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THE METHOD OF ANALYSIS OF RELIABILITY OF FREQUENCY PRESSURE SENSOR FOR SYSTEMS OF AIR SIGNALS OF AIRCRAFT

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Abstract—The system's of air signals reliability calculating method is based on robust criterion of system failure; criterion takes into account the physical processes of degradation of system during its operation the normalization subadjustment next time (duration of turnaround period) and calculate the system transition since the launch of its operation until the loss of parametric (robust) resistance, which limits the permissible value of the assigned resource in its design.

Index Terms—System of aircraft air signals; parametric failure criterion; reliability; frequency sensor.

I. INTRODUCTION

Reliability of means of measuring the altitude of the aircraft defines one of the most important properties of its quality.

Frequency static (barometric) pressure sensor with a cylindrical resonator [1], which is part of the system of air signals (SAS) of the aircraft, is a self-oscillating system for which it is important to define the limits of sustainability. When designing the oscillating circuit of a frequency-dependent system of "mechanical resonator – excitation oscillation system" of a frequency sensor and its reliability analysis we may use proposed in [2] parametric reliability criterion of robust stable automatic control systems, considering as a determining parameter the frequency of natural oscillations of the cylinder of mechanical resonator and using a linear probability model of physical change in the wall thickness over time due to its physical degradation.

The loss of stability of the system can be seen as its failure: unstable system being at the brink of (nonoscillatory or oscillatory) stability is not operational, any slight deviation leads to failure. If as a key parameter we consider oscillation frequency of a mechanical resonator (vibrating cylinder), then following the change in the frequency due to a physical degradation of a frequency-dependent system (aging, contamination, fatigue, wear-off, etc.) the change of the determining parameter in time shall lead to reaching the limits of stability, i. e. to failure of the system. The task of defining the limits of parametric stability in automatic control theory is solved by *the condition of parametric stability of the system*.

Development of a method of analysis of reliability of such systems is relevant in terms of improving the reliability and quality of technical objects and systems.

It is known that the change in the determining parameter in time and reaching the limits of tolerance

results in a system failure [3], [4]. In addition, the loss of stability of the system can be seen as its failure: unstable system being at the brink of (nonoscillatory or oscillatory) stability is not operational, any slight deviation leads to failure. In this regard, as the limits of tolerance of the determining parameter of the system its limit of parametric stability can be considered.

The task of defining the limits of parametric stability in automatic control theory is solved by *the condition of parametric stability of the system* [4]–[7]. This condition is considered only for stationary systems with no answer of how this condition affects the reliability of the system.

Scientific novelty lies in the use of *parametric failure criterion* of robust stable systems, which combines classic indicators of reliability of technical systems and stability criteria for calculating the reliability of the frequency-dependent automatic control systems, including pressure sensors with mechanical resonators.

This criterion will also enable to take into account the physical processes of physical degradation of system during its operation at timing of its consequent subregulation (duration of turnaround time).

Using parametric failure criterion of robust stable systems will allow to develop the reliability analysis method of static pressure sensor of aircraft SAS.

II. ANALYSIS OF THE PROBLEM

Reliability of frequency pressure sensor with a cylindrical resonator greatly depends on the efficiency of oscillating circuit frequency-dependent system of "mechanical resonator – excitation oscillation system", which at present is not effectively addressed. The method offers ways to solve it by means of accounting processes of physical degradation of automatic oscillating system during its operation during the timing of turnaround time (the following subregulation of the system).

III. STATEMENT OF THE PROBLEM

Parametric options stationary stable systems (due to aging, fatigue, physical degradation or other reasons) may change in time, i.e. these systems may be regarded as quasi-stationary or non-stationary. In such cases there is a challenge to build the system so that it would be resistant not only at fixed values of the parameters but also at all permissible values, set by-ranges of their variation when designing the system.

Objective of the paper is to when finding the limits of stability of parametric consider the time of achieving this limit by the determining parameter of the system that should be treated as the first time to system failure.

IV. SEPARATE ISSUES OF EVALUATION OF PARAMETRIC RELIABILITY OF THE SYSTEM

Many technical systems have the determining parameter that dominates as the “weakest link” in terms of parametric reliability i.e. is a measure of its quality, and can be periodically adjusted, that is setting its value according to the nominal, if this parameter is able to change over time and exceed the permissible limit. This option is called an *adjustable determining parameter (ADP)*, it identifies the need for maintenance. We denote ADP as $A(t)$, whose value equals to certain non-random nominal value of this system parameter A_0 .

