EXAMINATION OF HYDRAULIC AMPLIFIERS IN THE ASPECT OF LIFETIME PREDICTION

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Abstract

The paper presents the lifetime analysis for a hydraulic amplifier and considers two types of the flow distributing devices, i.e. a linear distributing slider and a rotary slider. Description of essential properties associated with operation of distributing devices in hydraulic amplifiers is included with particular attention to analysis of processes that affect wear and tear of hydraulic amplifiers and influence quality of their operation. In that context a set of parameters that determine operation quality of hydraulic amplifiers was found out where mutual independence of the parameters, their unambiguousness and measurability served as the criteria for selection thereof. Two methods of analysis were used that took account for the foregoing assumption, i.e. the method of maximum informative capacity of the parameter and the method that assumes maximum alteration of the technical condition due to execution of the test. The completed examinations made it possible to find out characteristic curves for hydraulic amplifiers with a linear distributing slider as well as with a rotary slider with regard to their accumulated operation time. Further predictions of the hydraulic amplifier lifetime take advantage of the assumption that the deterioration effect of functional parameters attributable to hydraulic amplifiers is represented by a series of time-related values $\langle y_1, y_2, \ldots, y_n \rangle$*, i.e. a set of discrete observations* $\{y_1=\varsigma(\theta)\}$ *associated with an unsteady stochastic process* $\varsigma(\theta)$*. The relationships how functional parameters of a hydraulic amplifier vary in pace with its operation time t are described by means of the Gaussian distribution with the assumption that the course of a functional parameter deterioration corresponds to its aggregated characteristic curve that represents resistance of a distributing device embedded into a hydraulic amplifier to wear and tear processes. Wear of crucial parts within a hydraulic amplifier is measured in terms how functional parameters of that part associated with its accuracy, sensitivity and switching speed are getting worse and worse as time goes by.*

Keywords*: hydraulic amplifier, distributing slider, hydrodynamic radial force, insensitivity (dead) zone of a hydraulic amplifier, durability (lifetime)*

1. Introduction

Hydraulic amplifiers are widely used in control systems for modern aircrafts (airplanes and helicopters). Such a device is a powering tracking unit with its aim to convert the input signal (a mechanical or an electric one) into an output hydraulic signal that is proportional to the input function.

Hydraulic amplifiers that are installed in aircrafts perform very responsible functions therefore requirements imposed to those subassemblies in terms of their operational accuracy, speed and repeatability are really strict. It is required that hydraulic amplifiers incorporated into hydraulically-aided control systems should operate in a steady way, i.e. after each disturbance, in spite of its origin and range, it should restore its equilibrium. Accuracy, speed and steady operation of a hydraulic amplifier depend on excellence of its distributing unit, i.e. on robustness of the hydraulic precise pair in that distributing unit. Hydraulic amplifiers incorporated into hydraulically-aided control systems of aircrafts are operated under heavy-duty conditions and, as the operation time go by, various processes and factors exert adverse effect onto their durability and cut down their lifetime. These subassemblies are exposed to variable input functions with superposed disturbances, chiefly associated with variable effect of aerodynamic loads onto the aircraft rudder and elevator planes.

Knowledge of intensity how fast the parameters attributable to operation quality of a distributing device within a hydraulic amplifier are subject to deterioration serves as a basis to predict its lifetime and to appoint directions for its revamping.

2. Crucial factors that determine operation of a distributing device in hydraulic amplifiers

Hydraulic amplifiers employ two types of solutions for distributing devices. One of them involves a linear sliding unit where a cylindrical slider performs reciprocal to and fro movements with short displacement against the amplifier cylinder. Another type of a distributing device uses a flat slider that performs rotation movements with small rotation angles against the amplifier body.

The basic feature of operating condition and load to distributing components of sliding pairs is the fact that translocation of the slider against the amplifier cylinder (sleeve) is carried out at random moments of time and must be feasible despite the value and stability of the working fluid. The slider of the distributing sliding pair is affected by the following forces:

a) friction between the slider and the amplifier cylinder (sleeve),
b) hydrodynamic radial forces that are entailed by the pressure in the working gap (construction clearances) caused by flow of working fluid throughout the gap,
c) axial forces.

