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On-board vibration diagnostics of shaft damage of the aviation engine

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Abstract

This work is devoted to the further researches and development a new on-board multilevel vibration control system of aviation gas-turbine engines (GTE). We propose to introduce new diagnosis level (subsystem) into development multilevel vibration control system for detection of the initial crack-like damage of rotor shaft. The proposed subsystem works at the non-steady-state modes of GTE, for example during startup at the acceleration to operating speed. The basis of this approach is the fact of the occurrence of sub harmonic resonances of accelerating cracked shaft response. It is necessary to extract the main rotor harmonic vibration at the non-steady-state mode for crack diagnosis in practice. The narrow-band digital tracking filter is carried out for this aim, the central frequency of pass band is changing according the rotor rotation frequency. The efficiency of the proposed subsystem is demonstrated by the results of computer simulation.

Keywords: gas-turbine engine, cracked shaft, vibration diagnosis, digital tracking narrow-band filter.

1. Introduction

Available on-board vibration control systems of aviation gas-turbine engines (GTE) are destined for current control and awareness about actual levels of vibration at the harmonics of the rotor rotation. However, many initial defects of rotor elements (microcracks of shafts, blades, disks) cannot be detected at early stages of the crack development in this case. We proposed to expand the functional capabilities of the above mentioned systems by using the auxiliary level for diagnostics of initial crack-like damages of engine blades. The new multilevel vibration control system of aviation GTE has been presented in the previous work [1]. The developed system contains complementary dedicated microcontroller for analysis of the "normal vibration" in order to predict or detect small damages of engine blades. In addition, another diagnostic level can be carried out for diagnostics of dangerous damages rotor elements such as crack-like damages of rotor shaft.

The theoretical bases of the vibration method were presented in [2] for diagnosis of the cracks of rotating shafts during acceleration through resonance. The model of the transverse crack is a function of "breathing", the changing of the rotor rigidity ΔK depends on cross location of crack section and stress-strain area of shaft. The accelerated rotation of the shaft with crack is investigated. It has been shown, the responses of cracked shaft have sub-critical peaks (1/2 order and 1/3 order sub-harmonics resonance of the main harmonic of rotor rotation). For example, the absence and the presence of 1/2 order sub-critical peak are illustrated in Fig. 1 at the absence (ΔK=0) and the presence of initial crack (ΔK=0,05), accordingly. The time plots are represented in the relative scale on the ordinate axis (non-dimensional vibration amplitude z) and on the abscissa (non-dimensional time τ). Value τ=1000 corresponds to transition through critical frequency of rotation.

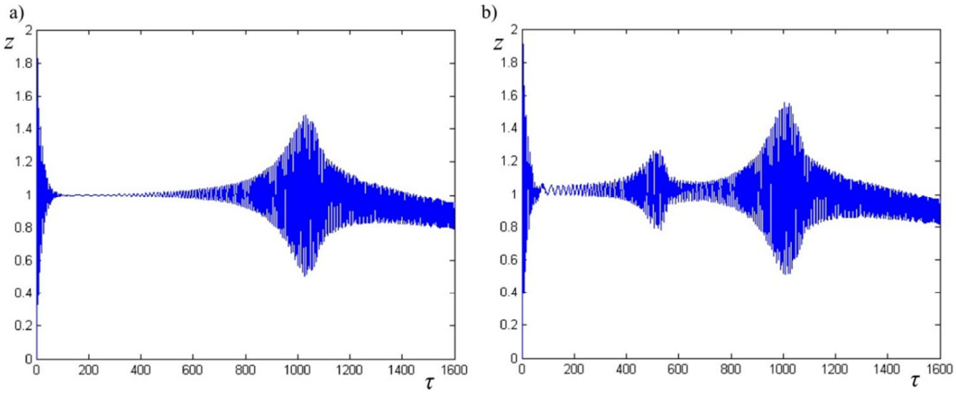

Figure 1. Vibration amplitude of accelerated rotor at the ΔK=0 (a) and ΔK=0,05 (b)

Researches have shown, that sensitivity of sub-critical peaks to crack presence many times over surpasses sensitivity of nature frequencies and shapes of oscillations. However it is necessary to estimate vibration levels on the rotor rotation harmonics at the essential changing of frequency of rotation for the usage of sub-critical peaks values as the features of crack-like damages of rotor shaft.

