30th Congress of the International Council of the Aeronautical Sciences
DCC, Daejeon, Korea ; September 25-30, 2016

IMPROVING THE EFFICIENCY AND RELIABILITY ASSESSMENT TECHNICAL STATE LIQUID SYSTEMS AIRCRAFT DURING ACCEPTANCE TESTS

Albert M. Gareyev, Yuliya P. Zlobina, Ilya A. Popelniuk
Samara State Aerospace University
gareyev@ssau.ru; yulya_zlobina11@mail.ru; osni204@yandex.ru

Keywords: *mathematical model, hydraulic system, hydraulic fluid, contamination.*

Abstract

The mathematical model of changes of complex technical systems deflated by the parameters of the working environment is reviewed in the article.

1 Introduction

Implementation of technology automatic test and state estimation of the diagnosed object on acceptance tests is one of the most prospective areas in the world for development of after-sale service system of complex technical systems (CTS).

It is based on collection and processing of data about current process in real time. It allows estimating the dynamics of running-in mechanisms and timely preventing their degradation.

But for the effective implementation of this technology it is necessary to have appropriate methods, means to diagnose and monitor of complex technical systems state and technologies of them realization, allowing to obtain the right information in real time. Analysis of hydraulic fluid can be one of these methods as complex technical systems working medium.

Any complex technical system can be described like a complex of interacting units. Each set of interacting units forms a single hierarchical level. It supposes characteristic description in the language of the space state with variable parameters belonging to that particular level. Interactive options at a higher hierarchical level are resulting moments processes dynamics taking place in the lower level. Higher level receives selective information of the lower level and in turn controls the dynamics at a lower level with regard anticipatory.

2 Mathematical models

Suppose that system *X* is given, including a set of friction units, which is placed in system *Y*. System *X* is defined as a set of interacting units, which give a very complex conduct of the experimental system *Y* by changing one or more parameters over the time, for example, a change of the mechanical impurities concentration in hydraulic fluid.

The physical system Y simulates a physical system *X*, if the system *Y* within the maintenance system can build the algorithm for the minimum length of a compressed the systems *X* description from the received time series, related to particles of final length contamination. These algorithms describe output behavior of the system *X* in time. Thus, the simulation is constructing of ‘if-then’ scripts that should show the state of the system *X*.

In order to system *Y* can reproduce (simulate) system *X* (or vice versa) a number of essential conditions are required.

First of all, the system must be hierarchical, i.e. to have, at least, *H*-level of hardware implementation (energy structural level) and *S*-level of software – symbol (cognitive), function level. The data in the form of discrete time series come from *S*-level of system $X(S_2)$ on *H*-level of system $Y(H_1)$, where a number of cross-correlations occur between accepted time series and internal dynamics of system *Y* on *H*-level. In the result of such convolution some collective property is sprang up, which has a much smaller number of degrees of freedom than level S_2 or H_1. This collective property is sent to S_1-level and form there the same complex state.

Thus, the connection between system *Y* and system *X* is carried out as system time evolution of two related nonlinear integral equations

$$S_1 = H_1 \otimes S_2, \quad S_2 = H_2 \otimes S_1, \tag{1}$$

where each pair correspond to one of statistical moments. The process for each pair of equations is reduced to a continuous iteration.

Consider a system as a complex of interacting units (for example, generators of contamination introduction particles), the number of which is not necessarily large (three interacting components may be enough to create a very complex behavior of experimental system.

It is known that systems with many degrees of freedom are stochastic. In turn, stochastic systems (macroscopic systems, whose dynamics is determined by the interaction of a great number of microscopic parts) de-facto hierarchical in the sense that allow the additional description, at least at two different levels: (1) at the microscopic level, where a very large number of particles cooperate on the basis of the Hamiltonian dynamics, and (2) at the macroscopic, phenomenological level, on which the system can be described by a small number of macro variables, such as volume, pressure, temperature, viscosity. These macro variables appear as the collective properties of dynamics, occurring at the microscopic level, or as moments of the probability density function, replacing the microscopic dynamic.

