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METHOD FOR ESTIMATING THE DURABILITY OF AVIATION HYDRAULIC DRIVES

METODA SZACOWANIA TRWAŁOŚCI LOTNICZYCH NAPĘDÓW HYDRAULICZNYCH*

Throughout previous practice, estimating the life of aviation hydraulic drive assemblies has been utilizing a variant, which requires conducting long-lasting studies of the drive assemblies until they move to the unfitness state. Such studies, which enable estimating life a posteriori, are costly and long-lasting. Hence the need to look for new strategies for estimating life. The article presents a method of estimating the durability of a hydraulic drive assembly based on the control of its change in technical condition. Inspection of the technical condition enables timely detection of the condition before the emergency hydraulic assembly. The novelty of the method is to use, to detect the condition before the emergency team, the principle of determining the pre-emptive control parameter tolerance. Pre-emptive tolerances are a set of control parameter values between threshold levels and pre-emergency (allowable) levels. The intensity of depletion of durability (intensity of aging, wear) is random. The paper presents a stochastic description of the control parameter change and the resulting empirical relationships between the control parameter verification time probability density (verification periodicity) and the control parameter value change probability density. The inter-relations between these two functions were described. It also presents empirical relationships enabling the determination of the permissible value for the control parameters and the periodicity of the control parameter checks after exceeding the limit value. An example of estimating the life of a hydraulic piston pump on-board an aircraft operated in the Polish Air Forces was shown. The permissible values and the time for the first control parameter verification after exceeding the limit value were determined for selected control parameters of the hydraulic pump. The proposed method binds life (fitness time) with the physical wear mechanisms concerning the assemblies. It can be applied in work aimed at determining the resource life of technical equipment. Furthermore, it enables utilizing technical equipment according to a technical state strategy with monitoring the parameters.

Keywords: *aviation, lifetime, hydraulic drive, hydraulic pump, technical condition.*

W dotychczasowej praktyce szacowania trwałości zespołów lotniczych napędów hydraulicznych stosowany jest wariant, który wymaga prowadzenia długotrwałych badań zespołów napędu do czasu ich przejścia w stan niezdatności. Badania tego typu, umożliwiające szacowanie trwałości a posteriori, są kosztowne i długotrwałe. Istnieje więc potrzeba poszukiwania nowych strategii szacowania trwałości. W artykule zaprezentowano metodę szacowania trwałości zespołu napędu hydraulicznego opartą o kontrolę jego zmiany stanu technicznego. Kontrola stanu technicznego umożliwia wykrycie we właściwym czasie stanu przed awaryjnego zespołu hydraulicznego. Novum metody jest wykorzystanie, do wykrycie stanu przed awaryjnego zespołu, zasady wyznaczania uprzedzających tolerancji parametru kontrolnego. Tolerancje uprzedzające stanowią zbiór wartości parametru kontrolnego zawartych między poziomami granicznym i przed awaryjnym (dopuszczalnym). Intensywność wyczerpywania się trwałości (intensywności starzenia, zużywania) ma losowy charakter. W artykule przedstawiono stochastyczny opis zmiany parametru kontrolnego oraz wynikające z niego empiryczne zależności funkcji gęstości prawdopodobieństwa czasu przeprowadzania sprawdzeń parametru kontrolnego (okresowość kontroli) i funkcji gęstości prawdopodobieństwa zmiany wartości parametru kontrolnego. Opisano wzajemne związki obu tych funkcji. Przedstawiono zależności umożliwiające wyznaczenie wartości dopuszczalnej parametru kontrolnego i okresowość sprawdzeń parametru kontrolnego po przekroczeniu wartości dopuszczalnej. Zaprezentowano przykład szacowania trwałości tłoczkowej pompy hydraulicznej z samolotu użytkowanego w Siłach Zbrojnych RP. Dla wybranych parametrów kontrolnych pompy hydraulicznej wyznaczono ich wartości dopuszczalne oraz czas pierwszej kontroli parametru kontrolnego po przekroczeniu wartości dopuszczalnej. Zaprezentowana metoda wiąże trwałość z fizycznymi mechanizmami zużywania się zespołów. Przedstawiona metoda może być wykorzystana w pracach mających na celu określanie zasobu pracy urządzeń technicznych. Umożliwia ona użytkowanie urządzeń technicznych według strategii stanu technicznego z kontrolowaniem parametrów.

Słowa kluczowe: *lotnictwo, trwałość, napęd hydrauliczny, pompa hydrauliczna, stan techniczny.*

1. Introduction

Estimating the life of aviation hydraulic drive is a broad forecasting issue at the engineering stage of their operational behaviours, as well as forecasting the change of their technical state throughout the operation stage. The experience from the operation of aircraft hydraulic propulsion in aircraft indicates that after using the normative durability established by the manufacturer, most hydraulic assemblies still have some work resource that can be used [21, 24]. This may indicate that at the design stage of hydraulic units, their operating conditions were incorrectly identified and inadequate redundancy was imposed when estimating their durability [21].