During maintenance ADP value A_{01} at time t_{01} may be set with some tolerance: $A_{01} \approx A_0$. In further operation of the system the ADP accidentally changes, which may presented as a terminal random function of time $A(t)$, with all its executions passing through a non-random point – “pole” (A_{01}, t_{01}). During the regular maintenance for all $j = 1, 2, \dots, n$ of such exploited systems at time t_{02} the initial value of the parameter $A_{02} \approx A_0$ shall be re-adjusted with a certain tolerance and a random process of subregulation is repeated again (Fig. 1).

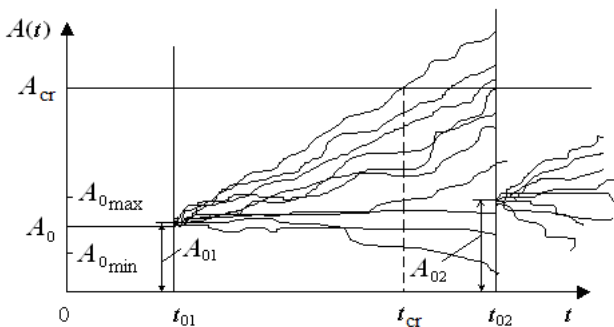


Fig. 1. Terminal random function $A(t)$ of regulated determining parameter of the object

Due to a very slow rate of change in ADP compared with time of reaching of parametric stability of

the system, the process we are considering may be approximated by a fibered linear function with a nonzero initial dispersion

$$A(t) = A_0 + \Psi t, \quad (1)$$

where Ψ is random speed of deregulation; t is the time counted from the date t_{0i} of the previous maintenance (Fig. 2).

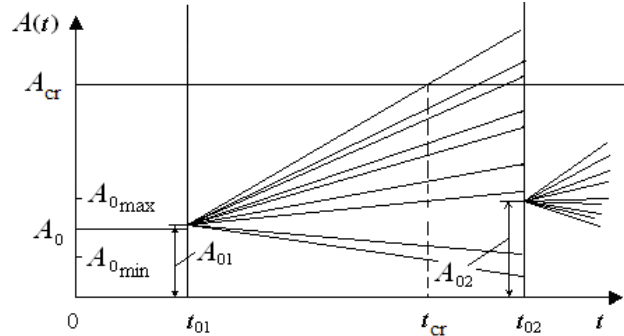


Fig. 2. Terminal random function ADP if approximated by fibered linear function

Linearization of deregulation process is carried out in the same manner as the linearization of process of wear. To determine ratings of characteristics of m_Ψ and S_Ψ , describing deregulation, we need to measure ADP value j of the same type systems, $j = 1, 2, \dots, n$ at least once. Also, we should know the time ($t_{0(i-1)}$) and the result ($A_{0(i-1)}$) of the previous regulation ($i - 1$) during maintenance. Note, that the nominal values of ADP A_0 mostly is set to tolerances of $A_0 \in (A_{0min}, A_{0max})$, where ΔA_0 – is a permissible regulation tolerance, $\Delta A_0 = A_{0min} - \Delta A_{0max}$ thus initial values A_0 for the i th regulations may vary within tolerances.

The values of the random rate of change in ADP are limited by lower Ψ_l and higher Ψ_h limits:

$$\Psi \in (\Psi_l, \Psi_h) \text{ for } \Psi_l > 0, \Psi_h > 0.$$

In this case, we assume that the argument Ψ of the model (1) has a truncated normal distribution, whose density is as follows

$$f(\Psi) = cf(\psi) = \frac{c}{S_\Psi \sqrt{2\pi}} \exp \left\{ -\frac{(\Psi - m_\Psi)^2}{2S_\Psi^2} \right\}, \quad (2)$$

where $f(\psi)$ is a density of normal (untruncated) distribution of Gauss; c is the normalization factor, which is due to the fact that the area under the distribution density curve is a unit value, i. e.

$$c \int_{\Psi_2}^{\Psi_1} f(\psi) d\psi = 1.$$

With substitution $z = \frac{\Psi - m_\Psi}{S_\Psi}$, where m_Ψ , S_Ψ

are relevant expectation and mean-square deviation of the normal untruncated distribution rate of change in ADP, after the conversion we get

$$c = \frac{1}{\Phi(z_2) - \Phi(z_1)}, \quad (3)$$

where $\Phi(z)$ is a normal Laplace function,

$$z_1 = \frac{\Psi_l - m_\Psi}{S_\Psi}; \quad z_2 = \frac{\Psi_h - m_\Psi}{S_\Psi}.$$

