ESTIMATION OF THE BASIC FREQUENCIES OF THE DETERMINISTIC COMPONENTS AT GAS-TURBINE ENGINE VIBRATION SIGNAL

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Vibration spectra of gas-turbine engines with balanced and unbalanced rotor are analysed. Random and regular components are divided using the PNRP approach to discover and analyze its hidden periodicity. The engine with unbalanced rotor is characterized by the power for the harmonic with rotation frequency about ten times more than balanced. The indicator for the description of the engine’s rotor state as a ratio of powers of harmonics with basic frequency of the deterministic component is proposed.

Keywords: periodically non-stationary random process; basic frequency; gas-turbine engines; balancing

Introduction. The vibration signal of the gas-turbine engines with unbalanced rotor in literature [1–5] are characterized by the peak values of their amplitude spectra at the points, defined by the first harmonic of rotor rotation frequency. As a rule, the amplitude spectrum of this signal is found using the Fourier transform (FT) of the raw signal, assuming that it is a periodical function. In the case of random-like signals, power spectrum densities obtain as a result of applying of the periodogram or Blackman-Tukey spectral estimator. If we suppose that the experimental data are the sum of harmonics and random process, then both processing procedures are inadequate to this representation and result will be inconsistent, so the amplitude and power values for the harmonics will be calculated with large errors. In these cases, the revealing of the harmonics of basic frequency as well as estimating of their values should be carried out using the vibration signal model in the form of the PNRP approach, used in this work.

Estimation of the basic frequencies of the deterministic components of vibration signal. Vertical component of the acceleration vibration signals $\xi(nh)$ were acquired from bearing fixes of two gas-turbine engines with balanced and unbalanced rotor. We analyzed the low-frequency part of vibration spectrums $(< 2kHz)$ of these signals. The covariance function estimators for these different cases, are shown in Fig. 1. In Fig. 2 the respective estimators of the power spectral densities are presented, herewith Hamming window was used.

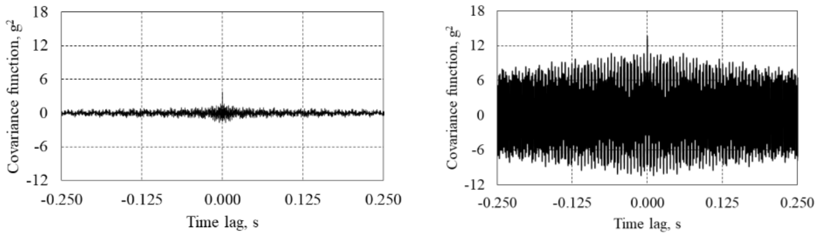

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Fig. 1. Estimators of the covariance function of vibration signals for the balanced (a) and unbalanced (b) engines.

As we can see, both covariance functions contain the random components with rapidly and slowly damping correlations as well as undamped oscillations. The total signal power in the case of unbalanced rotor equal to 13.63 g^2, it is essentially larger than in the case of balanced rotor (3.83 g^2). The availability of power undamped oscillations on the correlation functions (Fig. 1), testify about the presence in the signal composition of the deterministic harmonic components, herewith the total power of these components is much higher in the case of engine with the unbalanced rotor.

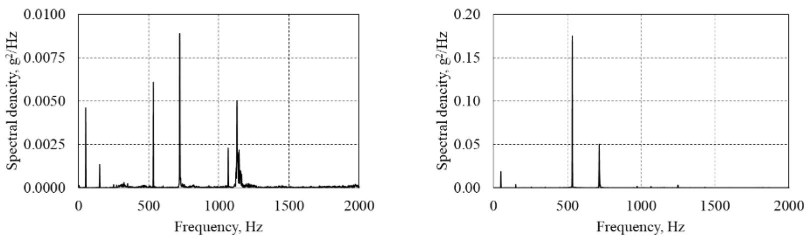

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Fig. 2. Estimators of the power spectral densities of the vibration signals for the balanced (a) and unbalanced (b) engines.

So, we have a mixed power spectrum of the signals. It means that the peak values in Fig. 2 can be caused both by the powers of deterministic harmonics and the values of narrow-band spectral densities of the random components. To divide the deterministic and random components we use the method for discovering of the first order hidden periodicities [6].