Therefore, there is a need for technical and scientific search for methods of estimating durability correcting adopted design assumptions while maintaining the functionality and effects of the hydraulic assembly. Based on available literature sources, one can draw up

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(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** a certain view regarding the general principles of determining the life of hydraulic assemblies, adopted by various research, scientific and production facilities [1, 14].

The current practice of estimating the durability of aviation hydraulic drive units is multi-faceted and multi-directional. The main direction of estimating durability is based on the principle that based on laboratory test data and bench tests, it is possible to assess the durability of the assembly in appropriate operating conditions [7, 23]. The second direction, supplementing the main one, is estimation of durability based on tests of operational reliability of the assembly [1,13]. Both directions use safe durability concepts for team design.

The first direction of durability estimation requires conducting long-term and costly tests of hydraulic assemblies until they become unfit [2, 7]. In this approach, at the design stage, wear tests of hydraulic units are carried out [4, 18]. These tests are carried out only in the workplace [5, 11]. They are aimed at checking the assumed hydraulic resistance of precise pairs of the tested assembly [2, 22]. These tests are conducted according to specially developed schedules for the entire unit, which usually provide for their accelerated mode and load conditions harsher than the ones recorded during operation [14]. They last until the hydraulic unit is damaged. In general, the test schedule, determined in the course of developing a given hydraulic unit or drive, includes the execution of a series of identical, subsequent stages, each of which consists of a number of sub-stages with varying values of load parameters for a given unit, conducted at a specified time, therefore, over a specified number of load cycles [9, 12]. Hence it can be seen that the study period of time is long, therefore, the tests are also expensive. However, wear tests do not take into account all operational forces, since the very reconstruction at a test bench of the loads actually occurring in the course of operation of a studied unit is a huge problem. The principles for the determination of each test schedule are also an issue, which is extremely comprehensive and time-consuming. The dispersion of the results of experimental wear tests when estimating the durability of a hydraulic unit is the basis for introducing a safety factor, i.e. an unnamed ratio of dangerous value to limit value. Most usually, a safety factor takes into account the potential inadequacy of the test schedule relative to actual operating conditions in the course of operation [2], the availability of wear location for verification [19], the nature of developing destruction and its rate [14], the degree of credibility of determining loads for a given unit [24] and the population of a test bench studied sample [2]. Agamirov and Reicher assumed the value of the coefficient taking into account the possible inadequacy of the test program to the actual working conditions of the team equal 1.0 [2], and Ignatowicz with the team equal 1.5 [14]. Taking into account the availability of the place of wear for control, the nature of the progressing destruction and the speed of destruction, Otshu and the team assumed a value of 1.2 [19]. Taking into account the sample size, in the case of one sample tested at the stand, the value of the factor of 5 was adopted, and for six samples the value of 3 [2]. Generally, the value of the safety factor is taken from 1 to 5 [14, 24]. Based on the results of wear tests and taking into account safety factors, normative durability is determined [1, 26].

Another approach for estimating the durability of hydraulic units using the concept of safe durability are operational reliability tests [17, 27]. This strategy involves using the assembly on the aircraft until damage occurs. This strategy uses statistical methods as well as computer simulation techniques and programmed reliability tests. This strategy can be used only if the consequences of damage do not violate the principles of occupational safety and do not increase the operating costs of hydraulic units [27].

Methods for estimating durability based on safety factors do not provide an opportunity to assess the function of the distribution of the durability of a hydraulic assembly at the design stage. Therefore, works are also carried out to ensure the efficient operation of hydraulic units, using modern diagnostic methods [16, 20]. The main direction of this work is the development of methodologies for prognostic management and management of the technical condition of teams based on combining many sources of information from exploitation. For the processing of operational data, modern techniques of tracking neural networks are used, as well as automatic inference algorithms and failure probability progression algorithms [6, 8]. The so-called research also falls under this trend residual stability, which uses extended Kalman filter technique models, time series prediction, multidimensional data distribution, and phase space reconstruction [9, 20]. The influence of contamination on the durability of various hydraulic pairs of precision hydraulic units is also investigated [25]. An experimental method of measuring sensitivity to pollution based on the pollution sensitivity model was used to predict the lifetime of the hydraulic assembly. In some works, the reliable operation time of a renewable technical object was identified by applying three criteria, which used the following statistics: modified Kolmogorov-Smirnov (MK-S) statistics, statistics of the average absolute deviation of the hypothetical and empirical cumulative distribution and statistics calculated on the basis of logarithmized reliability function [3, 21]. The values of these statistics were used to rank eleven damage probability distributions. It has been shown that based on the aggregate criterion taking into account three statistics of match compliance, the reliability of the estimation of the work time to damage distribution increases, thus avoiding mistakes that can be made by becoming addicted to only one of them.

