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THE PARAMETRIC METHOD OF EVALUATION OF TECHNICAL CONDITION OF THE WORKING TURBOMACHINE BLADE DEPENDING ON THE DISTRIBUTION COURSE REPRESENTING ITS ENVIRONMENT

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Abstract

This article presents tests results of monitoring technical condition of turbomachine blades. The method is based on a diagnostic model $\varphi_{T12,T01}$ that utilizes the difference of phase shift of signals that are the result of blade operation y(t) and a signal x(t) of its environment described with appropriate distribution when the blade moves away from the sensor and when the blade tip approaches the sensor. The adopted diagnostic model indirectly takes into account present blade environment x(t) without the need to measure it [13,15].
The results of diagnosing three blades (worn out to a great extent, considerably worn out and worn out to a little extent) with the use of different distribution courses were presented. Shown results differ to a little extent from each other. However, they unequivocally specify the character of blade wear. Thus, the choice of distribution that represents non-measurable blade environment while determining parameters of a model $\varphi_{T12,T01}$ for evaluation of technical condition of working turbomachine is optional and limited only by observation time.

Keywords: *diagnostics, turbomachine, rotor blades, phase shift, diagnostic model*

1. Introduction

A turbomachine blade is one of basic elements responsible for reliable and safe turbomachine operation. Even slight damage to the blade may lead to damage to a whole machine and in some cases (tearing of a part of blade or the whole blade) even to total destruction of a turbomachine which usually results in tragic catastrophes. Thus, in the process of turbomachine operation a great attention is given to the issues of reliability and diagnostics of turbomachine blades.

Nowadays there are many methods used for diagnosing technical condition of blades during turbomachine operation (the method of eddy currents, the ultrasound method, the radiographical method, the method of colour flaw detection and luminescence flaw detection as well as the vibroacustic method) which work successfully on specific technical objects (SO-3 engines).
Diagnostic inference used so far in the methods of evaluation of blades technical condition is based solely on modification of signals that were measured during diagnostic tests and that are the result of blade operation without sufficient consideration given to signals (of considerable power) of blade variable environment [2÷12, 24, 25, 26].

Measurement of blade environment signals during turbomachine operation is difficult and very often even impossible thus this measurement is not sufficiently considered in blade diagnostics.

Therefore it can be claimed that the methods that have been used so far for evaluation of blades technical condition during turbomachines operation do not entirely fulfill a basic principle of technical diagnostics that demands a test and technical condition analysis of an object in environment (PN-90/N-04002) thus these methods are not accurate nor reliable enough.

Therefore the need arises to develop a new method of diagnostics of blade technical condition during turbomachine operation with taking environment into account, but (if possible) without the need to use the measurement of environment signals that are unavailable and often difficult to measure. This problem can be solved by a blade diagnostics method based on a special diagnostic model that allows to eliminate real existing environment of the blade with the help of special methods.

2. BLADE OPERATION IN NON-MEASURABLE ENVIRONMENT

Fig. 1 shows construction and activity of a blade during its operation in variable environment [18, 21]. The blade consists of two parts: the first one is an operating part, also called a profile part – 1 (a blade) and the second one is a fastening part – 2 (of a lock). The operating part comprises also an edge of attack– 3, a trailing edge – 4, a blade tip – 5, a blade ridge – 6, a trough – 7.

Rotor blades are fastened in a shield with the use of a trapezoidal lock, also called “a dovetail lock”. Blades are covered with an epoxy enamel in order to increase their corrosion resistance.

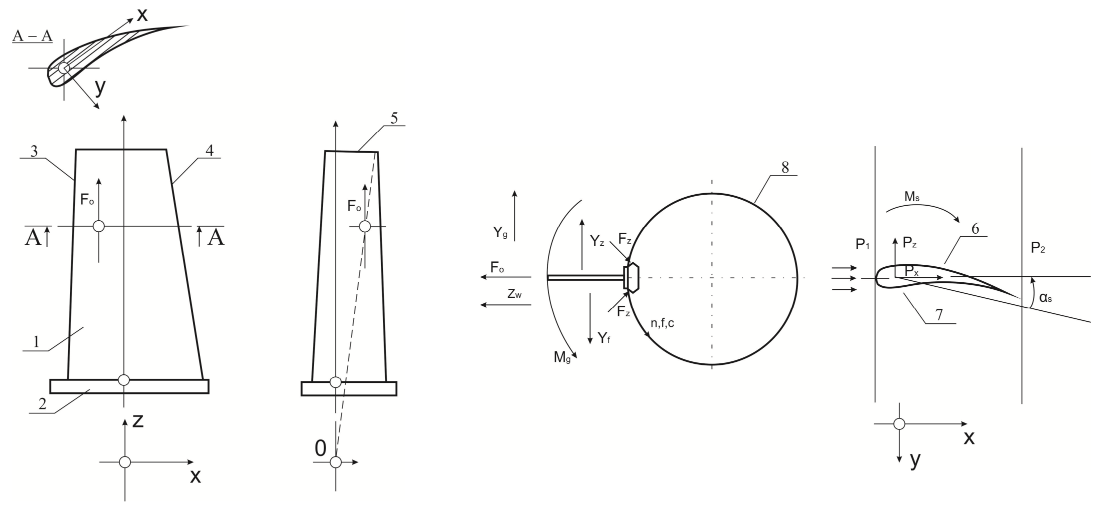

Fig. 1. A turbomachine blade in variable environment.