Friction between the slider and the amplifier cylinder (sleeve) depends chiefly on the design clearance of the sliding pair, smoothness of mating surfaces of the pair, viscosity of the working fluid or the material that the slider and the cylinder is made of [3]. Friction caused by hydrodynamic forces depend mainly on the differential pressure, manufacturing precision, i.e. how accurate geometrical dimensions of both the slider and the cylinder (sleeve) are shaped and their mutual alignment [4]. Under regular operating conditions the slider is hydraulically balanced. However, when displacement of the slider against the sleeve is initiated, the fluid stream flows through the gap that is left between the slider and the sleeve towards the internal channel of the sliding pair. It results in variability of pressure distribution inside the internal channel of the sliding pair. Due to effect of the fluid stream that flows into the internal channel of the sliding pair and pushes onto lateral surface of the slider working edges as well as due to pressure drops on those edges, the hydrodynamic axial force is originated. Research studies completed by authors of this paper serve as the proof that the hydrodynamic axial forces depend on the distance of the slider travel, radial clearance and pressure value [3, 5]. Variations of the axial force as the function of the slider travel are shown in Fig. 1. Variations of the axial force as the function of the slider travel at various working pressures are plotted in Fig. 2.

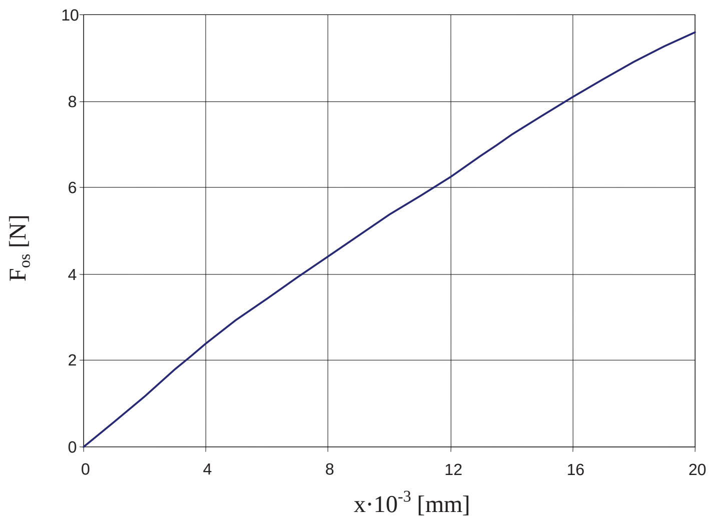

Fig. 1. Variation of the axial force F_{os} affecting the amplifier slider vs. its travel distance x

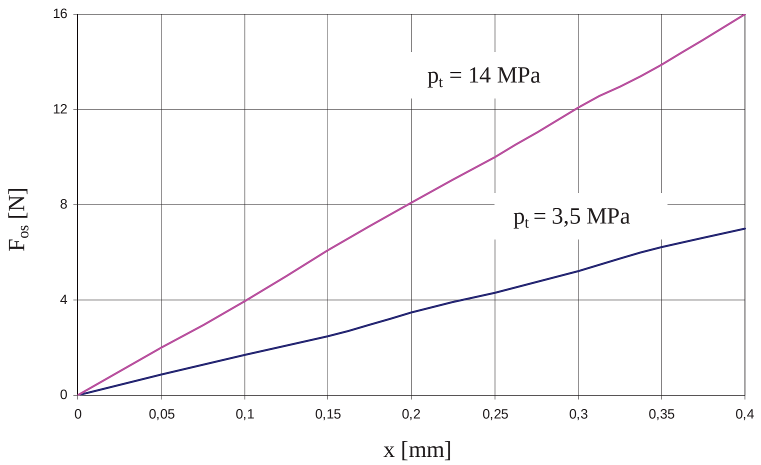

Fig. 2. Variation of the axial force F_{os} affecting the amplifier slider vs. its travel distance at working pressures p_t = 3.5 MPa i 14 MPa

With regard to criteria of load and kinematic features of the slider motion the distributing [3] device demonstrates the following properties:

1) slider motion is independent on delivery of working fluid that is supplied to a hydraulic precise pair,
2) even when the slider is in rest against the cylinder the working fluid continues to flow throughout clearances between components of the hydraulic pair,
3) relative speed of slider motions against the cylinder as well as the slider acceleration depend on values of control signals,
4) in case when pressure fluctuation of the working pressure may occur the slider is free of vibrations along the axial direction,
5) the hydraulic pair made up of the slider and the cylinder may be affected by unbalanced hydraulic forces that disturb stability of friction in the distributing device.