Agamirov and Vestyak and Blancke with the team showed that hydraulic drives have a strong correlation between parameters determining their condition and time of use [1, 7]. Therefore, one can predict the moment of change in the technical condition of the hydraulic drive assembly, provided that this condition is periodically checked [1, 24]. Using this property, the authors of this article proposed a priori-predictive method of estimating durability.

The method presented in this article is based on the observation of a selected control parameter of the hydraulic drive assembly during its use. The purpose of this check is to detect in advance the pre-emergency (allowable) condition. The novelty of the method is the use of pre-fault detection to detect pre-fault tolerance on the selected control parameter. Pre-emptive tolerances are a set of values of the selected control parameter contained between the threshold levels and before the emergency (allowable) levels. Periodic inspection of the technical condition of the hydraulic assembly using selected control parameters enables prediction of the moment of the limit state of the hydraulic drive assembly. The quantitative wear characteristics of hydraulic units change over time and their impact on the technical condition of the aviation hydraulic drive is random. The condition for implementing the method is knowing the limit level of the hydraulic drive control parameter. The limit value of the hydraulic drive unit control parameter is determined at the stage of its construction and design. It results from the design conditions of hydraulic precision pairs (plunger pairs, distribution pairs, control pairs) and functional conditions of the entire hydraulic assembly. depends largely from the materials used and the design solution of hydraulic precision pairs and is mainly confronted with the processes of destruction of these pairs as a result of their operation. The limit value for the most important parameters of a hydraulic assembly is given by the manufacturer in his technical documentation and is a reference criterion during operation.

The presented method is based on controlling the level of permissible value (pre-emergency) of the selected control parameter and determining the relationship of this parameter with the periodicity of its checks, while ensuring a given level of reliability (determined a priori reliability of the hydraulic assembly). The permissible level of the control parameter is its value at which this parameter measured at the moment t_1 does not reach the limit point t_2 with the probability $p(t) \geq p_w$, where p_w is the assumed probability level of trouble-free operation of the unit in time $\Delta\tau = t_2 - t_1$. If the value of any hydraulic control parameter η exceeds the limit value η_{dop}, but does not exceed the limit value η_{gr}, i.e. $\eta_{dop} \leq \eta \leq \eta_{gr}$, then the hydraulic drive is considered to be in a pre-emergency condition. Reaching the admissible level by the control parameter is associated with the change of the control frequency, i.e. $\Delta\tau = t_2 - t_1$. Pre-emptive tolerance $\Delta\eta = \eta_{gr} - \eta_{dop}$ is related to the frequency of the check $\Delta\tau = t_2 - t_1$ in such a way that the implementation of the process of changing the parameter determining the technical condition of the hydraulic unit, after cutting the permissible level η_{dop} at the time worked $t_1 \leq \tau \leq t_2$, does not cross until the level t_2 level η_{gr} with probability $p(t) \geq p_w$. Reaching the limit value by any control parameter enables the identification of assemblies that may soon reach the limit state. Any control parameter reaching the η_{gr} level limit, i.e. $\eta > \eta_{gr}$, means the end of the hydraulic unit's durability, i.e. the need to stop using it. It should be added here that in the case of renewable assemblies it can be subjected to a renovation procedure.

2. Description of the hydraulic unit control parameter change process

The following markings have been adopted in the following article:

$\eta(t)$ - random function of the control parameter,

η_{dop} -permissible value of the control parameter at random time T_{dop},

η_{gr} -limit value of the control parameter,

T_1 -time when the control parameter reaches the allowable level,

T_2 -time of checking the technical condition after exceeding the permissible level (residual durability range),

x -random time of intersection by the random function of the permissible control parameter η_{dop} or limit parameter η_{gr}.

The following assumptions were adopted for the description of the method for estimating the life of a hydraulic power unit:

1) Changes in the value of the control parameter for hydraulic power units are continuous over time and their transition from one state to another is the result of wear processes within the tribological pairs of such units.
2) The change of a hydraulic power unit control parameter η is a random process $\eta(t)$, ongoing under the influence of a wide spectrum of operating factors.
3) Data allowing for a formal description of the random process was obtained from the bench or operational tests.
4) At the design stage, the limit level ηgr of the hydraulic drive unit control parameter $\eta(t)$ was determined. The control parameter limit value does not change during the entire lifetime of the hydraulic assembly and is an impassable reference criterion.

To be able to estimate the durability of a hydraulic drive assembly, you must have a specific form of random variable distribution in the form of a probability density function.

Fig. 1 presents changes in the one-dimensional distribution density function $\phi(\eta, t)$ of the random control parameter and distribution density function $f(\eta_{dop}, t)$ of the intersection of the residual durability field border. Density function change courses divide drive life into three areas:

1) the area where the hydraulic assembly is in full working order,
2) the pre-emergency area in which there is a close relationship between the residual tolerance value of the controlled parameter and the periodicity of checks, while ensuring a given level of integrity,
3) border area, i.e. the area where the hydraulic assembly is in a state of inability to work.