1 – a blade; 2 – a blade lock; 3 – an edge of attack; 4 – a trailing edge; 5 – a blade tip; 6 – a blade ridge; 7 – a blade trough; 8 – a rotor drum; ; F_0 – centrifugal force; F_z – lock grip force; n - rotational velocity; Y_z- blade aerodynamic lift; P_x - resisting force; M_s – torque moment; M_g - bending moment; P_1 - gas pressure on rotor rim input; P_2 - gas pressure on rotor rim output; Y_g - blade deflection; α_s – a blade torsion angle; Z_w - blade longitudinal displacement; Y_f - a various vibration signal (bending, torsional, longitudinal); Y_c - thermal deformation; f – a vibration signal; c – a temperature distribution signal

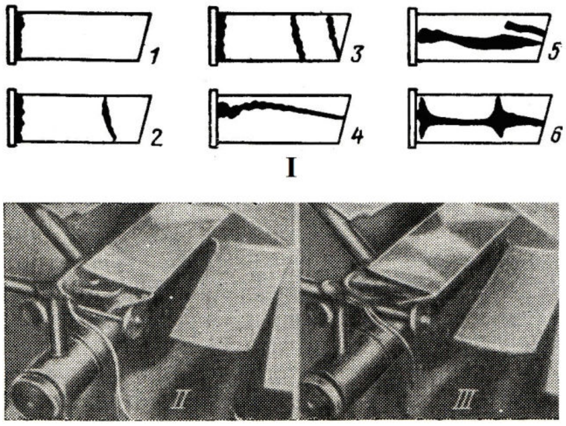

Fig. 2. Forms of vibration and lines indicating traces of vibration nodes.
Chart I: 1,2,3 - first, second and third form of bending vibration; 4 - first kind torsional vibration; 5 - second kind torsional vibration; 6 - combined bending-torsional vibration. Chart II: photograph of nodes traces in second form of bending vibration. Chart III: photograph of nodes traces in third form of bending vibration

During its use, the blade technical condition changes and, with time, various damage appears (such as fractures, deformations, pits, breaks of blade parts) [22].

Fig. 1 and Fig. 2 show that a blade (of a compressor, a turbine) is a technical object with complex principle of operation and that has to be specified with a multidimensional state of blade deformation.

Those deformations originate from environment and are caused by various reasons such as:

- centrifugal force F_0 loads that depend on rotational velocity and cause longitudinal and bending strains (Fig.1) – Z_w, Y_g;
- gas-dynamic Y_z and P_x loads from the stream of air (gas) depending also on flight velocity and altitude (Fig.1) Y_s (if a turbomachine is a compressor or an engine turbine);
- loads Y_g, α_s due to a curvilinear flight path (Fig. 1);
- dynamic loads at mechanical vibration (especially in a resonant range) due to pressure pulsation P_1 and P_2, rotational oscillations etc. (Fig. 2) Y_f;
- blade and casing vibrations f (Fig. 1) and thus Y_g, α_s;
- heat loads c due to uneven temperature distribution (Fig. 2 – complex strain, eg. I – 6) Y_c;

From a synthetic point of view, a state of blade operation in environment can be described by a signal of blade tip displacement y(t) which is a resultant of the following signals: Z_w, Y_g, α_s, Y_f, Y_c, (Fig. 1. and Fig. 2.):

$$y(t) = f\left(Z_w, \alpha_s, Y_g, Y_f, Y_c\right) \tag{1}$$

and an environment signal, x(t) which is a resultant of the following signals: n, F_0, Y_z, P_x, P_1, P_2, f, c (Fig. 1. and Fig. 2.):

$$x(t) = f\left(n, F_o, Y_z, P_x, P_1, P_2, f, c\right) \tag{2}$$

Blade technical condition $S_T(\theta)$ in accordance with diagnostics principles results from relations between the operation signal y(t) and the environmental signal x(t) at the moment of current diagnosing θ_1 and initial diagnosing θ_0.

Therefore the following may be noted:

$$S_T(\theta) = f(y(t)_{\theta_0}, x(t)_{\theta_0}, y(t)_{\theta_1}, x(t)_{\theta_1}, \theta, t) \tag{3}$$

Practice proved many times that there are real difficulties in the process of signals measurement, both for y(t), and x(t) (even to a greater extent), and thus also in the evaluation of blade technical condition during machine operation [13, 15, 17, 18].