Moreover, when a distributing device with a flat slider is applied, the slider is depressed to the amplifier body by the force of a spring as well as by pressure of the working fluid.

3. Searching for a set of parameters that determine quality of hydraulic amplifiers

To designate a set of working parameters that determine the quality of hydraulic amplifiers it was necessary to adopt the criteria of their mutual independence, unambiguousness and measurability [2]. Classification of parameters took account for such their properties as the ability to reflect alterations in technical condition of the hydraulic amplifier, amount of information on technical condition, sufficient variability of the parameter value and vulnerability to alterations associated with gradual deterioration of functional parameters.

To distinguish the most representative parameters from among the set of initial parameters in order to reflect quality of a hydraulic amplifier two methods were applied: the maximum informative capacity of the parameter and the method that assumes maximum alteration of the amplifier technical condition due to execution of the test [2]. The method of maximum informative capacity consists in choice of such a parameter that provides maximum amount of information about technical condition demonstrated by the hydraulic amplifier. The more the specific parameter is correlated with alterations in technical condition of a technical device and, simultaneously, the less it is correlated with other parameters, the more important it is for determination of technical condition attributable to the hydraulic parameter in question. The method that supposes maximum change of the amplifier technical condition due to execution of the test assumes that such a parameter is to be selected that takes the maximum account for the average rate of the parameter variation due to execution of tests on the hydraulic amplifier.

Having taken account for the foregoing postulates as well as requirements to accuracy, sensitivity and switching rates of hydraulic amplifiers the following parameters were selected for determination:
- friction force of the distributing slider,
- travel speed of the actuating stem,
- internal leaks within the system supply – feedback of the distributing slider,
- insensitivity (dead) zone of the distributing slider.

Friction force of the distributing slider was measured by determination of the force that must be applied to the control lever of the distributing slider to achieve full displacement of the slider. The friction force of the distributing slider is made up of the following components: friction of the slider during collaboration with the orifice faces, hydrodynamic force that results from flow of the working fluid as well as the friction caused by the obliteration effect that appears in the working orifice.

Measurements of the switching rates were carried out with no external loads, with the unit jump as the input function and for maximum travel of the distributing slider.

Internal leakage of hydraulic amplifier were determined under basis of oil quantity which flows through the construction clearances (supply - return of the amplifier distributor) during specific time - in neutral position of the slide divider.

Insensitivity zone of the hydraulic amplifier can be measured by finding such a location of the control lever for the distributing slider that corresponds to travel speed of the amplifier stem not more than 0.1 mm/s to the both sides when the amplified is supplied with pressurized working fluid.

In the Air Force Institute of Technology there were investigations of hydraulic amplifiers BU-220 with the flat slider distributive device [6] and BU-51MS with the cylindrical slider distributive device [7] in terms of estimating of its sustainability.

The results of research of given amplifiers are presented on graphs 3-6.

Figure 3 presents variations of the friction force for the distributing slider of a hydraulic amplifier with a linear distributing slider (red line) and with a rotary slider (blue line) as a function of accumulated lifetime. For the sound condition of the amplifier the friction force should never exceed 21 N.

Figure 4 presents variation of the travel speed for the actuating stem of a hydraulic amplifier with a linear distributing slider and with a rotary slider as a function of accumulated lifetime. The travel speed for the actuating stem should range from 55 to 65 mm/s.

Figure 5 presents variation of internal leaks demonstrated by a hydraulic amplifier with a linear distributing slider and with a rotary slider as a function of accumulated lifetime. Internal leaks should not exceed 300 cm^3/min.