Fig. 1 shows that for detecting - in good time - a pre-emergency (acceptable) state, the relationship between the periodicity of checks $\Delta\tau = t_2 - t_1$ and the preceding tolerance (residual durability) should be determined $\Delta\eta = \eta_{gr} - \eta_{dop}$ on the controlled parameter, while ensuring a given level of integrity. The moment of checking should be selected in such a way that $\eta_{dop} < \eta(T) < \eta_{gr}$.

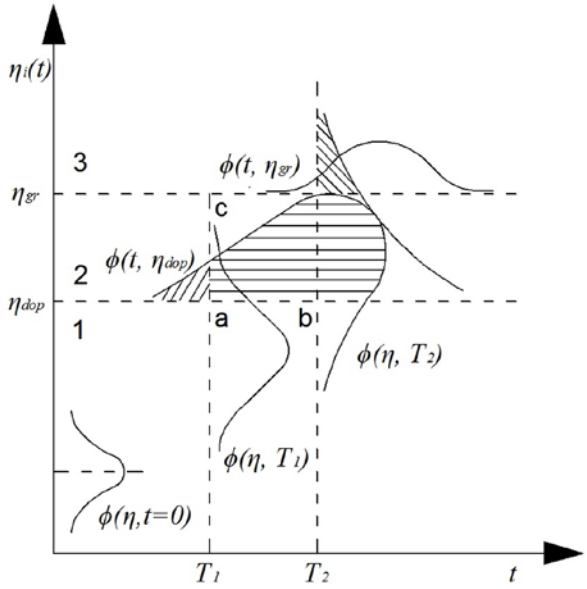

Fig. 1. The characteristics of hydraulic power unit lifetime for a random process η of this unit's control parameter change [Source: Own study]

For the control parameter level η_{dop} we have $x \leq T_1$ if and only if $\eta > \eta_{dop}$ and for the level η_{gr} we have $x \leq T_2$ if and only if $\eta \geq \eta_{gr}$. From here to the intersection of events at the level of η_{dop} we have $\{x \leq T_1\} \cap \{x \leq T_2\} = \{x \leq T_1\}$ if and only if for time T_2 we have $\{\eta > \eta_{dop}\} \cap \{\eta > \eta_{gr}\} = \{\eta > \eta_{gr}\}$. Therefore, we can note that:

$$P\{x \leq T_1\}_{\eta_{dop}} = P\{\eta > \eta_{gr}\}_{T_2},$$

which means that probability $P\{x \leq T_1\}$ at a permissible level η_{dop} is equal to the probability $P\{\eta > \eta_{gr}\}$ at moment T_2 of checking the technical condition after exceeding the permissible level. Hence:

$$\int_0^{T_1} f(x/\eta_{dop})dx = \int_{\eta_{gr}}^{\infty} \phi(\eta/T_2,)d\eta \tag{1}$$

where:

$f(x/\eta_{dop})$ - conditional density function of the random distribution of time x, provided that the control parameter has a value of η_{dop};

$\phi(\eta / T_2)$ - conditional random density function $\eta(t)$, provided that the working time has reached the time T_2 checking the technical condition after exceeding the permissible level.

Just like for equation, (1) equation for the permissible level η_{dop} at moment T_2 is derived:

$$\int_0^{T_2} f\left(x / \eta_{dop}\right) dx = \int_{\eta_{dop}}^{\infty} \phi(\eta / T_2) d\eta \tag{2}$$

Comparing the equation (1) to the equation (2), we get:

$$\int_{T_1}^{T_2} f\left(t / \eta_{dop}\right) dt = \int_{\eta_{dop}}^{\eta_{gr}} \phi(\eta / T_2) d\eta \tag{3}$$

The notation (3) indicates that for a monotonic random process $\eta(t)$ with a specified time T_1 and known limit level value η_{gr}, it is possible to determine the next technical condition inspection deadline T_2 and the permissible level value η_{dop} at that time. The following equation results from writing the equation (3):

$$\int_{T_1}^{T_2} f\left(t / \eta_{gr}\right) dt = \int_0^{T_1} f\left(t / \eta_{dop}\right) dt \tag{4}$$

The above equation shows that a change in the value of the selected control parameter, after crossing the permissible level η_{dop} at the time worked $t_1 \le \tau < t_2$, will not cross to the time t_2 level $_{gr}$. All trajectories of the process of the random control parameter passing from the *ab* area (see Fig. 1) to the *bc* area cause a change in the frequency of checking the hydraulic assembly.

Changes in the values of selected control parameters of a hydraulic assembly occur continuously over time and the transition of the hydraulic assembly from one state to another occurs as a result of wear processes of precise tribological pairs of these assemblies. Due to the fact that the occurrence of damage to a hydraulic assembly element is caused by accidental changes in the intensity of the wear process, a linear course of the wear process can be assumed. This allows us to describe the wear process of precise tribological pairs of the hydraulic assembly by normal distribution.