3. MEASURING POSITION PATTERN

Blade tests were conducted on a turbine engine test bed in the Air Force Institute of Technology (AFIT) in Warsaw. The tested objects were first degree blades of an axial-flow compressor of the SO-3 engine.

In the engine block, a non-contact inductive sensor (or sensor of other type) is mounted for good. (Fig. 3) in order to measure momentary position of compressor blade tips during operation. A signal from the sensor is registered with the use of specialized equipment and saved on a computer. Conducted tests were carried out for minimum rotational speed of 6900 rpm.

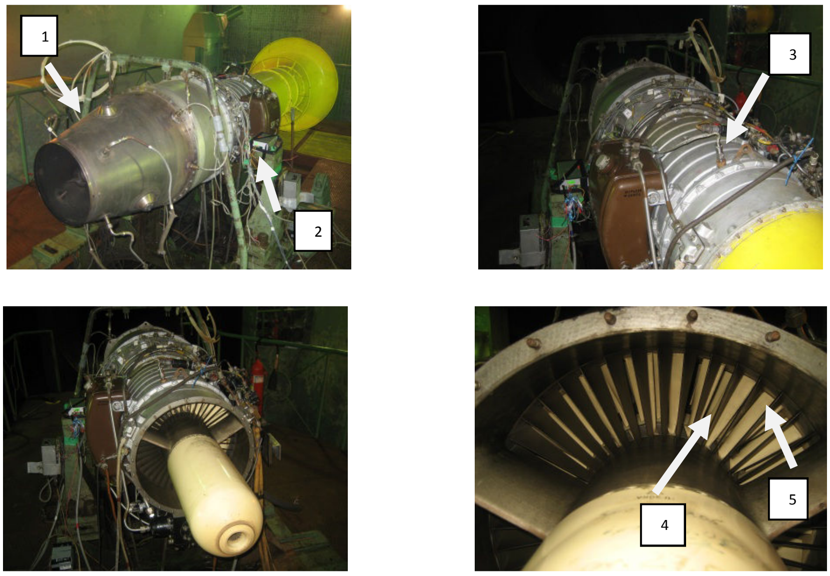

Fig. 3. Measuring position: 1 – SO-3 turbine engine, 2 – measuring device, 3 – non-contact inductive sensor, 4 – compressor blades, 5 – stator blades

4. GROUNDS FOR DETERMINATION OF MODEL $\varphi_{T12,T01}$ PARAMETERS.

A problem of blade diagnostics during turbomachine operation is very complex in its nature as in order to complete a process of blade diagnostics only two signals can be used: the first one is the measurable but interfered signal y(t) and the second one is the environment signal x(t) which is practically immeasurable (except signals n and Δn). It is assumed that environment x(t) is to be represented by distribution $x(t)=\frac{1}{\tau}e^{-\frac{\pi t^2}{\tau^2}}$.

The registered signal of blade tip displacement under the sensor is presented in Fig. 4.

Fixed observation time T_{02} (value T_{02d} or T_{02k}) of blade translocation below the sensor is divided onto two ranges: of blade approaching the sensor T_{01} and receding from it T_{12} (moment T_1 is exactly when the blade tip is below the sensor - Fig. 4.). Adopting long T_{02d} or short T_{02k} time of blade observation is the result of the need to fulfill the conditions of accurate conversion of the signal x(t) into $R_{xx}(\tau)$.

Initially, it is assumed that signals x(t) and y(t) are temporal, stochastic and interfered. In this situation it seems reasonable to switch from space domain “t” of the signals x(t) and y(t) to space domain „τ” of correlation function $R_{xx}(\tau)$ and $R_{xy}(\tau)$ [13, 15, 17, 18, 19, 21].

Afterwards estimates of cross-correlation function R^{*T01}_{xy} and R^{*T12}_{xy} are determined for y(t) translocation in observation periods T_{01} and T_{12} and proper analytic expressions are matched to them [1, 13, 14, 17, 18, 20].

Registered signal courses were multiplied by the Hanning window, then their mutual correlation was calculated. Obtained correlation courses were approximated by fifth degree multinomial with the accuracy of $R^2 > 0,997$ described with the coefficient of determination.

$$S_T(\theta) = f(y(t)_{\theta_0}, x(t)_{\theta_0}, y(t)_{\theta_1}, x(t)_{\theta_1}, \theta, t) \tag{4}$$

