METHOD FOR ESTIMATING THE DURABILITY OF AVIATION HYDRAULIC DRIVES

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.

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

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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. If the load schedule, determined in the course of developing a given hydraulic unit or drive, includes the test program to simulate actual working conditions, 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 deviation of the test program from 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 functional properties of hydraulic units of an 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].
hydraulic control parameter $\eta$ exceeds the limit value $\eta_{dop}$ but does not exceed the limit value $\eta_{gr}$, i.e. $\eta_{dop} \leq \eta < \eta_{gr}$, then the hydraulic drive is considered to be in a pre-emergency condition. Reaching the admissible level of the control parameter is associated with the change of the control frequency, i.e. $\Delta t = t_2 - t_1$. Pre-emptive tolerance $\Delta \eta = \eta_{gr} - \eta_{dop}$ is related to the frequency of the check $\Delta t = t_2 - t_1$ 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 $\eta_{dop}$ at the time worked $t_1 \leq t \leq t_2$, does not cross until the level $t_2$ level $\eta_{gr}$ 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 $\eta_{gr}$ 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,
- $\eta_{dop}$ - permissible value of the control parameter at random time $T_{dop}$,
- $\eta_{gr}$ - 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 $\eta_{dop}$ or limit parameter $\eta_{gr}$.

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 $\eta$ 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 level limit $\eta_{gr}$ 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 irrefutable performance 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 control 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 $\Delta t = t_2 - t_1$ 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 $\eta$ of this unit’s control parameter change [Source: Own study]

For the control parameter level $\eta_{dop}$ we have $x \leq T_1$ if and only if $\eta > \eta_{dop}$ and for the level $\eta_{gr}$ 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 $\eta_{dop}$ 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:

$$P\{x \leq T_1\} = P\{\eta > \eta_{gr}\} / T_2$$

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

$$\frac{T_1}{\int_{\eta_{dop}} \int_{\eta_{gr}} f(x, \eta) d\eta = \infty} \phi(\eta / T_2) d\eta$$

(1)

where:

$$f(x, \eta)$$ - conditional density function of the random distribution of time $x$, provided that the control parameter has a value of $\eta_{dop}$.
Conditional random density function \( \phi(\eta / T_2) \) - provided that the working time has reached the moment \( T_2 \) - checking the technical condition after exceeding the permissible level.

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

\[
T_2 \int_{0}^{\infty} f\left( x / \eta_{dop}\right) dx = \infty \int_{\eta_{dop}}^{\infty} \phi(\eta / T_2) d\eta
\]

(2)

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

\[
T_2 \int_{0}^{\infty} f\left( x / \eta_{dop}\right) dx = \infty \int_{\eta_{dop}}^{\infty} \phi(\eta / T_2) d\eta
\]

(3)

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

\[
T_2 \int_{0}^{\infty} f\left( t / \eta_{gr}\right) dt = \infty \int_{\eta_{dop}}^{\infty} \phi(\eta / T_2) d\eta
\]

(4)

The above equation shows that a change in the value of the selected control parameter, after crossing the permissible level \( \eta_{dop} \) at the moment \( t_1 \leq T < T_2 \), will not cross to the time \( T_2 \) value \( \eta_{gr} \). 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:

\[
m_{\eta}(t) = m_a + m_{\eta} t
\]

\[
\sigma_{\eta}(t) = \sigma_a + \sigma_{\eta} t
\]

(5)

Constant factors \( m_a \) and \( m_{\eta} \) in relationship (5) are determined with formulas:

\[
m_a = \frac{n_{\eta}}{T_{1} - T_{1}} - m_{\eta}(t_{1} - t)
\]

\[
m_{\eta} = \frac{m_{\eta}(t_{1}) - m_{\eta}(t)}{t_{1} - t}
\]

(5a)

Factors \( \sigma_a \) and \( \sigma_{\eta} \) 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:

\[
\phi(\eta / t_2) = \frac{1}{\sqrt{2\pi(\sigma_a + \sigma_{\eta})^2}} \exp \left( -\frac{(\eta - m_a - m_{\eta}t_2)^2}{2(\sigma_a + \sigma_{\eta})^2} \right)
\]

(6)

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

\[
f(\eta_{dop}, t) = \frac{1}{\sqrt{2\pi(\sigma_a + \sigma_{\eta})^2}} \exp \left( \frac{(\eta_{dop} - m_a - m_{\eta}t)^2}{2(\sigma_a + \sigma_{\eta})^2} \right)
\]

(7)

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

\[
\eta_{dop} = \eta_{gr} \left( \frac{\sigma_a + \sigma_{\eta} T_1}{\sigma_a + \sigma_{\eta} T_1 + \sigma_{\eta} T} \right) - \left( m_b \sigma_a - m_a \sigma_{\eta} \right) T
\]

(8)

\[
\Delta\eta = \frac{\left( \eta_{gr} - m_a \right) \sigma_{\eta} + m_a \sigma_a}{\sigma_a + \sigma_{\eta} T_1 + \sigma_{\eta} T}
\]

(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 \( P_{\eta_{gr}} \), as per the following expression:

\[
P_{\eta_gr} = \int_{\eta_{dop}}^{\infty} \phi(\eta / t_1) d\eta \leq \delta_{dop}
\]

(10)

where: \( \delta_{dop} = 1 - P_{\eta_{gr}} \) 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:

\[
T_1 = \frac{\eta_{gr} - m_a}{m_{\eta} - u_{p_{\eta}} \sigma_a}
\]

(11)

where: \( u_{p_{\eta}} \) is a normal distribution quantile corresponding to probability \( P_{\eta_{gr}} \).