The purpose of this work is the development a new diagnostics subsystem of above mentioned multilevel vibration control system for diagnostics of crack-like damages of rotor shaft at the non-steady-state mode of GTE.

2. Subsystem development

The generalized block scheme of the developed diagnostics subsystem is shown in Fig. 2. Signals arrive from vibration sensors to the digital tracking narrow-band filter after preliminary processing and conversion. The central frequency f_0 of a pass-band of the filter is time-dependent and changes synchronously with change of frequency of rotation of a rotor shaft. Sensors of frequency of rotation are used for this purpose. Instantaneous value $\omega_r(t)$ of the frequency of main rotor harmonic is defined, then coefficients of the tracking narrow-band filter are calculated for the given value of mentioned frequency. Recalculation of coefficients is carried out for each new value of the central frequency of a pass-band of the filter which is equal to the calculated value of instantaneous frequency of shaft rotation. Peak values of vibration amplitudes are determined after a filtration in the field of sub-harmonic resonances. The received values are compared with threshold and the decision is made on crack presence or absence of a shaft. The algorithm of the synthesis of digital tracking narrow-band filter and a filtration of a non-stationary vibrating signal is shown in Fig. 3.

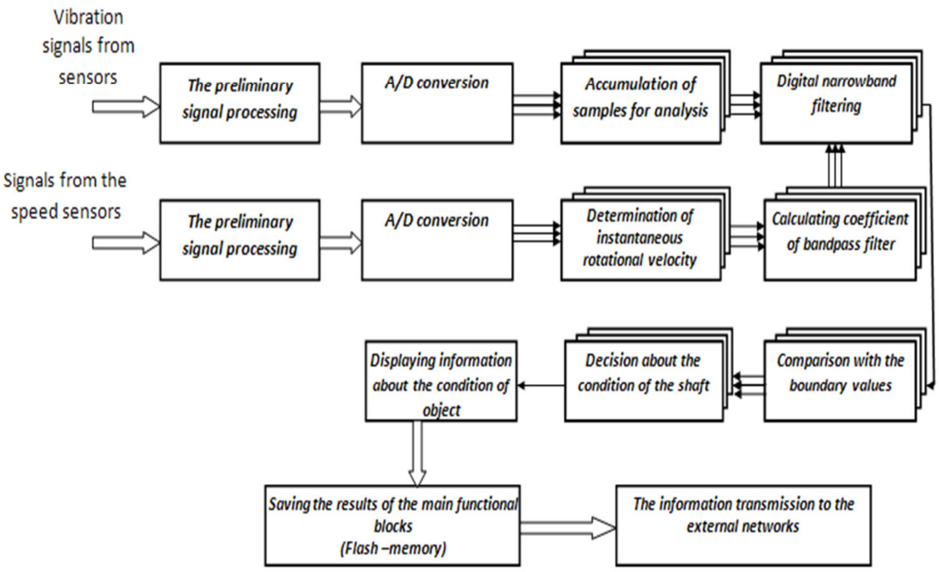

Figure 2. Generalized block scheme of the subsystem for diagnostics of crack-like damages of rotor shaft at the non-steady-state mode of GTE

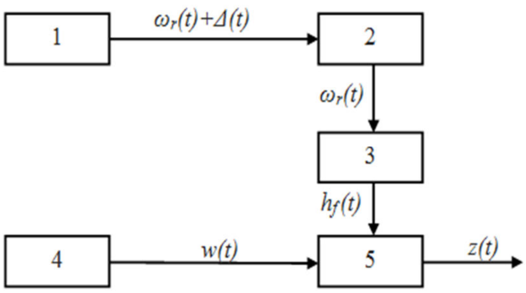

Figure 3. Algorithm of the synthesis of digital tracking narrow-band filter and the filtration of the non-stationary vibrating signal

The following symbols are indicated on Fig. 3: 1 - speed sensor; 2 - unit of determination of instantaneous rotation frequency; 3 - unit of calculating coefficient of digital filter; 4 - vibration sensor; 5 - filtration unit; Δ (t) - noise of measurement of the time-dependent rotation frequency; $h_f(t)$ - filter impulse response; w(t) – input vibration signal; z(t) - selected component of vibration.