On the basis of analytic forms of singular correlation functions R^{T01}_{xy} and R^{T12}_{xy}, functions of spectral power density $S^{T01}_{xy}(\omega)$ and $S^{T12}_{xy}(\omega)$ are determined that correspond to them with the use of Fourier transform:

$$F\{R_{xy}\} = \int_{-\infty}^{\infty} R_{xy}(\tau) e^{-j\omega\tau} d\tau \tag{5}$$

$$S^{T01}_{xy}(\omega) = F(R^{T01}_{xy}(\tau)) \tag{6}$$

$$S^{T12}_{xy}(\omega) = F(R^{T12}_{xy}(\tau)) \tag{7}$$

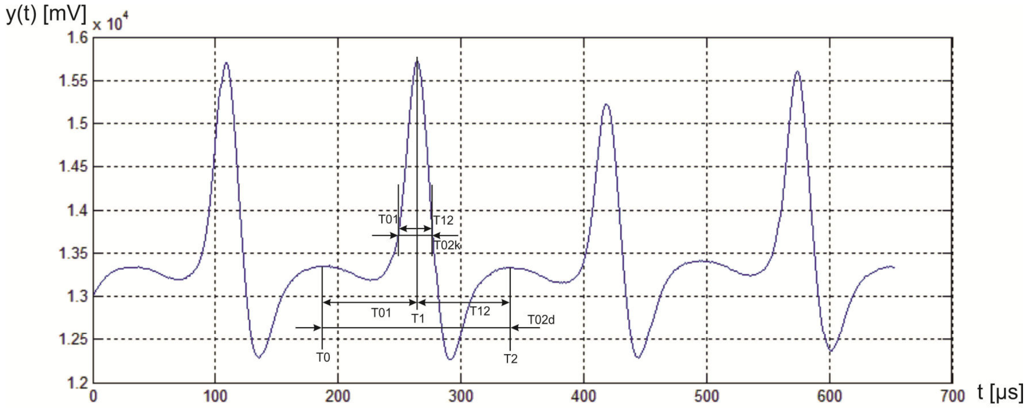

Fig. 4. An inductive sensor signal
T_{02d}, T_{02k} - respectively – a long and short observation period of a blade tip presence in the sensor area, T_0, T_1, T_2 - particular moments of observation of a blade tip under the sensor, T_{01}, T_{12} - observation subperiods of a blade tip for T_{02d} and T_{02k}, respectively, y(t)[mV] – a signal of blade tip displacement, t[μs] - blade displacement time

Expressing functions x(t) and y(t) as $S_{xx}(\omega)$ and $S_{xy}(\omega)$ allows in a very simple manner to take into account relations between diagnostic signals y(t) and environment signals x(t) (Fig. 4).

Thus it may be noted that:

$$\varphi_{T01} = Arg \frac{S^{T01}_{xy}}{S^{T01}_{xx}} \tag{8}$$

$$\varphi_{T12} = Arg \frac{S^{T12}_{xy}}{S^{T12}_{xx}} \tag{9}$$

where:
φ_{T01} – a phase shift of signals x and y while the blade approaches the sensor,
φ_{T12} – a phase shift of signals x and y while the blade moves away from the sensor.

Further it can be assumed that the observation period of T_{12} occurs shortly (ms) after observation time of signals T_{01}.
In this case it may be assumed that:

$$S_{xx}^{T12} = S_{xx}^{T01} \tag{10}$$

Then basing on formulas 8, 9 and 10 and assuming that the environment is eg. noise δ (t, $\hat{t}$) of a great intensity and that it can be correlated with the signal y(t), a new abstract quantity – but the one that can be physically interpreted in the form of phase shifts φ_{T01} and φ_{T12} – can be obtained:

$$\varphi_{T12,T01} = \varphi_{T12} - \varphi_{T01} = Arg\frac{\frac{S_{xy}^{T12}}{S_{xx}^{T12}}}{\frac{S_{xy}^{T01}}{S_{xx}^{T01}}} = Arg\frac{A_{T12}e^{-j\varphi_{T12}}}{A_{T01}e^{-j\varphi_{T01}}} = ArgA_{T12T01}e^{-j(\varphi_{T12}-\varphi_{T01})} \xrightarrow{S_{xx}^{T12}=S_{xx}^{T01}} Arg\frac{S_{xy}^{T12}}{S_{xy}^{T01}} \tag{11}$$

In this manner a new abstract diagnostic model may be determined (of phase shift difference). Its parameters give information about technical condition of the blade being diagnosed [16]:

$$\varphi_{T12,T01} = Arg\frac{S_{xy}^{T12}}{S_{xy}^{T01}} = Arg\frac{B_0 + B_1 s + B_2 s^2 + \ldots + B_5 s^5}{1 + A_1 s + A_2 s^2 + \ldots + A_5 s^5} \tag{12}$$

Difference in the technical condition of the next blades are determined on the basis of relative changes in parameters $M_0 \div M_5$, $L_1 \div L_5$.

$$\Delta\overline{L}_i = \frac{L_{i1} - L_{sr}}{L_{sr}}; \quad \text{i=1,2,3, … n,} \tag{13}$$

where:

$L_{śr}$ – average parameter value (reference value, initial)

$$\Delta\overline{M}_i = \frac{M_{i1} - M_{sr}}{M_{sr}}; \quad \text{i=1,2,3, … n,} \tag{14}$$

where:

$M_{śr}$ – average parameter value (reference value, initial)

Having calculated relative parameters, μ, σ, 2σ and 3σ are calculated (mean value and standard deviation). Then determined relative value changes into "+" if relative value exceeds σ, „++" if relative value exceeds 2σ, „+++" if relative value exceeds 3σ. In this manner, a blade portrait is obtained which confirms blade aptitude state. If countless "+++" occur, it means that the blade is damaged, "++" means that the blade is considerably worn out, "+" means that the blade is worn out only to a little extent.