Let us assume that for normal distribution, the expected value $m_\eta(t)$ and the mean quantile deviation $\sigma_\eta(t)$ are approximated linear relationships:

$$\begin{gathered} m_\eta(t) = m_a + m_b t \\ \sigma_\eta(t) = \sigma_a + \sigma_b t \end{gathered} \tag{5}$$

Constant factors m_a and m_b in relationship (5) are determined with formulas:

$$\begin{gathered} m_a = \frac{t_{i+1}\, m_\eta(t_i) - t_i\, m_\eta(t_{i+1})}{t_{i+1} - t_i} \\ m_b = \frac{m_\eta(t_{i+1}) - m_\eta(t_i)}{t_{i+1} - t_i} \end{gathered} \tag{5a}$$

Factors σ_a and σ_b are calculated using similar formulas. Moment functions $m_\eta(t)$ and $\sigma_\eta(t)$ are determined from histograms of the distribution $\phi(\eta, t_2)$ (see Fig. 2 to 4).

Density function for the distribution $\phi(\eta, t_2)$ of the random value $\eta(t)$ at moment t_2 of the technical condition inspection, after exceeding the permissible level has the form:

$$\phi(\eta / t_2) = \frac{1}{\sqrt{2\pi}\,(\sigma_a + \sigma_b t_2)} exp\left[-\frac{(\eta - m_a - m_b t_2)^2}{2(\sigma_a + \sigma_b t_2)^2} \right] \tag{6}$$

Based on the relationship (4), the density function for the distribution of the first intersection of the residual life level $f\left(\eta_{dop}, t\right)$ has the form:

$$f\left(t / \eta_{dop}\right) = \frac{1}{\sqrt{2\pi}\,(\sigma_a + \sigma_b t)} exp\left[-\frac{\left(\eta_{dop} - m_a - m_b t\right)^2}{2(\sigma_a + \sigma_b t)} \right] \frac{d}{dt}\left(\frac{\eta_{dop} - m_a - m_b t}{\sigma_a + \sigma_b t} \right) \tag{7}$$

Substituting expressions (6) and (7) to equation (3), after differentiation and necessary transformations, we get the relationship η_{dop} and $\Delta\eta = \eta_{gr} - \eta_{dop}$ for normal distribution of the parameter:

$$\eta_{dop} = \frac{\eta_{\mathrm{gr}}(\sigma_a + \sigma_b T_1) - (m_b \sigma_a - m_a \sigma_b)\tau}{\sigma_a + \sigma_b T_1 + \sigma_b \tau} \tag{8}$$

$$\Delta\eta = \frac{\left[\left(\eta_{gr} - m_a\right)\sigma_b + m_b \sigma_a\right]\tau}{\sigma_a + \sigma_b T_1 + \sigma_b \tau} \tag{9}$$

The moment of the control parameter reaching the permissible level T_1, that is the moment of the first verification of the control parameter, can be determined using the condition of the assumed permissible level of failure-free operation P_{b_p}, as per the following expression:

$$P\{\eta < \eta \le \infty, t_1\} = \int_{\eta_{gr}}^{\infty} \phi(\eta / t_1) d\eta \le \delta_{dop} \tag{10}$$

where: $\delta_{dop} = 1 - P_{b_p}$ is the permissible damage probability.

By substituting the distribution density function $\phi(\eta, t_2)$, i.e. relationship (6) to expression (10), it is possible to determine the time of the control parameter reaching the permissible level T_1, i.e., that is the moment of the first verification of the control parameter, in the following form:

$$T_1 = \frac{\eta_{gr} - m_a - u_{P_{bp}} \sigma_a}{m_b - u_{P_{bp}} \sigma_a} \tag{11}$$

where: $u_{p_{bp}}$ is a normal distribution quantile corresponding to probability P_{b_p}.

The time of the first inspection of the hydraulic assembly as a whole (any control parameter reaching the permissible level) will be determined from the condition:

$$t_1 = \min\left(T_{1v}, T_{1p}, T_{1\delta}\right) \tag{12}$$

where T_{1V} , T_{1p} , $T_{1\delta}$ are selected control parameters of the hydraulic unit, e.g. maximum discharge pressure, volumetric efficiency coefficient, etc.

3. Estimating the rotary lifetime of a hydraulic piston pump

Rotary piston pumps with a distribution disc and adjustable output will serve as an example showing the determination of the time needed for a control parameter $\eta(t)$ to reach the permissible level (limited life range) and the time for conducting the technical condition inspection after exceeding the permissible level (monitored life range), as well as the permissible level η_{dop} of the control parameter $\eta(t)$.

The pump test procedure involves recording, among others, its such control parameters as the maximum pumping pressure p_{tmax} , volumetric efficiency factor ϑ_{vp} and the total radial clearance in piston pairs δ_p. The aforementioned parameters shall be treated as random values, i.e. $\eta_p(t_i)$, $\eta_v(t_i)$, and $\eta_\delta(t_i)$.