Here, according to [1] it is appropriate to consider how averaging processes occur by which there is a rise from a lower (microscopic) level to a higher (macroscopic) level. The considered system in the state space can be represented in the form of *N*-dimensional vector *x*, the end of which describes a continuous curve – trajectory – and at a given time *t* is located at the predetermined coordinate or at the predetermined condition. Let *P(x, t)* be the probability of finding the system at the point *x* in time *t*. It is required to find how this probability density function evolves in time. The probability *P(x, t)* increases due to the transitions from the other points *x*' and decreases due to the transitions emanating from the coordinate (state) *x*, i.e. $dP(x;\, t)/dt$= 'the arrival rate' – 'the drift rate' = I-I' [2].

The article *I* takes into account all the transitions of the starting points $x' \to x$ and it is a sum over all starting points x', multiplied by the probability to make the transition per unit time $x' \to x$. Thus,

$$I = \sum_{x'} W(x, x') P(x'; t), \tag{2}$$

where *W(x, x')* – probability to make the transition $x' \to x$ per unit time.

For the 'incoming' transitions (I'), the relation is right

$$I' = P(x;t) \sum_{x' \neq x} W(x, x'), \tag{3}$$

where *W(x, x')* – the probability to make the transition $x' \to x$ per unit time.

Thus, the equation, describing the probability evolution *P(x; t)*, has the form

$$\frac{dP(x;t)}{dt} I = \sum_{x'} W(x, x') P(x'; t) - P(x;t) \sum_{x' \neq x} W(x', x), \tag{4}$$

Consider the equation (4) from the point of view of how to use this equation for moving from the microscopic to the macroscopic description. Multiplying both sides of equation (4) by *x* and integrating or summing over the corresponding interval *x*, we obtain the dynamic equation, the left part of which describes the median <*x*> time rate of change, namely:

$$\frac{d}{dt}\langle x \rangle = f_1\{\langle x \rangle, \langle x^2 \rangle, \ldots\}, \tag{5}$$

where f_1 – is the non-linear polynomial.

The averaging process described above leads to the right part of the equation, not only the median <*x*>, but also higher moments of the probability *P(x, t)*. If the function $f_1$would be linear, the equation (5) would have the form $\frac{d\langle x \rangle}{d} = f_1(\langle x \rangle)$.

The proposed approach is typical of chemical reactions, usually proceeding in the medium *Y* under the influence of factors, formed by system X (e.g. under the temperature influence).

However, it is necessary to solve the task of studying changes in the mechanical impurities concentration, which is mostly used to evaluate the medium Y for operational suitability. For that we consider hypotheses as combinations of certain non-derivative elements for configurations and images making, which are components. The set of components is the basis of the process images creation, representing subject of inquiry within the exact formalism. The components from common positions represent the elements of images, which store information about it [2].

The set of all components A consists of disjoint classes of components A^{α}, $A^{\alpha}\subset A$, where α – the overall index, the index of the components class,

$$A=\bigcup_{\alpha} A^{\alpha}, A^{\alpha} \qquad (6)$$

The aim of this fragmentation is to show that the qualitatively similar components will be referring to the same class.

To create specific image it is necessary to institute the certain principles, which limit the connection methods of established components. These principles lead to a typical images regularity and represent its combinatorial structure.

Received regular configurations are abstract constructs, not necessarily observed in all details. The identification accuracy of regular configuration depends on the visualization system. Observation results, corresponding to some set of regular configurations, are called the image.

The image corresponds to the results of monitoring under perfect conditions, if the observation isn't be influenced by limitations of using equipment or model imperfection. The image theory, not considering the conduct of images in real conditions, has a very limited application. Therefore, it is necessary to ensure the actuality of the theory so that it can operate with real images. In other words, the interest for consideration within the framework of the studied processes is the process of converting 'ideal' images in real by some deformation mechanism.