Such approach shows clear and unequivocal picture of evaluation of blade damage state.

5. BLADE PORTRAITS FOR DIFFERENT DISTRIBUTION COURSES

Tested objects were first degree blades of the axial-flow compressor of the SO-3 engine. For the purpose of analysis, 3 out of 28 available blades mounted in the rotor drum were taken. The choice was made on the basis of blade wear, i.e. one blade was to be in entirely different technical condition from the remaining ones and thus the most damaged blade was chosen – No. 1, the blade No. 11 that was considerably worn out and the blade No. 3, damaged only to a little extent is.

For the purpose of calculations, distribution $x(t)=\frac{1}{\tau}e^{-\frac{\pi t^2}{\tau^2}}$ was used [23].

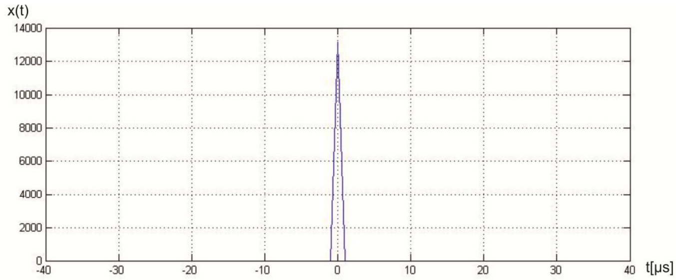

Fig. 5. Graph of distribution for τ =1292

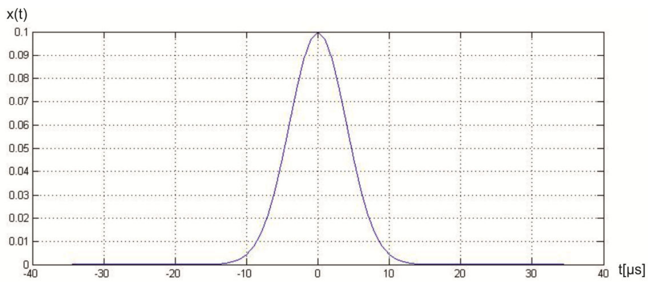

Fig. 6. Graph of distribution for τ =15

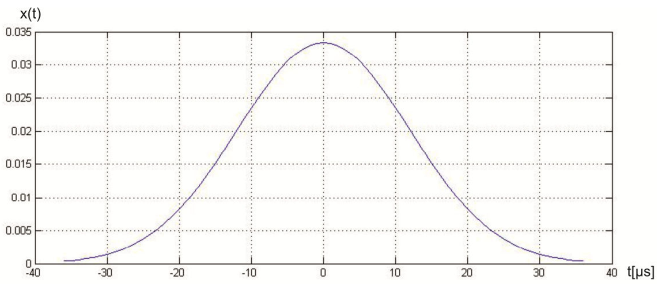

Fig. 7. Graph of distribution for τ =45

Fig. 5 shows distribution diagram for τ =1292 that equals maximum amplitude value of the signal multiplied by the Hanning window, Fig. 6 shows distribution diagram τ =15, Fig. 7 shows distribution diagram τ =45 (τ selected in such a way that the first distribution value was 0 and the number of distribution samples equaled the number of samples of the signal multiplied by the Hanning window). Fig. 8 shows the portrait of the blade No. 1 for distribution course shown in Figs. 5, 6, 7. Fig. 9 shows the portrait of the blade No. 11 for distribution course shown in Figs. 5, 6, 7. Fig. 10 shows the portrait of the blade No. 3 for distribution course shown in Figs. 5, 6, 7. Portraits of blades determined on the basis of formula No.12.

a)

