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Vibroacoustical diagnosis of the crack-like damages of aircraft engine blades at the steady-state and non-steady-state modes

Nadiia BOURAOU
National Technical University of Ukraine "Kiev Polytechnic Institute", 37 Peremogy Pr., Kyiv, Ukraine, 03056, burau@pson.ntu-kpi.kiev.ua

Iurii SOPILKA
National Technical University of Ukraine "Kiev Polytechnic Institute", 37 Peremogy Pr., Kyiv, Ukraine, 03056, sopilk@ukr.net

Abstract

The work is devoted to condition monitoring and vibroacoustical diagnosis of the crack-like damages of the gas-turbine engines (GTE) blades at the steady-state and non-steady-state modes of GTE. The developed diagnostic model of GTE is presented and the influence of damage on the measured vibro- and acoustical signals at the steady-state and non-steady-state modes of GTE is determined. The application of the following signal processing methods: Polyspectral (Higher-Order Spectral) analysis, Wavelet-transformation and dimensionless characteristics of the vibroacoustical signals is proved. The efficiency of signal processing methods is demonstrated by the results of numerical simulations of the turbine stage at the steady-state and non-steady-state modes of vibration excitation. The fault features are detected and investigated.

Keywords: gas-turbine engine, crack-like damage, vibroacoustical diagnosis, signal processing

1. Introduction

Statistics about aircraft gas-turbine engine (GTE) failures demonstrate that the most part of these failures, led to premature taking away the engine, are provoked by the damages of the compressor components (from 20% to 76%) and the turbine ones (from 15% to 65%). The mentioned engine failures are caused by typical totality of damages as: nicks, dents, bending of compressor blades; cracks and compressor blades break; nicks and burning turbine blades. After scheduled inspections and repair, more then a half of blades are culled because of erosion, nicks, initial cracks and burning. According to analysis, the some of these damages (named crack-like damages) could be found out at initial stage of its evolution without engine disassembling if the continuous monitoring of the engine components condition was conducted.

The problem of detection of the crack-like damages of blades at the steady-state and non-steady-state modes of GTE may be solved by using the vibration and vibroacoustical diagnostic methods [1]. Creation of the monitoring system is based on application and further development of low-frequency (0-25 kHz) vibroacoustical diagnostic methods which use vibrating and acoustical noise as diagnostic information. This noise is radiated by the turbine and compressor stages at the GTE operating.

Generally monitoring is a continuous process of information gaining about the object vibrating condition, its transformation, signal processing and making decision about object technical condition. The stages of the mentioned informative process depend on the engine operative modes. These modes define specific character of vibrating and acoustical excitation of the compressor and turbine blades, and consequently, they define the methods and algorithms of signal processing, which will allow to detect initial faults.

Initiation and increase of a crack-like damages in the blade lead the instantaneous change of its stiffness. Usually the change of stiffness is modeled by the piecewise-linear characteristic of the restoring force [1,2]. At low a level of a useful signal in vibrating and acoustic noise which is radiated by the engine at its operating, use of traditional spectral analysis is inefficient for incipient cracks detection. In this paper we propose to use the Bispectrum analysis (BS), Wavelet Decomposition (WD) and Dimensionless Peak Characteristics (DPC) of the vibroacoustical signals for the signal processing and fault features extraction.

2. Diagnostic model of GTE and measuring signal conditioning

The GTE is the compound system which consisting of many subsystems, assemblages and devices. Deriving of full mathematical exposition of GTE behavior is hampered, therefore for the purpose of diagnostic, as a rule, the simplified models of GTE are used (for example, at the engine separation on subsystems and devices with hierarchical structure of connections). According to mentioned diagnostic model of GTE has been developed. The main prominent features of diagnostic model are:

1. Model includes set of n stages (subsystems "disk-blades") which are rotation by a rotor of the engine.

2. The basic and most important source of vibration at the engine operation is the rotor, therefore rotor vibration $P(t)$ is considered as the basic entrance vibrating excitation on subsystems "disk- blades ".

3. Rotor vibration model at the steady-state mode (named m1) of GTE has been accepted in the form:

$$P(t) = \sum_{i=1}^{l} P_i(t) \sin\left[i\omega_p t + \varphi_i(t)\right] + \xi(t), \quad (1)$$

where $P_i(t)$ is the amplitude of a harmonic whith number i; ω_p is the main rotation frequency; $\xi(t)$ is the broadband normal noise.

4. Rotor vibration model at the non-steady-state modes (named m2 and m3) of GTE has been accepted in the form:

$$P(t) = \sum_{i=1}^{3} P_i(t) \sin\left[\omega_{p0} \pm 0{,}5 i\beta t^2 + \varphi_i(t)\right] + \xi(t), \quad (2)$$

where ω_{p0} is the initial value of rotation frequency; β is speed of frequency variation of the first rotor harmonic; the sign "+" corresponds to a mode m2 with the fast increase of the rotor rotation frequency and the sign "-" corresponds to a mode m3 with the decrease of the rotor rotation frequency.