For every such possible connection there is a connection indicator, usually denoted by the symbol β with the corresponding subscript.

A number of relations of every components a, appropriately numbered, form a component relation structure. The relations structure does not determine parameters values that are assigned in accordance to separate connections.

In addition to the properties of components a name or identifier is also needed to distinguish between the components.

In some cases, it may be necessary a certain component, entering in one and the same configuration more than once. Then we select identical copies of this component, which differ in identification labels, entered in indicator as constituents. From the context it will be clear when it is done.

The components are considered as indivisible units, however, sometimes splitting into smaller units is allowed. However, according to [2] it is sometimes quite objects, that are a formal description of the image at a certain level, consider components in the formalism of a higher level.

Universal operators are considered as more general multi-dimensional analogue. Every component is operator with v (variable) inputs $x_1,x_2,\dots,x_v$ and μ (variables) outputs $y_1,y_2,\dots,x_{\mu}$. Value range of any x_i is some space X_i, value rage of any y_i – some space Y_i.

In the case of operators with random variables we suppose that the sources of components Markov probabilistic source is used to represent condition changes of hydraulic fluid.

For the scientific substantiation of the hydraulic fluid condition we set up a hypothesis describing the environment processes 'source of components – hydraulic fluid' in terms of images theory. For this purpose it is necessary to choose a set of components A, defining the processes in this environment.

Consider the situation, when the arity of the configuration is not limited. The output arity of each component is equal to unity, but the input arity can be equal to a random non-negative quantity. On the set of components tree topology can be entered, at which output connection of some component (possibly) is connected by an irreversible arrow with one of the input connections of other component. It amounts to that $\omega_{out}(c)$ is always equal to unity, whereas $\omega_{in}(c)$ may be arbitrary and unlimited [3].

Using image theory, for clarity, we construct the graph of condition changes of hydraulic fluid by changing concentration of mechanical impurities. For this it is necessary to define indivisible image components. Take the following components:

- the change of physico-chemical properties;
- the filtering of impurities in the system;
- the total amount of contamination;
- the filtration indicator of filter 1;
- the filtration indicator of filter n;
- the contamination from plunger pairs;
- the contamination, resin;
- other contamination.

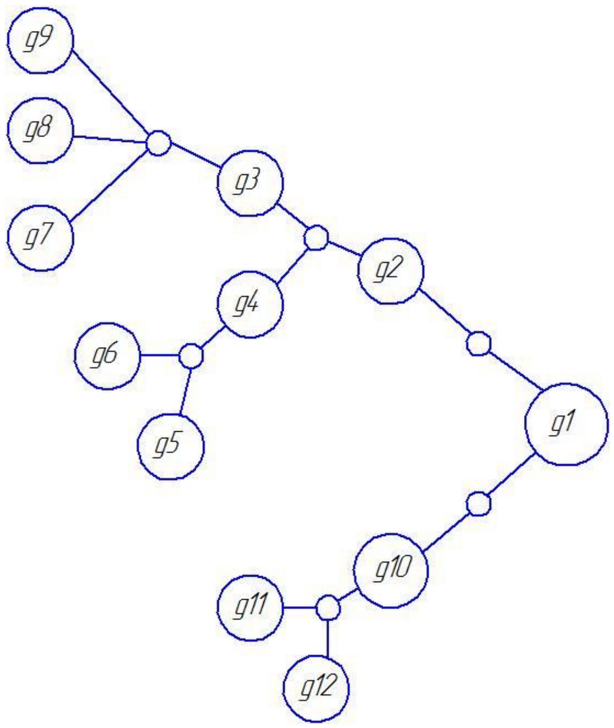

Fig. 1 Formal configuration of hydraulic system condition change

So the component g_1 represents the condition of hydraulic fluid, changing during the maintenance in the parameters of contamination and physico-chemical properties. The input connections for this component are the actual range of above-mentioned parameters. Changing the oil contamination represents two components: g_4 – the introduction of contamination in the system; g_3 – the filtering of contamination in the system. The actual range g_3 is defined by actual range of three components, which is the pollutant individually and: g_7 – the plunger pairs; g_8 – the gumming, g_9 – other contamination.