	Portrait of blade No. 1 for the model $\phi_{T12,T01}$ - minimum velocity											
	L0	L1	L2	L3	L4	L5	M0	M1	M2	M3	M4	M5
Cycle 1		+	+	+	+							
Cycle 2		++	++	++	++	++	+	+	+	+		+
Cycle 3		+	+	+	++	+			+	+		
Cycle 4		+	+	+	+							
Cycle 5		+	+	++	++							
Cycle 6		+	+	+	+	+						
Cycle 7		++	++	++	++	++	+	+	+	+		++
Cycle 8		++	++	++	++	+	+	+	+	+		+
Cycle 9		++	++	++	++	+	+	+	+	+		+
Cycle 10		++	++	++	++	+	+	+	+	+		+
Cycle 20		++	++	++	++	+	+	+	+	+		+
Cycle 30		+	++	++	++							
Cycle 40		+	+	+	+							
Cycle 50		++	++	++	++	+	+	+	+	+		+
Cycle 60		++	++	++	++	+	+	+	+	+		+
Cycle 70		+	+	+	++							
Cycle 80		++	++	++	++	++	++	++	++	+		++
Cycle 90		+	+	++	++	+		+	+	+		+
Cycle 100		++	++	++	++	+	+	+	+	+		+
Cycle 200		+	+	+	+							
Cycle 300		+	+	+	+						+	
Cycle 400		++	++	++	++	+	+	+	+	+		+
Cycle 500		++	++	++	++	+	+	+	+	+		+
Cycle 600		++	++	++	++	+	+	+	+	+	+	+
Cycle 700		+	+	+	++							
Cycle 800		++	++	++	++	+	+	+	+	+		+
Cycle 900		+	+	+	+					+	+	
Cycle 1000		++	++	++	++	+	+	+	+	+		+
Cycle 2000		+	+	+	+	+	+	+	+	+	+	+

b)

	Portrait of blade No. 1 for the model $\phi_{T12,T01}$ - minimum velocity											
	L0	L1	L2	L3	L4	L5	M0	M1	M2	M3	M4	M5
Cycle 1		+	+	+	+							
Cycle 2		++	++	++	++	++	+	+	+	+		++
Cycle 3		+	+	+	+	+						+
Cycle 4		+	+	+	+							
Cycle 5		+	++	++	++	+						+
Cycle 6		+	+	+	+	+						+
Cycle 7		++	++	++	++	++	+	+	+	+		++
Cycle 8		++	++	++	++	+	+	+	+	+		+
Cycle 9		++	++	++	++	+	+	+	+	+		+
Cycle 10		++	++	++	++	+	+	+	+	+		+
Cycle 20		++	++	++	++	+	+	+	+	+		+
Cycle 30		++	++	++	++	+						
Cycle 40		+	+	+	+	+						
Cycle 50		++	++	++	++	+	+	+	+	+		+
Cycle 60		++	++	++	++	+	+	+	+	+		+
Cycle 70		+	+	+	+	+						
Cycle 80		++	++	++	++	++	+	+	+	+		++
Cycle 90		+	+	++	++	+			+	+		+
Cycle 100		++	++	++	++	++	+	+	+	+		+
Cycle 200		+	+	+	+	+						
Cycle 300		+	+	+	+							
Cycle 400		++	++	++	++	++	+	+	+	+		++
Cycle 500		++	++	++	++	+	+	+	+	+		+
Cycle 600		++	++	++	++	+	+	+	+	+		+
Cycle 700		+	+	+	++	+						
Cycle 800		++	++	++	++	+	+	+	+	+		+
Cycle 900		+	+	+	+						+	
Cycle 1000		++	++	++	++	+	+	+	+	+		+
Cycle 2000		+	+	+	+	+	+	+	+	+	+	+

c)

	Portrait of blade No. 1 for the model $\phi_{T12,T01}$ - minimum velocity											
	L0	L1	L2	L3	L4	L5	M0	M1	M2	M3	M4	M5
Cycle 1		+	+	+	+	+						+
Cycle 2		++	++	++	++	++	++	++	++	++		++
Cycle 3		+	+	+	+	+	+	+	+	+		+
Cycle 4		+	+	+	+	+						+
Cycle 5		++	++	++	+	++	+	+	+	+		++
Cycle 6		+	+	+	+	++	+	+	+	+		++
Cycle 7		++	++	++	++	++	++	++	++	++		++
Cycle 8		++	++	++	+	++	+	+	+	+		++
Cycle 9		++	++	++	++	++	+	+	+	+		++
Cycle 10		++	++	++	++	++	++	++	++	+		++
Cycle 20		++	++	++	++	++	+	+	+	+		++
Cycle 30		++	++	++	+	++						++
Cycle 40		+	+	+	+	+						+
Cycle 50		++	++	++	++	++	+	+	+	+		++
Cycle 60		++	++	++	+	++	+	+	+	+		++
Cycle 70		+	+	+	+	+						+
Cycle 80		++	++	++	++	++	++	++	++	++		++
Cycle 90		++	++	++	+	++	+	+	+	+		+
Cycle 100		++	++	++	++	++	++	++	++	+		++
Cycle 200		+	+	+	+	+						+
Cycle 300		+	+	+	+	+						+
Cycle 400		++	++	++	++	++	+	+	++	+		++
Cycle 500		++	++	++	+	++	+	+	+	+		++
Cycle 600		++	++	++	+	++	+	+	+	+		++
Cycle 700		+	+	+	+	+						+
Cycle 800		++	++	++	+	++			+			++
Cycle 900		+	+	+	+	+						+
Cycle 1000		++	++	++	++	++			+			++
Cycle 2000		+	+	+	+	+			+			+