For ADP we set a certain threshold (critical) value A_{cr} (Figs 1, 2), that leads to a disturbed performance of the object if reached. Random time of reaching by ADP $A(t)$ the value of A_{cr} is found by:

$$t_{cr} = \frac{A_{cr} - A_0}{\Psi}.$$

The density distribution of time for ADP to reach the value A_{cr} with truncated normal distribution (2) of rate Ψ using fiber models with zero initial dispersion [2] is as follows:

$$f(t) = f[A(t)] = \frac{c\beta}{t^2\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left(\frac{\beta}{t} - \alpha\right)^2\right\}, \quad (4)$$

for $t_1 < t < t_2$, where t_1, t_2 are limits of changes in time $\{t\}$ for ADP to exceed the value A_{cr} ,

$$t_1 = \frac{A_{cr} - A_0}{\Psi_B}, \quad t_2 = \frac{A_{cr} - A_0}{\Psi_H}, \quad \text{distribution density}$$

$f[A(t)]$ according to the formula (4) corresponds to alpha distribution, which parameters equal to

$$\beta = \frac{A_{cr} - A_0}{S_\Psi}; \quad \alpha = \frac{m_\Psi}{S_\Psi}, \quad \text{while a normalization factor}$$

c can be found by the formula (3); such being the case the alpha distribution shall be

$$z_1 = \frac{\beta}{t_2} - \alpha; \quad z_2 = \frac{\beta}{t_1} - \alpha.$$

Equivalence of the examined model in adopted formulation together with the efficiency time evaluation model makes it possible to determine the time limit after the system's failure by going beyond sustainability limits t_{cr} as the interval since the previous adjustment of ADP (for $t_{0i} = 0$) up to its failure. Assessing the value t_{cr} , we may set the optimum maintenance period in terms of parametric reliability associated with regulation of ADP, i. e. during the time of maintenance and tuning, it is necessary to

check whether the normalized time exceeds $t_{reg} = t_{0i} - t_{0(i-1)}$ until the following adjustment of estimated value t_{th} , and to limit the adjustment period t_{reg} (to reduce normalized time to value $t_{reg} = t_{cr}$).

V. PRACTICAL APPLICATION

While analyzing the reliability of self-oscillating circuit of frequency-dependent system of "mechanical resonator – excitation oscillation system" of frequency pressure sensor of aircraft SAS, we propose to use the proposed criterion, considering as a determining parameter own cylinder oscillation frequency of mechanical resonator. This parameter is always regulated as in each resonant system because the process of setting electronic board of oscillating circuit is carried out during the manufacture and checkout procedures.

We consider the random nature of the approximation to the failure by the example of self-maintained pressure sensor with mechanical resonator as a thin-walled cylinder. This sensor may be viewed as ACS, which performance is determined by the scalar ADP A (for example, the resonant frequency of the cylindrical resonator that is most dependant on the thickness of the cylinder). Such being the case the space of ADP A will be one-dimensional while the workspace Ω will be limited by line segment (limit value of DP A_{cr}). Suppose there is a set $j = \overline{1, n}$ of identical sensors simultaneously engaged in the operation (for $t = 0$), and DP of each sensor is measured at the same time t_i ($i = \overline{1, k}$).

For the approximation of the mathematical model of change in frequency over time we use linear physical probability model (1) of changes in the own frequency of the cylindrical resonator over time due to its physical degradation (thickening of the wall of the cylinder by the added mass of condensation and contamination of the working environment, change of modulus of elasticity due to fatigue and aging, etc.). Examined linear models are suitable for approximating stochastic processes of changes in ADP that make it possible to characterize these processes by a limited number of arguments of the model and to determine them one needs a minimum amount of experimental data.

Change of ADP in such sensors in operation (increasing the thickness of the cylinder due to the gradual contamination, changes in thickness due to the change in density of added mass that resonates together with the cylinder, etc.) we will examine as a random function of time $A(t)$. For each j th sensor ($j = \overline{1, n}$) change in DP is an execution (part) of $A_j(t)$ random function $A(t)$. The points of intersec-

tion of execution $A_j(t)$ of a random process with the limit A_{cr} of the workspace (tolerance field set by parametric stability condition) correspond to the time of failures of j -s sensors. Random nature of consequent failures' origin in operation of these sensors is described by the distribution density $f\{X(t)\}$ of time of exceeding the limit by DP A_{cr} i. e. distribution density of time to failure.