5. In relation to described above rotor excitation set of n stages is represented in the form of parallel connection of n subsystems "disk- blades". Generally reaction of system on rotor vibration represents the following n-dimensional vector of reactions:

$$R_p(t) = [R_{p1}(t), ..., R_{pn}(t)],$$

where $R_{Pj}(t)$ is the reaction of subsystem with number *j* on excitation $P(t)$, and which are represented by the following expression in case of elastic and dynamic independence of oscillations of blades and the disk:

$$R_{Pj}(t) = \sum_{q=1}^{z_j} r_{Pjq}(t) + r_{Pjd}(t). \tag{3}$$

In the expression (3) following designations are used: $r_{Pjq}(t)$ is reaction of blade with number *q*; $r_{Pjd}(t)$ is reaction of disk; z_j is blades quantity at the selected stages.

6. Unfailing blades are described by the model of an linear oscillating system with natural frequency ω_* ($f_* = 600$ Hz). The impulse response of it is:

$$g_*(t) = \frac{1}{\omega_*} \sin \omega_* t . \tag{4}$$

The model of a blade with a crack-like damage is presented by the model of an oscillating system with piecewise-linear (asymmetrical) characteristic of the elastic force. The impulse response of this system is expansion in Fourier series at harmonics of the cracked blade model base frequency ω_0 [1]:

$$g(t) = \frac{a_0}{2} + \sum_{k=1}^{K} a_k \cos k\omega_0 t , \tag{5}$$

where $a_0 = \dfrac{4(1-\varsigma)}{\pi\omega_*\varsigma}$; $a_k = \dfrac{4(1+\varsigma)^3(1-\varsigma)^2}{\pi\omega_*\varsigma[(\varsigma+1)^2-4k^2][(\varsigma+1)^2-4\varsigma^2k^2]}\cos\dfrac{\pi k}{\varsigma+1}$; $\omega_0 = \dfrac{2\omega_*\varsigma}{1+\varsigma}$;

$\varsigma = \sqrt{1-\vartheta}$; ϑ - crack parameter, relative rigidity changing at the crack presence.

The reaction of one blade on excitation $P(t)$ in the form (1) or form (2) can be defined by Duhamel integral:

$$r_{Pjq}(t) = \int_{-\infty}^{t_k} P(\tau) g_{jq}(t,\tau) d\tau , \tag{6}$$

where $g_{jq}(t,\tau)$ is the blade impulse response (4) or (5).

7. Each stage oscillates vibration of an aerodynamic origin $Q_j(t)$ on rotor frequency and in z_j times more. Mathematical expression of vibration similarly to (1). Other aerodynamic vibration $S_j(t)$ is excited by processes in an air-gas tract of a GTE and described as additional random entrance effects on each blade $s_{jq}(t)$. In case of not correlated $P(t)$ and $s_{jq}(t)$ reaction of a blade on $s_{jq}(t)$ is represented additive component $r_{Sjq}(t)$ in vector of reactions by using integral (6). Let's consider also acoustical noise $B_j(t)$ directly radiated by a compressor and turbine, which model is similar (1), noise

with continuous spectrum $D_j(t)$ on an exit of each stage, which is caused by turbulent phenomena and an eddy generation, and also broadband vibration of low intensity $N(t)$ from non-power elements of GTE.

Stated above has allowed to generate model of measured vibroacoustical signal $X(t)$ in the following form:

$$X(t)=\sum_{j=1}^{n}\{\sum_{q=1}^{z_j}[r_{Pjq}(t)+r_{Sjq}(t)]+\sum_{i=1}^{n_1}Q_{ji}\sin\left(i\omega_p t+i\,z_j\omega_p t+\varphi_{j0i}\right)+ \\ +\sum_{i=1}^{n_2}B_{ji}\sin\left(i\,z_j\omega_p t+\varphi_{j0i}\right)+D_j(t)\}+N(t) \quad . \tag{7}$$

Depending on impulse response (4) or (5) model (7) reflects a state of the GTE at the absence or presence of blade crack-like damages, and it allows to research influence of a fault on behaviors of signal $X(t)$.

3. Signal processing and fault features analysis

The received model (7) is used for simulation and analysis of vibroacoustical processes which occur at the steady-state (m1) and non-steady-state (m2, m3) modes of GTE at absence and presence of small cracks in one blade of the turbine stage (the relative rigidity changing at the crack presence is considered ϑ=0,01;0,03;0,05;0,07;0,09). Parameters of vibration excitation (2) at the non-steady-state modes are selected such that at least the third harmonics of excitation at increase or a decrease of rotational speed transited through a resonance region of blades. The Fig. 1 presents examples of drawings of the simulated signals.