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:
where $T_{V'}, T_{p}, T_{δ}$ 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 $\eta_{dop}$ of the control parameter $\eta(t)$.

The pump test procedure involves recording, among others, its such control parameters as the maximum pumping pressure $P_{\text{max}}$, volumetric efficiency factor $\vartheta_{\eta}$, and the total radial clearance in piston pairs $\delta_{p}$. The aforementioned parameters shall be treated as random values, i.e. $\eta_{p}(t)$, $\eta_{t}(t)$, and $\eta_{δ}(t)$.

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 $m_{\eta}$ and mean quantile deviation $\sigma_{\eta}$. Stochastic parameters $\phi(\eta_{i}, t_{i})$, $m_{\eta}$ and $\sigma_{\eta}$ 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 $\vartheta_{\eta}$, the hydraulic pump piston pair parameter moment functions will be:

$$m_{\vartheta}(t) = 0.942 - 0.000065 \cdot t$$
$$\sigma_{\vartheta}(t) = 0.024 + 0.000015 \cdot t$$

For the maximum pressure $P_{\text{max}}$ in [Pa], the hydraulic pump piston pair parameter moment functions will be:

$$m_{\eta}(t) = (215.6 - 0.0031 \cdot t)10^5$$
$$\sigma_{\eta}(t) = (3.43 + 0.00054 \cdot t)10^5$$

For the total radial clearance in piston pairs $\delta_{p}$ in [$\mu$m], the hydraulic pump piston pair parameter moment functions will be:

$$m_{\delta}(t) = 49.34 - 0.00973 \cdot t$$
$$\sigma_{\delta}(t) = 18.8 + 0.0012 \cdot t$$
The limit levels in hydraulic pumps were determined for the volumetric efficiency factor, i.e. $\eta_{grv} = 0.75$, maximum pump pressure, i.e., $\eta_{grp} = 200.9 \times 10^5$ Pa and the total radial clearance in piston pumps, i.e., $\eta_{grv} = 0.150 \mu m$. 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 $\eta_{dop}(\tau)$ are shown in Table 1. The verification of the hypothesis on normal distribution $\phi(\eta, \tau)$, 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 $t_v = 857$ hrs, due to its maximum pressure $t_{p_{max}} = 1232$ hrs, and due to its total radial clearances in piston pairs $t_{\delta} = 1326$ hrs.

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

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

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 $\eta_{dop}$ and the inspection periodicity for the pump parameters in question:

$$\eta_{dop} = \frac{0.0263 + 0.00001243 \cdot \tau}{0.0268 + 0.000012 \cdot \tau},$$

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

$$\eta_{dop} = \frac{2879 - 0.6879 \cdot \tau}{18,95 + 0,012 \cdot \tau} \text{ [\mu m]}.$$

Control parameter permissible value levels $\eta_{dop}$ 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 $\phi(\eta, \tau)$, $m_1$ and $\sigma_1$ 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 $\eta_{dop}$ and the anticipating tolerance $\Delta \eta$ for the selected control parameter from the periodicity of checks $\tau$.

For $\tau = 0$, the allowable value of the selected control parameter reaches the limit value of this parameter, i.e. $\eta_{dop} = \eta_{grv}$ 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...
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 ensuring the set level of a priori determined reliability of the hydraulic unit. The achievement of the pre-emergency (acceptable) level by ensuring the set level of a priori determined reliability of the hydraulic unit. The achievement of the pre-emergency (acceptable) level by ensuring the set level of a priori determined reliability of the hydraulic unit. The achievement of the pre-emergency (acceptable) level by ensuring the set level of a priori determined reliability of the hydraulic unit. The achievement of the pre-emergency (acceptable) level by ensuring the set level of a priori determined reliability of the hydraulic unit. The achievement of the pre-emergency (acceptable) level by ensuring the set level of a priori determined reliability of the hydraulic unit. The achievement of the pre-emergency (acceptable) level by ensuring the set level of a priori determined reliability of the hydraulic unit. The achievement of the pre-emergency (acceptable) level by ensuring the set level of a priori determined reliability of the hydraulic unit. The achievement of the pre-emergency (acceptable) level by ensuring the set level of a priori determined reliability of the hydraulic unit.

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