Having information about the real value of time for ADP to reach the limit value $t_r < t_{exc}$ in the design phase of frequency pressure sensor for SAS one may analytically calculate the time of keeping its operating condition, that is to make a reasonable prediction of its future performance. This will help to prevent failures in time, and to manage the condition of frequency-dependent system, and by conducting its adjustments to replace its components by spare ones or change operating conditions of such system.

Non-stationary random process $A(t)$ describes the long-term irreversible changes in parameters resulting from wear, aging or deregulation. Process $A(t)$ is the main cause of failure, it can be called a **process of wear**. Wear processes models must be functionally dependent of time, and their random nature is caused by random parameters that are independent of time. Similar random processes are sometimes called quazy – or semi-random.

VI. METHOD OF ANALYSIS OF RELIABILITY FREQUENCY SENSOR FOR SYSTEM OF AIR SIGNALS OF AIRCRAFT

The method of analysis of reliability oscillating system according to reliability parametric criterion [2] of stable nonlinear ACS is the following: 1) the conditions of self-oscillations in the system; 2) determination of parameters of self-oscillations (amplitude a_0 and frequency ω_0 of its own oscillations); 3) evaluation of the stability of self-oscillatory regime, calculation of the stability limits $|\omega_0| \ll \omega_{cr}$; 4) determining the time of ADP to reach these limits of stability ω_{th} using a linear model (1) of physical degradation of mechanical resonator; 5) determination of the operating time of the system to failure.

Examination of reliability pressure sensors based on cylindrical resonator for SAS of aircraft is carried out by the following algorithm.

1. Flow diagram of the examined self-oscillating system (frequency pressure sensor) has to be lead to the design scheme containing a nonlinear element (NE) and collected into a single unit of linear $W_l(a)$ (Fig. 3).

2. When performing this conversion a zero setting action has to be set because self-oscillations are free oscillations.

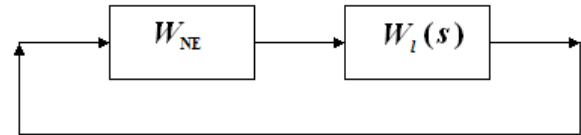


Fig. 3. Flow diagram of the nonlinear self-oscillating system

3. To derive an expression for the equivalent complex transmission coefficient of nonlinear element $W_{NE}(s)$, following the construction of the output signal of this element in the input sinusoidal signal and the necessary integration operations. Equivalent complex transfer coefficient of nonlinear element based on self-oscillations amplitude a :

$$W_{NE}(a) = w(a) + jw'(a).$$

Since the static nonlinear characteristic of frequency pressure sensor is a single-value, then $jw'(a)$.

4. The method of coherent balance using logarithmic characteristics self-oscillation parameters and their stability have to be determined.

Conditions of self-oscillations in nonlinear systems are defined by using coherent balance equation:

$$W(j\omega)W_E(a) = -1, \quad (5)$$

which may be written as equations:

$$\arg W(j\omega) + \arg W(a) = (2k + 1)\pi, \quad k = 0, 1, 2, \dots;$$

$$|W(j\omega)| |W_E(a)| = 1.$$

Taking the logarithm of equation (5), we obtain:

$$L(\omega) = -L(a), \quad (6)$$

where $L(\omega) = 20\lg|W(j\omega)|$, $L(a) = 20\lg|W_E(a)|$. For a system with a nonlinear element has a single value characteristics, $W_E(a) = w(a)$, conditions of self-oscillations take the form of:

$$\varphi(\omega) = -(2k + 1)\pi, \quad k = 0, 1, \dots; \quad (7)$$

$$L(a) = 20\lg[w(a)]; \quad \varphi(\omega) = \arg W(j\omega), \quad (8)$$

$$|W(j\omega)| \leq \left| \frac{1}{W_E(a_0 + \Delta a)} \right|.$$

In order to determine the possibility of self-oscillation and to obtain parameters of stable self-oscillations of the it is necessary to:

– build a logarithmic amplitude $L(\omega)$ and phase $\varphi(\omega)$ frequency characteristics of a linear part of the system and the logarithmic amplitude characteristic $[-L(a)]$ of the linear coherent nonlinear element; self-oscillations may arise in the linear system, as follows from (6) and (7), if any of ordinates of LAFC

$L(\omega)$ of the linear part of the system, taken at the values of ω , when LPFC $\varphi(\omega)$ intersects lines $\varphi(\omega) = -(2k+1)\pi$, $k = 0, 1, \dots$, we may find ordinate of LAC $[-L(a)]$ of nonlinear element equal to $L(\omega_0)$;

– at the points of intersection of LPFC $\varphi(\omega)$ with lines $\varphi(\omega) = -(2k+1)\pi$, $k = 0, 1, \dots$, we find the frequencies ω_0 of possible oscillatory modes;

– to explain the values of ordinates of LAFC $[-L(a)]$ of the linear part of the system corresponding to the frequencies found, and then examining the condition (8) to find graphically possible self-oscillation amplitudes (Fig. 4).