Fig. 8. Portrait of blade No. 1 for the model $\varphi_{T12,T01}$
a) with τ =1292, b) with τ =15, c) with τ =45

a)

	Portrait of blade No. 11 for the model $\phi_{T12,T01}$ - minimum velocity											
	L0	L1	L2	L3	L4	L5	M0	M1	M2	M3	M4	M5
Cycle 1		+	+	+		+	+	+	+	+		+
Cycle 2		+	+	+	+	+	+	+	+	+		++
Cycle 3		+	+	+		+	+	+	+	+		+
Cycle 4												
Cycle 5						+						+
Cycle 6												
Cycle 7						+						+
Cycle 8						+	+	+	+	+		+
Cycle 9												
Cycle 10		+	+	+		+	+	+	+	+		+
Cycle 20												
Cycle 30						+						+
Cycle 40		+	+	+		+	+	+	+	+		++
Cycle 50						+						+
Cycle 60						+						+
Cycle 70												
Cycle 80						+	+	+	+	+		+
Cycle 90		+	+	+		+	+	+	+	+		+
Cycle 100		+	+	+		+	+	+	+	+		++
Cycle 200												
Cycle 300		+	+	+		+	+	+	+	+		+
Cycle 400		++	++	++		++	++	++	++	++		++
Cycle 500												
Cycle 600		+	+			+	+	+	+	+		+
Cycle 700		+	+	+		+	+	+	+	+		+
Cycle 800		++	++	+	+	++	+	+	+	+		++
Cycle 900												
Cycle 1000		+	+	+		+	+	+	+	+		+
Cycle 2000		+	+	+		++	+	+	+	+		++

b)

	Portrait of blade No. 11 for the model $\phi_{T12,T01}$ - minimum velocity											
	L0	L1	L2	L3	L4	L5	M0	M1	M2	M3	M4	M5
Cycle 1		+	+	+		+	+	+	+	+		+
Cycle 2		+	+	+	+	+	+	+	+	+		++
Cycle 3		+	+	+		+	+	+	+	+		+
Cycle 4												
Cycle 5						+						
Cycle 6												
Cycle 7						+	+	+	+			+
Cycle 8						+	+	+	+	+		+
Cycle 9												
Cycle 10		+	+	+		+	+	+	+	+		+
Cycle 20												
Cycle 30						+						+
Cycle 40		+	+	+		+	+	+	+	+		++
Cycle 50						+	+	+	+			+
Cycle 60						+						
Cycle 70												
Cycle 80						+	+	+	+	+		+
Cycle 90		+	+	+		+	+	+	+	+		+
Cycle 100		+	+	+		+	+	+	+	+		++
Cycle 200												
Cycle 300		+	+			+	+	+	+	+		+
Cycle 400		++	++	+	+	++	++	++	++	++		++
Cycle 500												
Cycle 600		+	+			+	+	+	+	+		+
Cycle 700		+	+	+		+	+	+	+	+		+
Cycle 800		++	++	+	+	++	+	+	+	+		++
Cycle 900												
Cycle 1000		+	+			+	+	+	+	+		+
Cycle 2000		+	+	+		++	++	++	+	+		++

c)

	Portrait of blade No. 11 for the model $\phi_{T12,T01}$ - minimum velocity											
	L0	L1	L2	L3	L4	L5	M0	M1	M2	M3	M4	M5
Cycle 1		+	+	+		+	+	+	+	+		+
Cycle 2		+	+	+	+	+	++	++	++	+	+	+
Cycle 3		+	+	+		+	+	+	+	+	+	+
Cycle 4												
Cycle 5												
Cycle 6												
Cycle 7							+	+	+	+		
Cycle 8							+	+	+	+		
Cycle 9												
Cycle 10		+	+	+		+	+	+	+	+	+	+
Cycle 20												
Cycle 30							+					
Cycle 40		+	+	+		+	++	++	+	+	+	+
Cycle 50												
Cycle 60												
Cycle 70												
Cycle 80												
Cycle 90		+	+	+		+	++	+	+	+	+	+
Cycle 100		+	+	+		+	++	++	+	+	+	+
Cycle 200												
Cycle 300						+	+	+	+	+		+
Cycle 400		+	+	+	+	++		+	++	++		++
Cycle 500												
Cycle 600						+	+	+	+	+	+	+
Cycle 700		+	+	+		+				+		+
Cycle 800		+	+	+	+	++			+	++		+
Cycle 900												
Cycle 1000						+				+		+
Cycle 2000		+	+	+		+			+	+		+

Fig. 9. Portrait of blade No. 11 for the model $\varphi_{T12,T01}$
a) with τ =1292, b) with τ =15, c) with τ =45

a)