For fixed values of hydraulic piston pump operating time t_i of: 0 hrs, 500 hrs and 1000 hrs, each random value $\eta_i(t_i)$ has a determined empirical distribution density function $\phi(\eta_i, t_i)$, expected value m_i and mean quantile deviation σ_i . Stochastic parameters $\phi(\eta_i, t_i)$, m_i and σ_i for the control parameters, namely, maximum pumping pressure, pump volumetric efficiency factors and the total radial clearance in piston pairs were obtained following laboratory tests and verification inspections in the course of pump operation onboard an aircraft, the results of which can be found in the internal elaborations of the Air Force Institute of Technology. By substituting the values of control parameters to relationship (5a) and then the values of these coefficients to (5), we get the function of hydraulic piston pump parameter moments for the assumed pump operating time.

Histograms for distributions $\phi(\eta, t)$ and moment functions $m_\eta(t)$, $\sigma_\eta(t)$ for the maximum pressure are shown in Fig. 2, the hydraulic pump volumetric efficiency factor in Fig. 3, and the total radial clearances in hydraulic pump piston pairs in Fig. 4.

For the volumetric efficiency factor ϑ_{vp}, the hydraulic pump piston pair parameter moment functions will be:

$$m_{\eta_v}(t) = 0{,}942 - 0{,}000065 \cdot t$$

$$\sigma_{\eta_v}(t) = 0{,}024 + 0{,}000015 \cdot t$$

For the maximum pressure p_{tmax} in [Pa], the hydraulic pump piston pair parameter moment functions will be:

$$m_{\eta_p}(t) = \left(215{,}6 - 0{,}0031 \cdot t\right)10^5$$

$$\sigma_{\eta_p}(t) = \left(3{,}43 + 0{,}00054 \cdot t\right)10^5$$

For the total radial clearance in piston pairs δ_{pt} in [μm], the hydraulic pump piston pair parameter moment functions will be:

$$m_{\eta_\delta}(t) = 49{,}34 - 0{,}00973 \cdot t$$

$$\sigma_{\eta_\delta}(t) = 18{,}8 + 0{,}0012 \cdot t$$

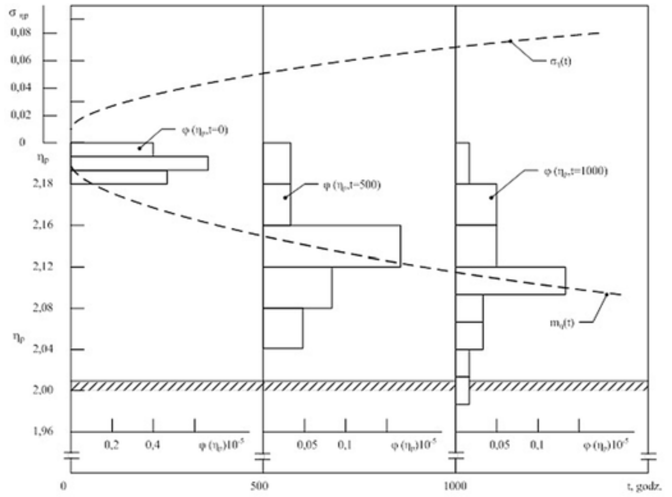

Fig. 2. Histograms for distributions $\phi(\eta, t)$ and moment functions $m_\eta(t)$, $\sigma_\eta(t)$ for the maximum pressure [Source: Own study]

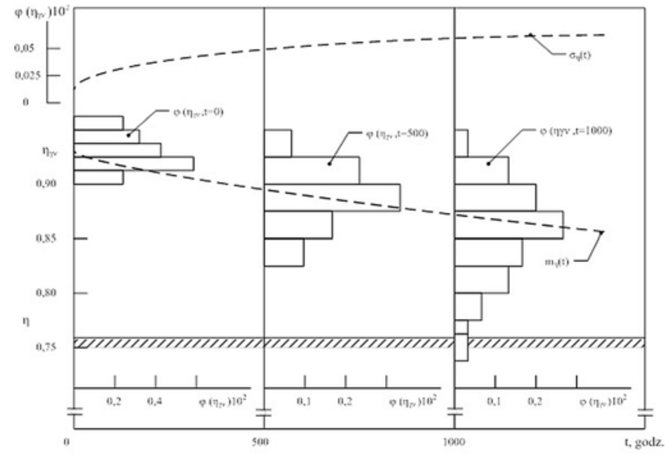

Fig. 3. Histograms for distributions $\phi(\eta, t)$ and moment functions $m_\eta(t)$, $\sigma_\eta(t)$ for hydraulic pump volumetric efficiency factor [Source: Own study]