Figure 6 presents variations of the insensitivity zone demonstrated by a hydraulic amplifier with a linear distributing slider and with a rotary slider as a function of accumulated lifetime. The insensitivity zone should range from 0.25 mm to 0.40 mm.

4. Prediction of the total lifetime estimated for a hydraulic amplifier as a function of its operation time

One of possible methods that enable prediction of the total lifetime anticipated for hydraulic amplifiers makes use of historical variations demonstrated by its parameter(s) that reflects the amplifier quality in pace with accumulated lifetime of the unit. The presumption is used that the deterioration effect of the functional parameter attributable to the amplifier is represented by a time-dependent series of values $\langle y_1, y_2, \ldots, y_n \rangle$, i.e. a set of discrete observations $\{y_1 = \varsigma(\theta)\}$ associated with an unsteady stochastic process $\varsigma(\theta)$.

Time-dependent deterioration of the functional parameter y associated with the hydraulic amplifier (i.e. intensification of the wear effect) is the rate of the parameter variations

$$\upsilon = \frac{dy}{dt} = f(y). \tag{1}$$

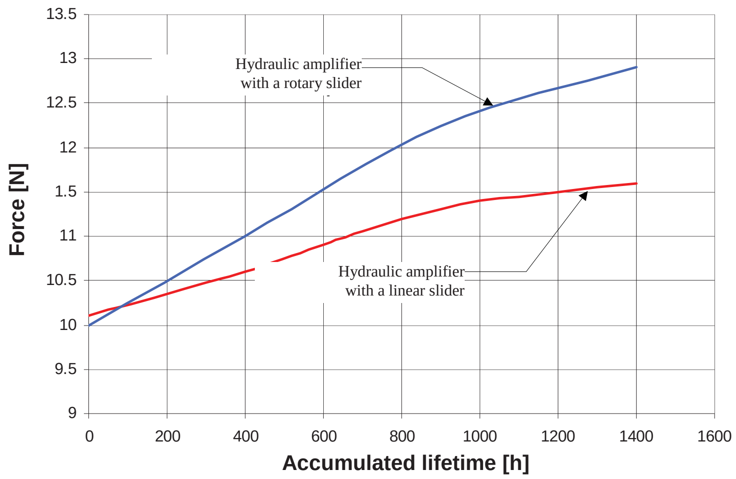

Fig. 3. Variations of the friction force for the distributing slider of a hydraulic amplifier with a linear distributing slider and with a rotary slider as a function of accumulated lifetime

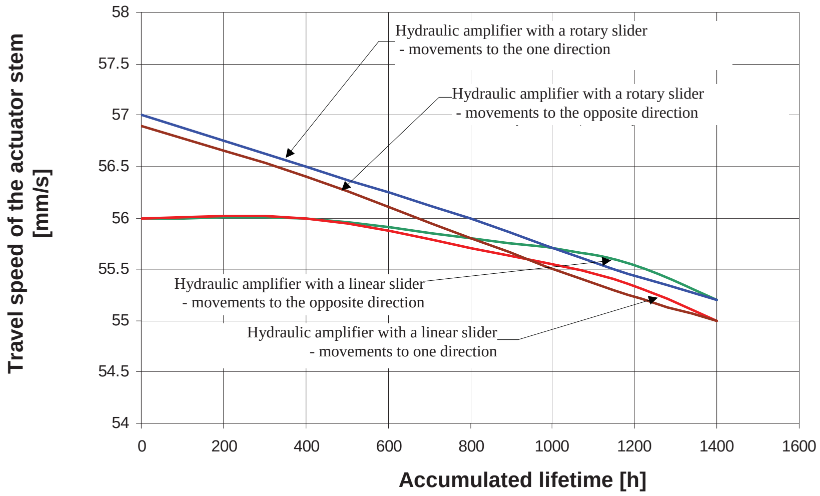

Fig. 4. Variation of the travel speed for the actuating stem of a hydraulic amplifier with a linear distributing slider and with a rotary slider as a function of accumulated lifetime