Recalculation of coefficients of the digital tracking narrow-band filter is carried out at change of the central frequency of a pass-band according to change of frequency of rotor rotation. It is necessary to provide recalculation of coefficients with the period of definition of current frequency of rotor rotation in this case. As a rule, regular means of registration of parameters of the engine provide the period of registration 0,25 second at flight tests. Therefore, it is necessary to consider the restrictions connected with change of frequency rotation and the period of registration. We propose to use filters with the infinite pulse characteristic [3] and the least optimum order for a delay exception in calculations of filter coefficients. The Butterworth adaptive (tracking) filter is designed, minimal order is equal to 10 at the change of central frequency f_0 of a pass-band in the range of 10….100 Hz, the pass-band of filter is constant and it is equal Δf_p=3 Hz. The time of calculation of coefficients of the mentioned filter is equal to 0,122 second.

Computer simulation is carried out for the validation of efficiency of the designed filter. Vibration signals are simulated at the accelerated rotation of a shaft without damage (ΔK=0) and with damage (ΔK=0,05; 0,1; 0,15; 0,2) by using the mathematical model of rotary shaft, presented in [2]. Various corners of crack orientation relative to vector of vibration and various corners of unbalanced weight orientation relative to a middle line of a crack are considered. The mentioned vibration signals together with the white noise and high-frequency interferences are used as the input signals to the filtration unit (Fig. 3). Difference values Δz of amplitudes of signals after filtering at the presence (ΔK≠0) and at the absence (ΔK=0) shaft damages and their approximations are used for an estimation of quality of tracking filtration [4]. The non-dimension time set of values Δz and approximation are represented in Fig. 4.

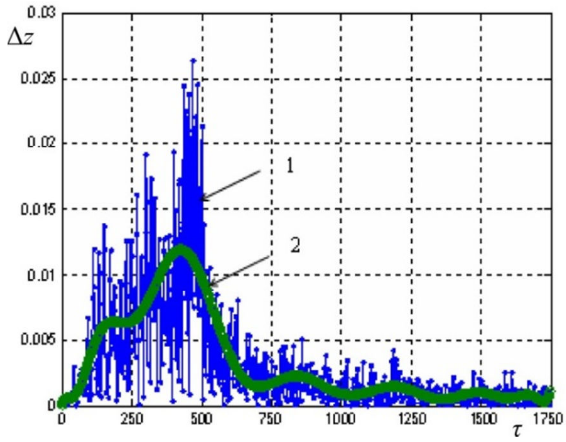

Figure 4. Set of difference values Δz (1) and approximation (2) of amplitudes of signals after filtering by using Butterworth adaptive (tracking) filter

Maxima of difference values Δz are located in a range of 1/2 order and 1/3 order subharmonics resonances of the main harmonic of rotor rotation. The presence of crack do not influence on resonance of main harmonic of rotor rotation, therefore difference values Δz are small. The presented results confirm the efficiency of the adaptive (tracking) filtering of non-steady vibration signals.

The subsystem for diagnostics of crack-like damages of rotor shaft at the non-steady-state mode of GTE is developed as virtual device by using LabVIEW (NI, USA). The front panel of virtual device is represented in Fig. 5.