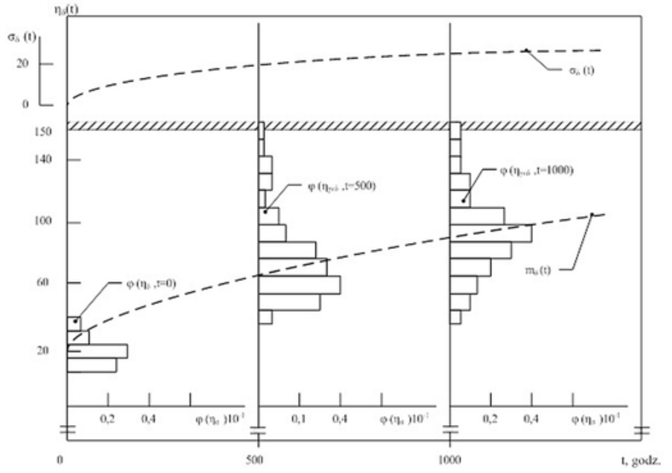

Fig. 4. Histograms for distributions $\phi(\eta, t)$ and moment functions $m_\eta(t)$, $\sigma_\eta(t)$ for hydraulic pump total radial clearances in piston pumps [Source: Own study]

Table 1. Output data for the determination of hydraulic pump control parameter moments

Parameters	η_{gri}	m_{ai}	m_{bi}	σ_{ai}	σ_{bi}
Pump volumetric efficiency factor	0,750	0,915	-0,000062	0,020	0,000012
Maximum pumping pressure [Pa]	$2000{,}9\cdot10^5$	$214{,}9\cdot10^5$	$-0{,}0033\cdot10^5$	$3{,}53\cdot10^5$	$0{,}00059\cdot10^5$
Total radial clearance in piston pairs [μm]	0,150	51,73	0,0397	18,5	0,0012

The limit levels in hydraulic pumps were determined for the volumetric efficiency factor, i.e. η_{grv}= 0.75, maximum pump pressure, i.e., η_{grp}= 200.9x10^5 Pa and the total radial clearance in piston pumps, i.e., η_{grv}= 0.150 μm. With known limit levels for control parameters and using formula (12), it is possible to determine the time for the control parameter to reach the permissible level, i.e., the moment of the first verification of the control parameter.

The output data for the determination of hydraulic pump parameter moment functions and the relationship $\eta_{dop}(t_i)$ are shown in Table 1. The verification of the hypothesis on normal distribution $\phi(\eta_i,t_r)$ using Kolmogorov's compliance test showed its compliance with optimal data.

The time for the control parameter of the pump to reach the permissible level due to its volumetric efficiency factor is $t_{1_{vp}}$ = 857 hrs, due to its maximum pressure $t_{1_{pmax}}$ = 1232 hrs, and due to its total radial clearances in piston pairs t_{1_δ} = 1326 hrs.

The time for the control parameter of the hydraulic pump to reach the permissible level shall be determined with (12):

$$t_1 = min(857{,}1232{,}1326) = 857\,\text{hrs}$$

Based on the output data shown in Tab. 1, using formula (8), it is possible to determine the relationship between the control parameter permissible level η_{dop} and the inspection periodicity for the pump parameters in question:

$$\eta_{dopv} = \frac{0{,}0263 + 0{,}00001243\cdot\tau}{0{,}0268 + 0{,}000012\cdot\tau},$$

$$\eta_{dopp} = \frac{(801{,}12 + 0{,}1502\cdot\tau)10^5}{4{,}02 + 0{,}0006\cdot\tau}\ [Pa],$$

$$\eta_{dop\delta} = \frac{2879 - 0{,}6879\cdot\tau}{18{,}95 + 0{,}012\cdot\tau}\ [\mu m].$$

Control parameter permissible value levels η_{dop} due to the pump's volumetric efficiency factor are shown in Fig. 5, due to pump's maximum pressure in Fig. 6, and due to the total radial clearance in piston pairs in Fig. 7.

The graphs presented in Fig. 5, 6 and 7 were made on the basis of calculations using the formulas (8) and (9) for functions and moments of distribution $\phi(\eta_i,t_i)$, m_i and σ_i control parameters for working time t > 500 hrs. They have they are for reference only. They present the nature of the change in the permissible level η_{dop} and the anticipating tolerance $\Delta\eta$ for the selected control parameter from the periodicity of checks τ.

For τ = 0, the allowable value of the selected control parameter reaches the limit value of this parameter, i.e. $\eta_{dop} = \eta_{gr}$ and the leading tolerance $\Delta\eta$ = 0. The end of life of the assembly is reached due to the specific control parameter. Based on the graph, e.g. the pump volume coefficient, we can determine the periodicity of checks due to