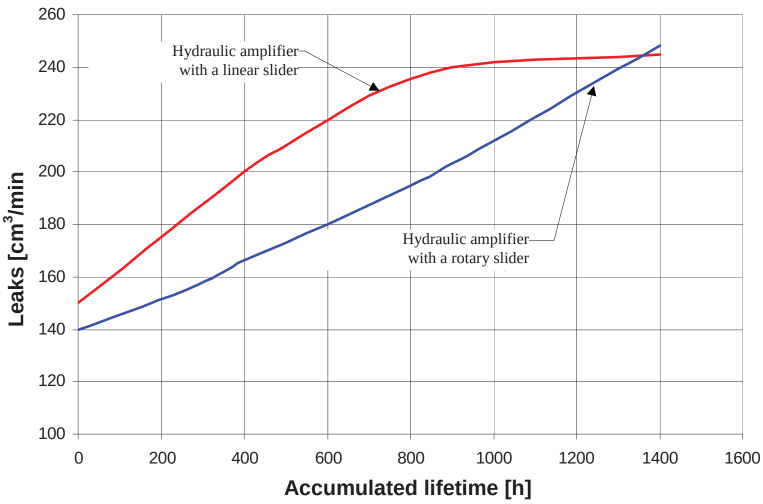

Fig. 5. Variation of internal leaks demonstrated a hydraulic amplifier with a linear distributing slider and with a rotary slider as a function of accumulated lifetime

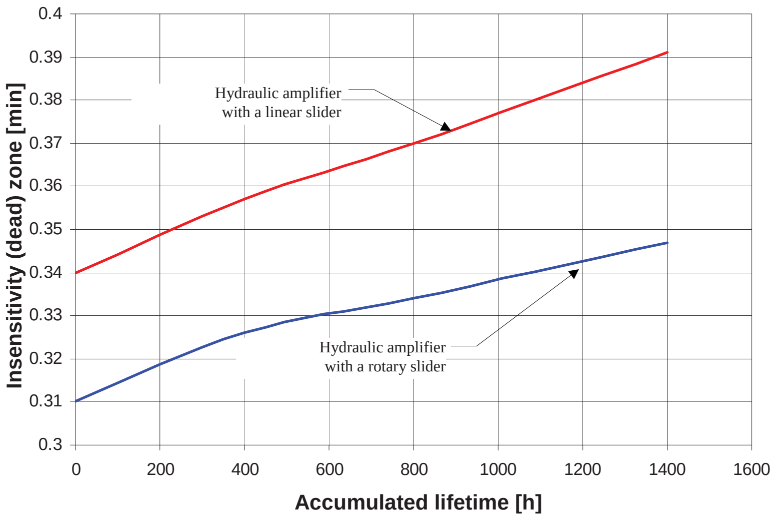

Fig. 6. Variations of the insensitivity zone demonstrated by a hydraulic amplifier with a linear distributing slider and with a rotary slider as a function of accumulated lifetime

Actually, the wear rate for the sliding pair of the distributing device is a function of many variables that can be generally considered as random parameters. Prediction of the hydraulic amplifier lifetime imposes the need to know how the functional parameters have varied during the examination time and which distribution of random variables, i.e. the function of probability densities vs. time, may apply. Description of functions for distribution densities $f(y,t)$ (under the assumption that for the specific population of hydraulic amplifiers the distribution function is the Gaussian distribution) as well as functions for moments of functional parameters, i.e. its expected value $m_y(t)$ and the standard deviation $\sigma_y(t)$ can be found in [5].

When the variation rate for the functional parameter y is constant (intensification of the wear and tear effect is steady over time) the linear model of the parameter variation can be applied to specific implementation. This linear model is represented by the following relationship:

$$\upsilon = \frac{dy}{dt} = c + ky\,, \tag{2}$$

where:
$k = tg\,\varphi$ - φ is the slope angle for implementation of the functional parameter whilst
c - stands for displacement of the functional parameter.