The actual range of the component g_3 illustrates contamination cleaning process by filters, installed in the system. The range definition of this component depends on filtration parameter and filter contamination degree of the system. For a given image suppose that the system has two filters: filters of delicate and deep cleaning, which are the components g_5 and g_6.

The component g_{10} is the changes of hydraulic fluid physico-chemical properties, splitting into viscosity g_{11} and acidity g_{12}.

The object, diagnosed during the supporting, can be represented as the environment of indicators, characterizing this object. This environment represents the product of indicator sets A_v (where v – the total intensity generation of fluid contamination λ_{Nc}).

The algebra of sets a^v is given for v-indicator to each indicator A^v, which show the fullness of information in touch input Y. At the same time each derivable vector of configuration condition multiplex for specialist P based on a_v – measurable sets and received subvectors for each components $u=u(g_j)$ during the time $t=\sum_{i=1}^{n}\Delta t_i$. $a^v(g)$ go into the analog-digital converter from sensor built-in control, situated in service tank of fluid system. Then the signal comes in the union of indicators φ_j^v, belonging to the algebra of sets a^v, and is transmitted as a sensory subvectors $u^{\lambda_{Nc}}$, which are multiplexed in 2 times and is sent to the network (main processor) N [2].

Contamination concentration of diagnosed object is transformed with built-in control sensor in electric signal, which is supplied to an electronic unit for processing after amplification and shaping and then is output to the detector and is used as a control in a closed system of automatic management and control.

Researchers have discovered that the most responsive during diagnosed contamination concentration of hydraulic fluid in complex technical system in real time is photoelectric method with photoelectric integrated control sensor of fluid mechanical impurity.

Information about mechanical impurity concentration by size groups and dispersed structure of mechanical impurity particles is formed in built-in control sensor and turn into the input-output device in the form of a random bell-shaped pulse. Their amplitude *Ω* is connected with the particles *d* size by quadratic dependence:

$$\Omega = k \cdot d^2,$$

where *k* – the sensor calibration.

very informative, i.e. p has a powerful hardware, and then the algebra of sets is accurate in the technical sense of the word, and vice versa.

Among the sets belonging to the algebra of sets a^v, select non-empty sets that do not contain their own subsets; of course, the number of such sets is finite.

We denote them via φ_1^v, $\varphi_2^v, \varphi_3^v \dots$. Moreover, according to [3], the set $F \in a^v$ may be represented as the union of sets φ_j^v. In [2] it is proved that these sets φ_j^v connect with a^v.