The estimation of the basic frequencies of the deterministic components is the first issue of the vibration harmonic analysis. To find the basic frequencies, the special functionals can be used [6, 7], that are similar to the PNRP coherent or component statistics for mean function estimators with the except that test basic frequency is inserted to replace the true period. These functionals have extreme values at the points, which are asymptotically unbiased and consistent basic frequency estimators. To improve the efficiency of estimating of basic frequencies, the least square (LS) method was proposed in [7]. As the signal realization length increases, the LS functional for determining of the basic frequencies of the mean function quickly tends to:

$$\hat{F}_1(f) = \frac{1}{2}\sum_{k=1}^{L_1}\left[\left[\hat{m}_k^c(f)\right]^2 + \left[\hat{m}_k^s(f)\right]^2\right], \tag{1}$$

where

$$\begin{Bmatrix}\hat{m}_k^c(f)\\ \hat{m}_k^s(f)\end{Bmatrix} = \frac{2}{2K+1}\sum_{n=-K}^{K}\xi(nh)\begin{Bmatrix}\cos(2k\pi fnh)\\ \sin(2k\pi fnh)\end{Bmatrix},$$

2Θ is the realization length, $h = \Theta/K$ is the sampling step and L_1 is number of harmonics for each component, f is a test frequency. The maximum points $\hat{f}_0^{(i)}$ of (1) is asymptotically unbiased and consistent estimator for the mean basic frequency. The functional (1) at the maximum point $f = \hat{f}_0^{(i)}$ is close to the sum of time-averaged power of the chosen harmonics:

$$\hat{F}_1\left(\hat{f}_0^{(i)}\right) = \hat{P}_t^{(d_i)} = \frac{1}{2}\sum_{k=1}^{L_1}\left[\left[\hat{m}_k^c\left(\hat{f}_0^{(i)}\right)\right]^2 + \left[\hat{m}_k^s\left(\hat{f}_0^{(i)}\right)\right]^2\right].$$

The quantities $\hat{m}_k^c\left(\hat{f}_0^{(i)}\right)$ and $\hat{m}_k^s\left(\hat{f}_0^{(i)}\right)$ are asymptotically unbiased and consistent estimators of the Fourier coefficients for the mean function of each component.

We calculated the functional $\hat{F}_1\left(\hat{f}_0^{(i)}\right)$ changing the test frequency f in the neighborhood of the points at which the spectral density estimator reaches maximum values (Fig. 2). The graphs of the dependencies for $\hat{F}_1(f)$ on test frequency in the spectral interval close to 533 Hz (rotor rotation frequency) for balanced and unbalanced engines are shown in Fig. 3.

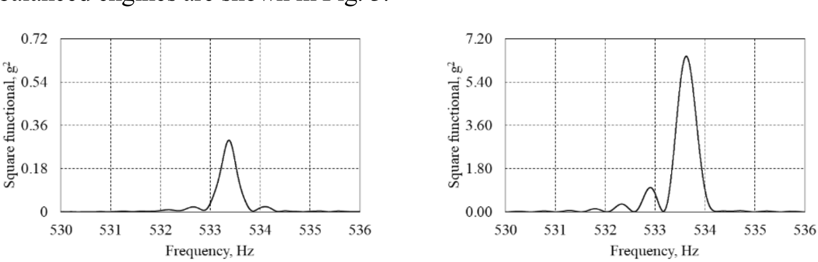

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Fig. 3. Dependences of functional $F_1(f)$ on test frequency 533 Hz for balanced (a) and unbalanced (b) engines.

The peak values of $\hat{F}_1(f)$ in all cases are clearly visible, and the maximum points $\hat{f}_0^{(i)}$ are easily determined. As we can see, the amplitude spectrum of deterministic oscillations contains the rotor rotation frequency 533.62 Hz, as well as the harmonics with higher frequencies. The values of all amplitudes increase as the fault occurs (in the case with unbalanced rotor), however the amplitude of harmonic with rotation frequency increases most of all. The ratio of the amplitudes for the unbalanced (u) and balanced (b) engines is equal to: $A^{(u)}\left(k\hat{f}_0^{(1)}\right) \big/ A^{(b)}\left(k\hat{f}_0^{(1)}\right) = 5.36$. The harmonic power in the second case becomes more then twenty-eight times as much as in the first case. Then we can choose the ratio $I_1 = \left[A^{(u)}\left(k\hat{f}_0^{(1)}\right)\right]^2 \Big/ \left[A^{(b)}\left(k\hat{f}_0^{(1)}\right)\right]^2$ as one of the indicators for the description of the engine's rotor state.

Conclusions. It is shown that the vibration spectra of gas-turbine engine with balanced and unbalanced rotor are mixed, i.e. they contain the deterministic and stochastic components. These components are divided using the PNRP approach to discover and analyze hidden periodicities. The engine with unbalanced rotor is characterized by the largest increasing of the power for the harmonic with rotation frequency. It is shown that the measure of non-stationary becomes larger for the engine with unbalanced rotor. The indicator, in which the change of the powers for the deterministic component took into account, is proposed.

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