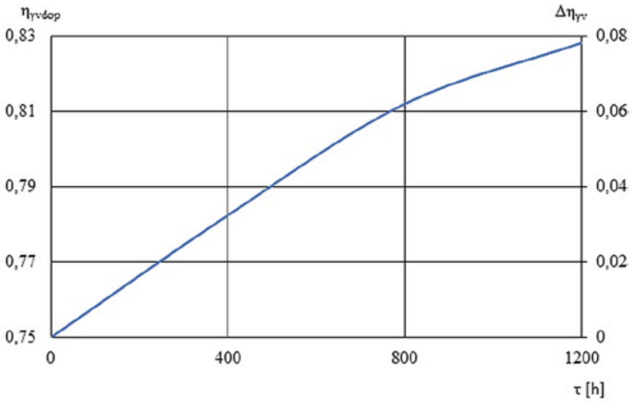

Fig. 5. Dependence of the permissible level η_{dop} and residual tolerance $\Delta\eta = \eta_{gr} - \eta_{dop}$ on verification periodicity τ the pump's volumetric efficiency factor [Source: Own study]

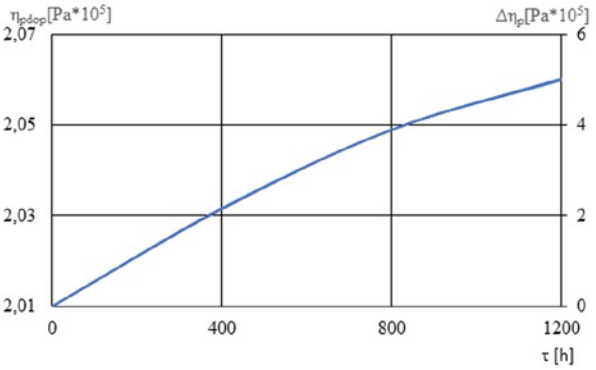

Fig. 6. Dependence of the permissible level η_{dop} and residual tolerance $\Delta\eta = \eta_{gr} - \eta_{dop}$ on verification periodicity τ for pump's maximum pressure [Source: Own study]

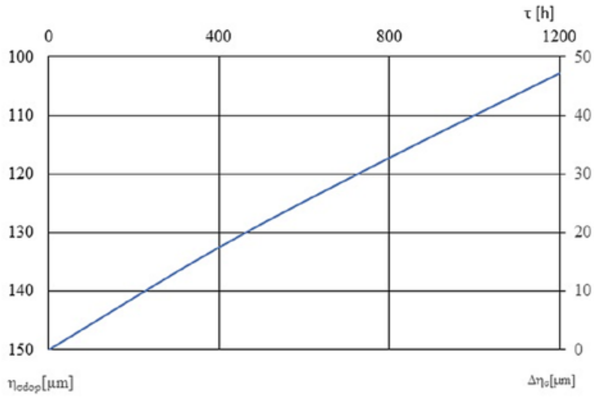

Fig. 7. Dependence of the permissible level η_{dop} and residual tolerance $\Delta\eta = \eta_{gr} - \eta_{dop}$ on verification periodicity τ for the total radial clearance in piston pairs [Source: Own study]

this parameter. If during the control the value of the volumetric efficiency coefficient will be 0.81, the time of the next inspection will be 800 hrs, while if the value of this coefficient would be 0.78, the time of the next inspection will be 400 hrs. changes the time of checking (checking).

4. Final remarks

The presented method for estimating life utilizes the property of aviation hydraulic power units, which involves a strong correlation between the parameters defining their fitness state with their operating time. It enables forecasting the hydraulic power unit limit state occurrence moment, provided that a periodic inspection of its technical condition using selected control parameters has been introduced. The purpose of this check is to detect in advance the pre-emergency (allowable) condition. In the presented method, the preceding tolerances use pre-tolerances of the selected control parameter.

The relationship between the preceding tolerance of the selected control parameter and the periodicity of its checks is presented, while ensuring the set level of a priori determined reliability of the hydraulic unit. The achievement of the pre-emergency (acceptable) level by the control parameter is associated with a change in the frequency of checks, i.e. $\Delta\tau = t_2 - t_1$ Pre-emptive tolerance size $\Delta\eta = \eta_{gr} - \eta_{dop}$ is related to the frequency of inspections $\Delta\tau = t_2 - t_1$ in such a way that the process of changing the selected control parameter that determines the technical condition of the hydraulic unit, after cutting the permissible level η_{dop} at the time worked $t_1 \leq \tau < t_2$ did not intersect the level η_{gr} until t_2 with a probability not exceeding the assumed probability of trouble-free operation of the team during $\Delta\tau$. Reaching the limit value by any control parameter enables the identification of assemblies that may soon reach the limit state. If any control parameter reaches the limit level η_{gr}, i.e. $\eta \geq \eta_{gr}$, it is necessary to stop using the hydraulic assembly.

Refinement of the presented method involves binding the general relationship expressing life (fitness time) with the physical mechanisms for hydraulic unit wear and degradation of controlled elements.

To implement the method, it is necessary to specify at the design stage the limit level η_{gr} of the parameter of the controlled hydraulic drive unit $\eta(t)$.

The presented method is applied in work aimed at determining the resource life of military aircraft hydraulic drives. The method enables utilizing technical equipment according to a technical state strategy with monitoring the parameters.

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