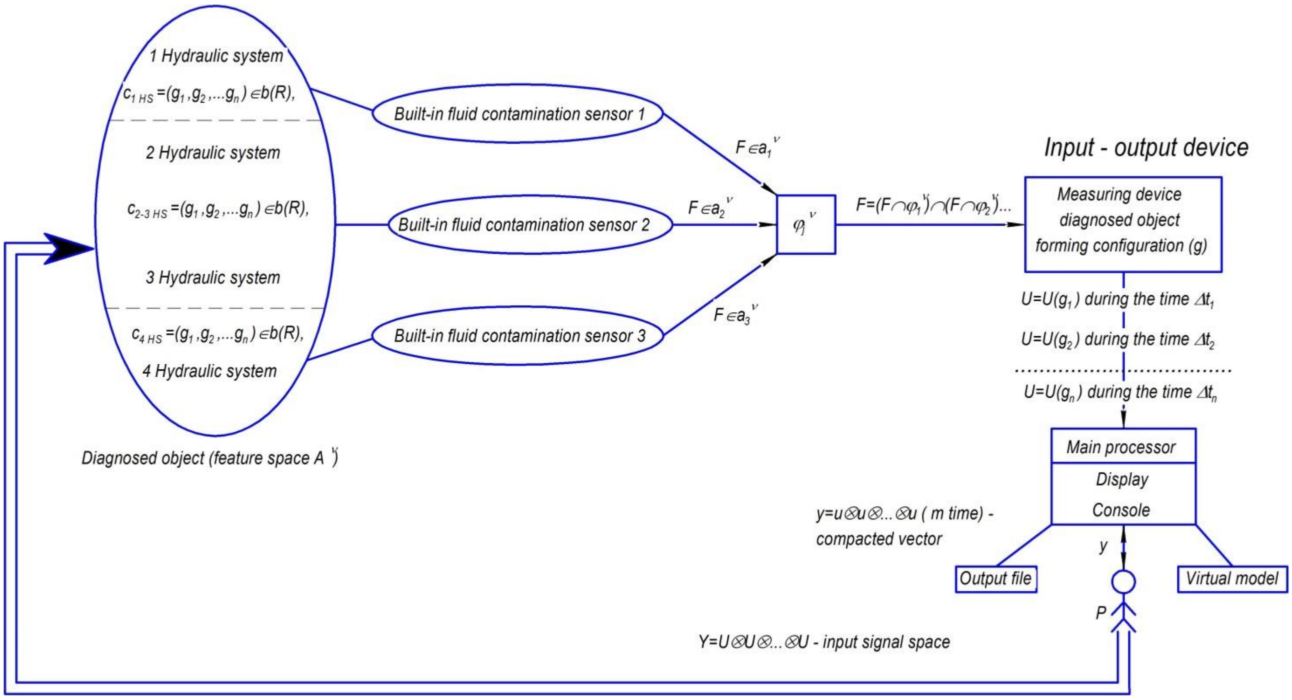

Fig. 2. The architectural scheme of hydraulic fluid diagnosis in complex technical system

Input-output device analyzes the generated pulse sequence, and issues results in digital or analog form on the liquid crystal display. The measuring results of the particles parameters are presented to the observer specialist *p*. Furthermore, the results are being recorded in the file.

For the indicator of each type *v* on A^v some algebra of sets a^v, inducing *A* algebra-product, is given:

$$a = a^1 \times a^2 \times a^3 \dots .$$

The algebra of sets has the following interpretation: it shows how information, contained in the touch input is detailed. If it is

Indeed, many A^v is the union of all sets φ_j^v, because

$$k = A^v \cap \left(\varphi_1^v \cup \varphi_2^v \cup \varphi_3^v \dots\right)^c \neq \varnothing;$$

a^v- measurable set *k*, which can suppose splitting into smaller a^v- measurable sets, as in this case it would be equal to some set φ_j^v.

On the other hand, it can't be represented as the union of $\varphi_1^v \cup \varphi_2^v \cup \varphi_3^v \cdots$, because

$$k = \varphi_1^v \cup \varphi_2^v \cup \dots \left(\cap \left(\varphi_1^v\right)^c \cap \left(\varphi_2^v\right)^c \dots\right) = \varnothing.$$

Therefore, $k = \varphi$, and therefore

$$A^v = \varphi_1^v \cup \varphi_2^v \cup \dots$$

Then, for any a^v-measurable set F, owned A^v, we get

$$F=\left(A^v \cap F\right)=\left(F \cap \varphi_1^v\right) \cap \left(F \cap \varphi_2^v\right) \cap ...$$

In addition there is $\varphi_j^v \subseteq F$ or $\varphi_j^v \cap F = \varphi$, because the sets are not amenable to fragmentation.

In addition there is any, or because the set can't be partition. It means that the items, belonging to the union, are equal to some set φ_j^v, or this items are empty sets.