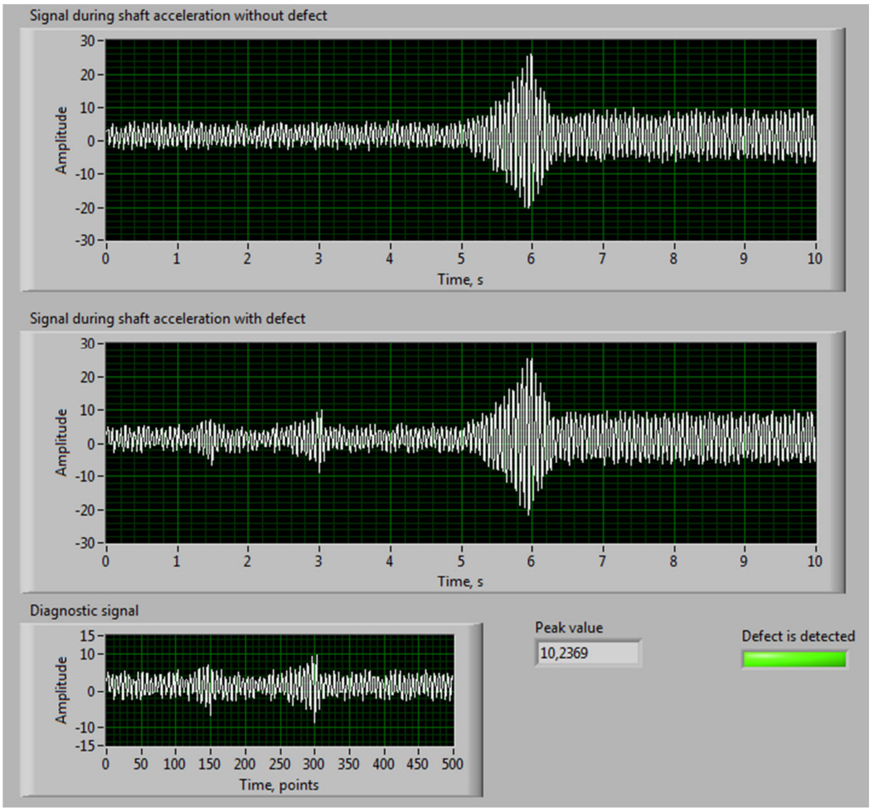

Figure 5. The front panel of virtual device - subsystem for diagnostics of crack-like damages of rotor shaft at the non-steady-state mode of GTE

The window "Diagnostic signal" contain the informative part of vibration signal to resonance of main harmonic of rotor rotation. Peak values z_p are estimated in this range and compared with the installed threshold (vibration amplitude is egual to 10 m/s). The alarm indicator "Defect is detected" lights up at excess of threshold value.

The carried out researches of virtual device have shown, that the increase of a crack parameter ΔK calls increase in peak values of vibration amplitude in the range of a sub-harmonic resonances at the same values of corners of crack orientation relative to vector of vibration and corners of unbalanced weight orientation relative to a middle line of a crack. The functional relation is similar to linear function (Fig. 6).

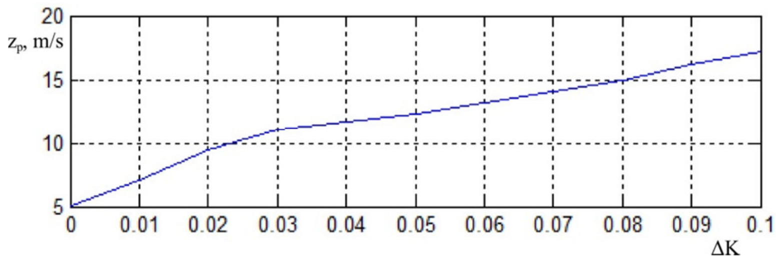

Figure 6. Relation between peak values of vibration amplitude and the crack parameter

3. Conclusions

The new diagnostics subsystem of multilevel vibration control system is developed for diagnostics of crack-like damages of rotor shaft at the non-steady-state mode of GTE.

The generalized block scheme of the subsystem is designed and principle of its operation is substantiated. The digital tracking narrow-band filter is designed in order to extract of vibration signal on the time-depended frequency of rotor rotation. The central frequency of a pass-band of filter is changing according to change of frequency of rotor rotation. Sub-critical peaks values (1/2 order and 1/3 order sub-harmonics resonances) of extracted vibration signal are used as the features of crack-like damages of rotor shaft. The diagnostics subsystem as a virtual device is developed and investigated.

The developed subsystem of multilevel vibration control system will allow to detect initial crack-like damages of rotor shaft and to ensure awareness of GTE.

References

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