pairs in hydraulic units depends on the fact how much slider (spools) or pistons are resistant to wear and tear.

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References

[1] Ułanowicz L.: Outline for evaluation of the expected operability lifetime of hydraulic drives in use. Issues of Machinery Exploitation, Tome 2 (134) Vol. 38, 2003, pp. 77÷93 (in Polish language).

[2] Ułanowicz L.: Outline for probabilistic assessment of hydraulic drive durability. Issues of Machinery Exploitation, Tome 1 (137) Vol. 39, 2004, pp. 83÷97 (in Polish language).

[3] Ułanowicz L.: Identification of technical condition of the fluid power transmission on the basis of variation-related description of structural parameters. Issues of Machinery Exploitation, Tome 1 (145) Vol 41, 2006, pp. 61÷87.

[4] Ułanowicz L., Zboiński M.: Assessment of technical condition of avionic hydraulic systems during the process of operation thereof. Issues of Research and Exploitation of Avionic Technique, Vol. 5, The Air Force Institute of Technology (ITWL), Warsaw, 2004 (in Polish language).

[5] Collective output: Analysis of opportunities to unify the resource of hydraulic systems in the Su-22 aircrafts, Internal development of The Air Force Institute of Technology (ITWL) (non-published), Warsaw, 1996 (in Polish language).

[6] Fitch E.: An Encyclopedia of Fluid Contamination Control for Hydraulic Systems. Hemisphere. Washington 1979.

[7] Ułanowicz L.: Examination of reasons for failures of avionic hydraulic pumps NP-52M-2 during operation thereof. Internal development of The Air Force Institute of Technology (ITWL) (non-published), Warsaw, 1991 (in Polish language).

[8] Kolasa B., Ułanowicz L.: Examination of reasons for chipping of hydraulic pumps from the An-26 aircrafts. Internal development of The Air Force Institute of Technology (ITWL) (non-published), Warsaw, 1995 (in Polish language).

[9] Ułanowicz L., Waręcki T.: Examination of components included into hydraulic on-board system of Su-22 aircrafts in relation to spontaneous movement of the control stick, Internal development of The Air Force Institute of Technology (ITWL) (non-published), Warsaw, 1987 (in Polish language).

[10] Ułanowicz L., Zboiński M.: Examination of faults in steering systems of aircrafts, 3rd conference: Methods and techniques for inspection of aircrafts in flight, Mrągowo, 1998 (in Polish language).
[11] Ułanowicz L., Waręcki T.: Examination of technical condition of the NP-34M-1T hydraulic pumps, Internal development of The Air Force Institute of Technology (ITWL) (non-published), Warsaw, 1991 (in Polish language).
[12] Ułanowicz L.: Test for durability and reliability of the BU-210 and BU-51MS hydraulic amplifiers, Internal development of The Air Force Institute of Technology (ITWL) (non-published), Warsaw, 1991 (in Polish language).
[13] Collective output: Long-term tests of the BU-210 and BU-51MS hydraulic amplifiers. Internal development of The Air Force Institute of Technology (ITWL) (non-published), Warsaw, 1984 (in Polish language).
[14] Kolasa B., Ułanowicz L.: Report file on the research work: Investigation and evaluation of technical condition of both the first and the second hydraulic systems along with on-board hydraulic pumps NP-34M-1T for the first and the second hydraulic systems of the Su-22 aircraft (54K and 52UM3K) with the aim to increase the hour-scheduled and year-scheduled MTBR resource. Aircraft numbers: 29307, 28919, 27820, 37307, 24605. Internal development of Air Force Institute of Technology, Warsaw, 2002 (in Polish language).
[15] Kolasa B., Ułanowicz L.: Report file on the research work: Investigation and evaluation of technical condition of hydraulic systems and the NP-34M-1T on-board hydraulic pumps in the both hydraulic systems of the MiG-21bis aircraft with the aim to increase their MTBR resource. Aircraft numbers: 8705, 8859, 8971, 8801, 8888. Internal development of Air Force Institute of Technology, Warszawa 2002 (in Polish language).
[16] Kolasa B., Ułanowicz L.: Report file on the research work: „Investigation and evaluation of technical condition of hydraulic systems and the NP-34M-1T on-board hydraulic pumps in the both hydraulic systems of the MiG-21UM aircraft with the aim to increase their MTBR resource. Aircraft numbers: 9231, 9323, 9351, 9292, 9308". Internal development of Air Force Institute of Technology, Warsaw, 2001 (in Polish language).
[17] Kolasa B., Ułanowicz L.: Investigation of the hydraulic oil Orlen Oil H-515-Pl with the aim to use the same in hydraulic systems of combat aircrafts. Ground-based investigations. Laboratory tests, Internal development of Air Force Institute of Technology, Warsaw, 2002 (in Polish language).

Parametryczna identyfikacja procesów destrukcyjnych lotniczych napędów hydraulicznych

S t r e s z c z e n i e

W artykule dokonano identyfikacji procesów destrukcji lotniczego napędu hydraulicznego i jego zespołów oraz wpływu tych procesów na wartość parametrów charakteryzujących jego strukturę i funkcjonowanie. Zdefiniowano i opisano hydrauliczne pary precyzyjne napędu hydraulicznego, warunki ich pracy oraz fizyczne mechanizmy ich zużywania. Naświetlono również fizyczne podstawy procesów zużywania elementów napędu hydraulicznego i omówiono przyczyny, które doprowadzają do destrukcji napędu. Omówiono także główne zjawiska powodujące zmianę wartości parametrów charakteryzujących strukturę i funkcjonowanie pomp hydraulicznych, hydraulicznych urządzeń śledzących, hydraulicznych zespołów rozdzielczo-regulacyjnych. Dokonana analiza polegała na podzieleniu badanego zjawiska (destrukcja napędu) na procesy elementarne bez uwzględnienia relacji między nimi. Umożliwia ona jednak stwierdzenie istnienia związku między procesami zużywania (destrukcji) a degradacją parametrów charakteryzujących strukturę i funkcjonowanie napędu hydraulicznego. Oceniono, że występuje korelacja między zużyciem hydraulicznych par precyzyjnych napędu hydraulicznego a odchyleniem od nominału parametrów charakteryzujących jego strukturę i funkcjonowanie.