Touch vector of particular component $u=u(g)$, described above, influences the network N of diagnostic control system of liquid system state over a period of time. Firstly g_1 is represented $u(g_1)$ and delivered to the network N within a certain period of time, then g_2 is represented $u(g_2)$ and delivered to the network N, etc. Aside from this algorithm a scanning configuration is allowed, when p attempt to estimate configuration state as a single whole.

It amounts to that the configuration, where $n>1$, appears as a set intensity of particle generation contamination. The vector u as a time function is some periodic function, e.g. with the period Δt, so that

$u = u(g_1)$ during the time Δt_1,
$u = u(g_2)$ during the time Δt_2,
……………………………………
$u = u(g_n)$ during the time Δt_n,
$t = \Delta t_1 + \Delta t_2 + \ldots + \Delta t_n$,

than the period iterations are occurring. Scanning speed per configuration C is limited to predetermined time interval, which is defined by the information strategy about liquid system state. When p evaluates state of components g_v, belonging to configuration, each of them is processed independently from the others. In all representation $u(g_1)$, $u(g_2)$, … we will use one value u_0, i.e. for the configuration the coding is coherent. In other words, the coding is coherent for components from the same configuration, the coding is not coherent for configuration, alternating with each other time.

But, according to the theory, presented in [3], the measuring period does not have sufficient power to transmit all the information necessary p for analysis ξ. Because linearity implies superposition of the input signal and excludes the results of the mutual influence of different sensor coordinates, refuse for a while from u_0 putting $u_0=1$.

Thus, to solve this problem by using multiplexing of the touch vector, and the introduction of the input fields y of the network. For a given sensory vector $u = u(g)$ form a packed variant (the order of the multiplexing, or the multiplicity of t)

$$y = u \otimes u \otimes \ldots \otimes u \ (m \text{ times}),$$

where y takes values in the space of input signals

$$Y = U \otimes U \otimes \ldots \otimes U.$$

The multiplex operator $\otimes$ has the following meaning. If you specify a vector $\upsilon=(\upsilon_i)$, then the m-dimensional array with elements $v_{i_1}, v_{i_2} \ldots v_{i_m}$ packed variant with multiplicity m – it is the result of the multiplication component. The multiplicity t is not bigger than the original dimensionality of U and U^v.

In general we can consider the situation when the multiplicity is changed from 1 to some maximum. In particular if the information system has a high redundancy, it is advisable to multiplex only part of each touch of subspace.

3 Experimental set-up

Developed model was studied under laboratory conditions at the training airfield of Samara State Aerospace University by means of modern technology National Instruments. Select National Instruments technology as a means of implementing this model was due to the simplicity and efficiency of its use in the software environment LabVIEW. As an integrated sensor of fluid contamination control was used sensor 'FLOW', developed in the laboratory 'Radio-electronic devices and methods of diagnostics of aircraft systems' of Samara State Aerospace University figure 3. As an input and output devices was selected platform 'Comact DAQ', which provides a flexible hardware solution for the development of various systems for the collection and control signals from the USB port on the base program complex LabVIEW.

Fig. 3. Integrated sensor of fluid contamination control

The sensor is mounted in a hydraulic line and connected to the input-output device.

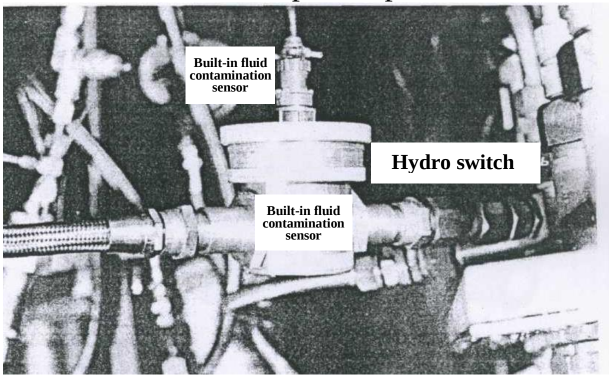

Fig. 4. Installation of the sensor in the drain line of the hydraulic system

Information on the number density of solids by size groups and dispersed solids particles formed in the flow sensor and into the input-output in the form of a random sequence of bell-shaped pulses whose amplitude is related to the quadratic dependence on the size (diameter) particles. Input-output analyzes formed by a sequence of pulses and results in the issuance of digital or analog form on the LCD.