Portrait of blade No. 3 for the model $\phi_{T12,T01}$ - minimum velocity

	L0	L1	L2	L3	L4	L5	M0	M1	M2	M3	M4	M5
Cycle 1												
Cycle 2												
Cycle 3												
Cycle 4												
Cycle 5		+	+	+								
Cycle 6												
Cycle 7												
Cycle 8												
Cycle 9												
Cycle 10												
Cycle 20												
Cycle 30												
Cycle 40												+
Cycle 50												
Cycle 60												
Cycle 70												
Cycle 80												
Cycle 90												
Cycle 100												+
Cycle 200												
Cycle 300												
Cycle 400											+	+
Cycle 500												
Cycle 600												
Cycle 700												
Cycle 800												
Cycle 900												
Cycle 1000												
Cycle 2000												

b)

Portrait of blade No. 3 for the model $\phi_{T12,T01}$ - minimum velocity

	L0	L1	L2	L3	L4	L5	M0	M1	M2	M3	M4	M5
Cycle 1												
Cycle 2												
Cycle 3												
Cycle 4												
Cycle 5		+	+	+								
Cycle 6												
Cycle 7												
Cycle 8												
Cycle 9												
Cycle 10												
Cycle 20												
Cycle 30												
Cycle 40												+
Cycle 50												
Cycle 60												
Cycle 70												
Cycle 80												
Cycle 90												
Cycle 100												+
Cycle 200												
Cycle 300												
Cycle 400												
Cycle 500												
Cycle 600												
Cycle 700												
Cycle 800												
Cycle 900												
Cycle 1000												
Cycle 2000												

c)

Portrait of blade No. 3 for the model $\phi_{T12,T01}$ - minimum velocity

	L0	L1	L2	L3	L4	L5	M0	M1	M2	M3	M4	M5
Cycle 1												
Cycle 2												
Cycle 3												
Cycle 4												
Cycle 5		+	+	+		+						+
Cycle 6												
Cycle 7												
Cycle 8					+							
Cycle 9												
Cycle 10												
Cycle 20					+							
Cycle 30												
Cycle 40							+	+	+	+		
Cycle 50							+					
Cycle 60												
Cycle 70												
Cycle 80												
Cycle 90												
Cycle 100							+	+				
Cycle 200												
Cycle 300							+	+				
Cycle 400												
Cycle 500												
Cycle 600												
Cycle 700												
Cycle 800												
Cycle 900												
Cycle 1000												
Cycle 2000												

Fig. 10. Portrait of blade No. 3 for the model $\varphi_{T12,T01}$
a) with τ =1292, b) with τ =15, c) with τ =45

On the basis of portrait analysis of blades Nos. 1, 11, 3 shown in Figs. 8, 9, 10, it is found that the choice of the course of a distribution function does not matter to a great extent. However, it is recommended that its course (number of samples) equals the number of signal samples and the initial value is 0.

From portraits it can be also inferred that the blade No. 1 is the most damaged one (has a lot of "++"), considerably worn out is the blade No. 11 (has only few "++") and worn out only to a little extent is the blade No. 3 (almost without "+").

6. CONCLUSION

Method of current assessment of blade technical condition changes basing on diagnostic model $\varphi_{T12,T01}$ is innovative method of blade diagnostics without environment signal measurements.

The equation $\varphi_{T12,T01}$ (11) comprises diagnostic signals y(t) with environment signals x(t) so this is a diagnostic model. Characteristic features of this model are: its determination only on the basis of the measurable signal y(t) in observation periods T_{01} and T_{12} that occur shortly one after another and, what is the most important, taking environment of x(t) into account without the need to measure it as well as sufficient noise suppression of signal y(t) [13, 15, 17, 18].

In order to determine signals $S^{T12}{}_{xy}$, $S^{T01}{}_{xy}$, distribution in the form of the function $\delta(t, \hat{t})$ has to be used because it can be easily proven that the quotient of the reciprocal power density function of the signal y and the signal x is insensitive to environment signal x, thus, to a sufficient extent, it eliminates real environment from the model $\varphi_{T12,T01}$ [1,18,23].

Method of blade technical condition monitoring may be based on diagnostic model in form of difference phase shift of output y(t) signal to environment signal x(t) for observation time T_{01} and T_{12}. This method consists in fact that time T_{02} (Fig. 4.) of blade tip movement in sensor area is divided onto two ranges: of blade tip approaching the sensor T_{01} and receding from it T_{12}.

Periods T_{01} and T_{12} of signal y(t) observation are placed so close to each other that the environment x(t) for those periods of signals y(t) observation may be considered identical.

Distinctive feature of model $\varphi_{T12,T01}$ is no necessity of environment signals measurement although these are indirectly taken into account within special research (two observation periods, determination of diagnostic model as a quotient of models binding diagnostic and environment signals to technical condition parameters).

Presented results for the model $\varphi_{T12,T01}$ do not differ when distribution courses are different. Thus, it can be found that there are real opportunities of employing the diagnostic model $\varphi_{T12,T01}$ in diagnosing turbomachine blades during their operation without the need to measure an environment signal.

Blade portraits determined from the model $\varphi_{T12,T01}$ confirm the state of damage presented in the pictures.

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