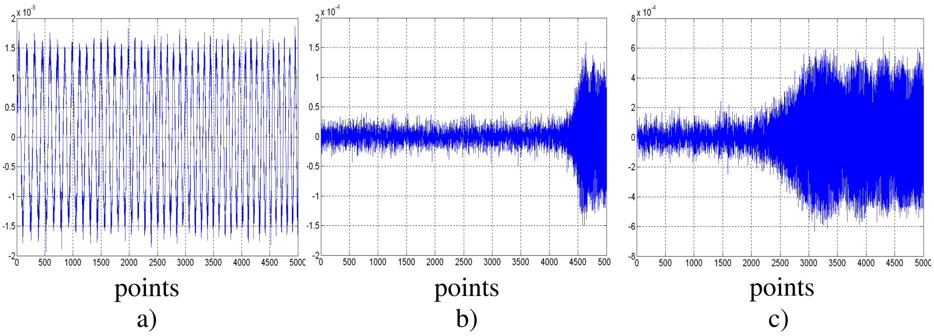


Figure 1. Examples of the simulated signals for modes m1 (a), m2 (b) and m3 (c)

Simulated signals were processed using BS, WD and DPS [2-4]. The examples of BS analysis results at the steady-state (m1) mode of GTE are shown on Fig. 2 for ϑ=0 and ϑ=0,05 at the crack presence. They are presented in a form of three-dimensional images characterizing bispectrum module dependence on frequencies f_1 and f_2 .

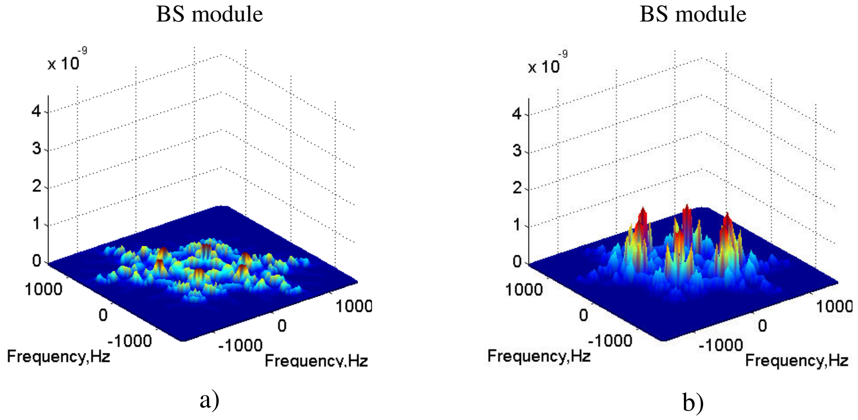


Figure 2. Examples of the BS module simulated signals for steady-state (m1) mode of GTE at the absence (a) and the presence crack (b)

As the results of diagnostic information processing demonstrate, appearance and development of a crack in the engine turbine lead to change of global and local extremum intensity of BS module estimators. We propose to use the ratio $D_{BS} = I_g / I_l$ as a fault features, where $I_{g(l)}$ is value of intensity of global (local) BS module maximum. The relationships between ϑ and D_{BS} for m1, m2 and m3 modes are illustrated in Table 1.

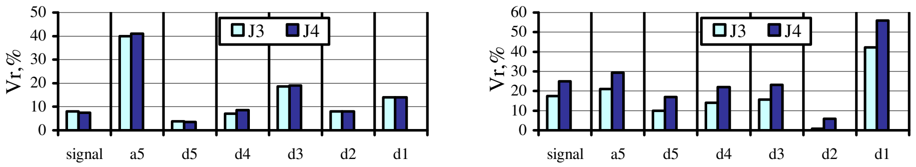
Table 1. Diagnostic features dependencies on a fault parameter.

ϑ	0	0,01	0,03	0,05	0,07	0,09
m1	2,10	2,23	2,55	2,82	3,02	3,30
m2	2,31	2,34	2,38	2,43	2,61	3,05
m3	1,82	1,83	1,85	1,91	1,98	2,01

The following DPC are used: J_3 - peak factor and J_4 - factor of background. The preliminary WD of signals is applied for the sensitivity increasing of DPC of the vibroacoustical signals as fault features. We used wavelets of Daubechies family db10 and 5 levels of decomposition, results are used as drawings of each level for next DPC evaluation. Fig.3 represents the values of relative speed in percents of the DPC changing (from ϑ=0 to ϑ=0,05) evaluated for initial signals and approximations (a5) and details (d1-d5) of their WD for m1 and m2 modes of GTE operation. Relative speed of the DPC changing is calculated in the following form:

$$V_r = \frac{\left| J_r - J_r^* \right|}{J_r^*} \cdot 100\% ,$$

where J_r, J_r^* are feature values at the crack presence and absence, accordingly.



a) b)

Figure 3. Relative speed of the DPC changing evaluated for signals and elements of their WD for m1(a) and m2 (b) modes of GTE

Apparently from the presented results, DPC of approximation a5 are the most sensitive fault features for a mode m1, and DPC of a detail d1 are the most sensitive fault features for a mode m2. For a mode 3 (schedules are not presented) expediently to use DPC for a detail d2, their relative speed of change makes 20%.

4. Conclusions

Developed diagnostic model of GTE allows to form the model of measured vibroacoustical signals for further simulation and analysis the influence of damages on the vibroacoustical characteristics of GTE at the steady-state and non-steady-state modes.

Application of a modern signal processing methods allows to detect fault features, which are sensitive to small crack-like damages. The received results can be used to create a vibroacoustical monitoring system for aircraft engine rotor components.

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