The sensor operates according to principle of light flows measuring, scattered by contamination parts. The liquid is pumped through the measuring channel of small diameter, on one side of which an optical transmitter system is installed, and the other – the photodetector with the optical system.

If there is a discontinuity in the optical measuring volume (for example, mechanical impurities) light is scattered in all directions. Measuring the intensity of scattered light using the photodetector, you can get information about the parameters of contamination parts.

Contamination parts sizes determination is made according to the electric pulse amplitude, which obtained from the output signal of the photodetector. Each size of contamination parts has its own signal amplitude that is proportional to the square of the equivalent diameter of the part.

Thus pulses, which selected according to amplitude, one can calculate the number of particles of a certain size. Two variants of the comparative analysis were considered in the experiment course, which were implemented twice on the different levels of fluids contamination.

The first experiment would allow to compare the analysis results of the fluid contamination, obtained by in-line and off-line control methods.

Off-line method implementation: in order to eliminate the subjective factor, fluid sampling was performed by continuously draining the fluid (bypassing the sampling in an intermediate tank) through sampling crane into a glass ща the device type AZG-975 with its subsequent analysis of the photoelectric sensor of the device (in table 1 – ‘AZG’).

In-line method was implemented according to the system ‘Foton-965’, equipped with built-in fluid control sensor type ‘Potok’, which was installed directly in hydraulic system (in table 1 – ‘Potok’).

Table 1. Results of monitoring the level of purity of the working fluid in the HS

№ variant	№ test	Type of sensor	Number of contamination parts in 100 ml of fluid / purity group according to GOST 17216-2001			
			5-10 μm	10-25 μm	25-50 μm	>50 μm
1	1	Potok	307/5	106/4	6/3	0
		AZG	338/5	5/0	0	0
	2	Potok	294/5	89/4	3/1	0
		AZG	305/5	2/00	0	0
2	1	Potok	-	188/5	42/6	0
		OS-04	-	198/5	4/2	0
	2	Potok	-	314/6	20/5	0
		OS-Q4	-	312/6	4/2	0

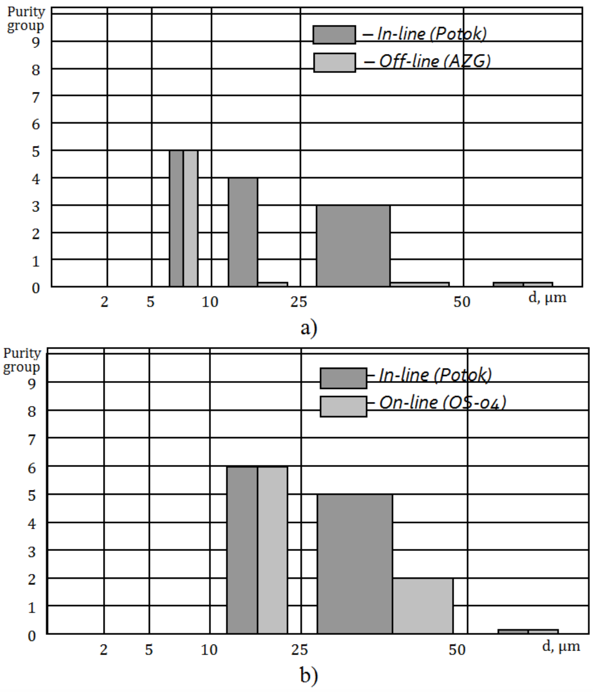

Fig. 5. The results of fluid contamination level control of hydraulic systems (of purity groups according to GOST 17216-2001), obtained by different methods

During the comparing results of fluid purity control, conducted by a system of ‘Foton-965’ and device AZG-975 (Fig. 5a), there is good agreement between the results only for fractions of 5...10 μm, and fractions of 10...25 and 25...50 μm there is a significant discrepancy.