By transformation of the above equation, integration of the left and right sides respectively by time and growth of the wear effect and under assumption that after the lifetime of t_1 the average alteration of the functional parameters is y_1, the following relationship is obtained:

$$t - t_1 = \frac{1}{k} \ln \frac{c + ky}{c + ky_1}\,, \tag{3}$$

$$y = \left(y_1 + \frac{c}{k} \right) e^{(t - t_1)k} - \frac{c}{k}\,. \tag{4}$$

Let us substitute $\frac{1}{k \ln e} = A$ and $\frac{c}{k} = h$ and replace the natural logarithm with the common one. The equation adopts the form:

$$y = (y_1 + h) 10^{\frac{t - t_1}{A}} - h\,. \tag{5}$$

The A parameter is the lifetime coefficient (determines shape of the curve for deterioration of the functional parameter attributable to the amplifier) whilst h is the translation coefficient (determines location of the curve).

The upper limit for the process associated with deterioration of the functional parameter attributable to the amplifier can be found out from the equation:

$$y_{\max} = (y_1 + \sigma_1 + h)10^{\frac{t-t_1}{A}} - h\,, \tag{6}$$

whilst the lower limit is defined in the following way:

$$y_{\min} = (y_1 - \sigma_1 + h)10^{\frac{t-t_1}{A}} - h\,, \tag{7}$$

where:
y_{max} - current upper limit,
y_{min} - current lower limit,
σ_1 - standard deviation for deterioration of the functional parameter over the time interval t_1.

Coefficients A and h can be found out from the following relationships:

$$A = \frac{t_2 - t_1}{\lg \frac{\sigma_2}{\sigma_1}}\,, \tag{8}$$

$$h = \frac{y_2 - y_1 \frac{\sigma_2}{\sigma_1}}{\frac{\sigma_2}{\sigma_1} - 1}\,, \tag{9}$$

where:
y_2 - stand for average alterations of the functional parameter in the moment of t_2.
σ_2 - standard deviation for the moment of t_2.

When the statistical moments, i.e. the expected value $m_y(t)$ and the standard deviation $\sigma_y(t)$ for the functional parameters of the amplifier are known it is possible to find out the average value $y_{śr}$ for the parameter variation as well as confidence intervals for deterioration of that parameter.

Table 1 summarizes average values of $y_{śr}$ for alteration of the functional parameter after 1400 hours of operation and current limits y_{max} and y_{min} for variation of that parameter when a hydraulic amplifier with a distributing unit for cylindrical slider and flat rotary slider is considered.

Tab. 1. Average values $y_{śr}$ for alteration of the functional parameter after 1400 hours of operation and current limits y_{max} and y_{min} for variation of that parameter when the hydraulic amplifier incorporates a distributing unit with a rotary flat slider and a cylindrical slider

Functional parameter		Unit	Average value for alteration of the functional parameter $y_{śr}$		Current limits for variation of the functional parameter			
					upper limit y_{max}		lower limit y_{min}	
			rotary flat slider	cylindrical slider	rotary flat slider	cylindrical slider	rotary flat slider	cylindrical slider
Friction force of the distributing slider		N	11.5375	11.15	14.2625	12.05	8.4625	9.05
Travel speed of the actuating stem	to left	mm/s	56.04	55.72	57.96	56.28	54,36	54,68
	to right		55.88	55.62	57.92	56.38	54,12	54,38
Internal leaks within the system supply – feedback of the distributing slider		cm^3/min	185.357	225.175	310.64	264.825	94.64	74.825
Insensitivity zone of the distributing slider		mm	0.3293	225.175	0.36475	264.825	0.29075	0.3155

References

Changes in functional parameters of hydraulic amplifier during random time can be described using normal distribution under assumption that worsening process of the parameter includes full probabilistic resistance characteristic of distributive hydraulic amplifier device on consumption. Important matter during determining the present functional parameter value is that the worsening process is similar to average process. For practical use of the functional parameter density function you should use the real changes processes of functional parameter as a function of working time. By knowing the real value of the amplifier functional parameter y you can distinguish: expecting value $m_y(t)$, average square deviation $\sigma_y(t)$, average value of parameter change $y_{śr}$ and the trust divisions of the worsening process during specific time.

The knowledge about the degradation intensity of characteristic work quality parameters of hydraulic amplifier distribution device is a base of its lasting prediction.

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