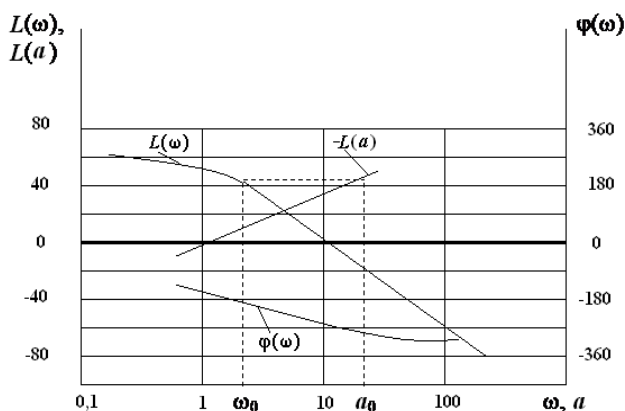


Fig. 4. Determination of self-oscillation parameters a_0 and ω_0

Self-oscillations with amplitude a_0 will be stable if small neighborhood with coordinates $[a_0, -L(a_0)]$, tangential to the characteristics $[-L(a)]$ have a positive slope to the horizontal axis (to the axis ω and a). So, self-oscillations with amplitude a_0 will be stable if $L(\omega_0 + \Delta\omega) < L(a_0 + \Delta a)$, where $\omega_0 + \Delta\omega = \omega_{cr}$, to find time to failure of the system t_{th} , i.e. reaching oscillating limits of sustainability ω_{cr} by ADP (own frequency ω_0) by the method of successive approximations using linear models of degradation processes of ADP functionally dependent on time.

CONCLUSIONS

Parameters of a stationary system as a function of time (variation in time of its determining parameter) are demonstrated by parametric failure of the system.

Classic indicators of reliability of technical objects are combined with the criterion of parametric stability of the system, a new stability criterion of robust stable system as a **parametric criterion of its failure** has been applied.

This criterion also enables to take into account the physical degradation processes of self-oscillating

system during its operation at the normalization time of the following subregulation (duration of turnaround time).

Based on parametric failure criterion of robust stable system we have developed a method of reliability analysis of frequency pressure sensor for SAS of aircraft, namely reliability of self-oscillating circuit “mechanical resonator – excitation oscillation system”, if adjustable determining parameter is set as own oscillation frequency of mechanical resonator.

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О. М. Нечипоренко. Метод аналізу безвідмовності частотного датчика тиску для системи повітряних сигналів літака

Запропоновано методику розрахунку безвідмовності системи повітряних сигналів з частотними датчиками тиску на основі робастного критерію відмови системи; критерій дозволяє враховувати процеси фізичної деградації системи повітряних сигналів під час її експлуатації при нормуванні часу наступного підрегулювання (тривалості міжремонтного періоду) і розраховувати час переходу системи з початку її функціонування до моменту втрати параметричної (робастної) стійкості, що обмежує допустиме значення призначеного ресурсу системи повітряних сигналів під час її проектування.

Ключові слова: система повітряних сигналів; параметричний критерій відмови; надійність; частотний датчик.

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Е. Н. Нечипоренко. Метод анализа безотказности частотного датчика давления для системы воздушных сигналов самолета

Предложена методика расчета безотказности системы воздушных сигналов с частотными датчиками давления на основе робастного критерия отказа системы; критерий позволяет учесть процессы физической деградации системы воздушных сигналов во время ее эксплуатации при нормировании времени последующего подрегулирования (длительности межремонтного периода) и рассчитать время перехода системы с начала ее функционирования до момента потери параметрической (робастной) устойчивости, ограничивающее допустимое значение назначенного ресурса системы воздушных сигналов при ее проектировании.

Ключевые слова: система воздушных сигналов; параметрический критерий отказа; надежность; частотный датчик.

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