This is caused by the filtration effect of the contamination parts during the sampling, occurring due to the small clearance in the valve sampling crane. Small clearance is necessary to damp excessive pressure in hydraulic stand. Thus, during the monitoring the hydraulic system with the pressure 15...20 MPa (this pressure was used in the experiment hydraulic stand) clearance in the valve must be set to 10 μm. Therefore, in this case it is not possible to provide reliable control of contamination parts over 10 μm.

Analyzing the results of this experiment it should be noted that the greatest impact on the accuracy of the sample analysis results provides the purity factor of sampling of dishes, which was not considered in this experiment. However, it is particularly difficult to ensure a high level of dishes purity in airfield conditions, when the sampling process can be complicated by bad weather conditions (low air temperature, strong winds, and etc.).

The second variant of experiment allows to compare the analysis results of purity fluid, obtained by on-line and in-line monitoring methods (Fig. 5b). These methods have been implemented using the OS-04 device, developed by Hayyak/Royko (USA), and "Foton-965" system. Because OS-04 device was equipped with a photoelectric sensor with a sensitivity of 10 microns, the table 1 and fig. 5b shows the monitoring results for the size of more than 10 microns.

Analysis of the results shows that the number of contamination parts in a size fraction of 25...50 μm, registered by OS-04 device, in 5...10 times less than the number of contamination parts, registered by "Foton-965." The reason for this is that contamination parts larger than 25 microns are being ‘lost’ in the supply lines in OS-04 device, and because of its imperfections of sampling node.

Comparison the number of contamination parts size of 10...25 μm, fixed by these devices, shows that this fraction has a very good reproducibility. Obviously, using a more sensitive sensor of OS-4 device allows to obtain a good match in the number of contamination parts in the 5-10 μm size fraction.

Thus, analysis of the results of the experiment leads to the following conclusions.

1. The in-line method has the lowest methodological inaccuracy of fluid purity level measurement, when the sensor is installed directly into the gap of hydraulic system line, and fluid with operating pressure, flow and temperature influences the transducer.

2. On-line monitoring method also has the high accuracy. Because of using the analysis of small contamination parts parameters for hydraulic system states diagnosing, this monitoring method could potentially be used for designed control system of aircraft hydraulic system.

3. The off-line monitoring method of fluid purity level is characterized by large methodical measurement error. This method cannot produce results in real time. Therefore it is not suitable for use in a control system, which implements a proactive approach to the hydraulic system

maintenance. This fluid purity control method is advisable to use only during a small amount of research by highly qualified operator-assistant, following a number of requirements (methods of laundering and control the degree of inner surface purity of the sample dishes, sampling techniques of high pressure lines, etc.).

4 Conclusions and future work

The resulting model is the basis for the development of analysis and control methodology of the hydraulic fluid state within the framework of proactive aircraft maintenance.

5 Acknowledgement

This article is written on the results of the research work in The President of the Russian Federation Grants for the state support of young Russian scientists MK-6480.2016.8.

References

[1] Gareyev A.M., *The Modeling of the fluid contamination control process* // Vestnik of Samara State Aerospace University - 2010. - №4. - P.117 - 124.
[2] Grenander, U. *Lectures on image theory* // Vol. 1 – Moscow: Publishing house “Mir”, 1979 – 382 pp.
[3] Gareyev, A.M., Tiz S.N. *Proactive maintenance of aircraft hydraulic systems*. – Samara: Publishing house “SSC RAS”, 2010 – 112 pp.
[4] Gareev A. *Modeling of fluid condition of aircraft hydraulic system* / 28th Congress of the International Council of the Aeronautical Sciences. – Australia, Brisbane, - 2012. – pp. 121 -126.

Copyright Statement