Vibroacoustic Condition Monitoring of the Complex Rotation System Based on Multilevel Signal Processing

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Abstract

This work is devoted to further research and improvement of the vibroacoustic condition monitoring of complex rotation system during operation. The low-frequency vibration and acoustic noise in the range 0-10 kHz is used as diagnostic information. We propose to use Bispectrum (BS) Analysis at the first level of signal processing, and Fractal Analysis of BS contour images at the second level of signal processing for the diagnosis of small imbalance of rotation system. The experimental studies of forced vibrations of the physical model (PM) of the rotation system are carried out under steady-state and non-steady-state rotation excitations. The results of the BS Analysis of vibroacoustical signals, which are emitted by a rotating PM during different excitation modes, are processed in order to determine fractal box-counting dimension (Minkowski dimension). The research shows that a small imbalance can be efficiently detected by the proposed multilevel signal processing in all modes of PM operation.

Keywords: rotation system, signal processing, Bispectrum Analysis, fractal box-counting dimension

1. Introduction

The operation of a complex rotation system, such as, for example, a gas-turbine engine (GTE), is accompanied by forced and resonant vibrations of its subassemblies and components. That is why most of the faults that occur in engines during their operation are either directly caused by vibrations, or are reflected in them. This work is devoted to further research and improvement of the condition monitoring of complex rotation systems to ensure their trouble-free operation. In [1] an Advanced Gas Turbine Health Monitoring System was proposed for GTE monitoring and prediction of the performance degradation. The mentioned overview includes the generalized monitoring algorithm which allows evaluating performance and detecting the trouble operation. In connection with this, the processing of diagnostic information in order to identify the features of faults is one of the basic procedures of condition monitoring [1,2].

Vibroacoustic monitoring is based on analysis of the low-frequency vibration and acoustic noise in the range 0-10 kHz. The results of processing of such noise-like signals are often rather complex for interpreting, comparing and deciding on the technical condition of the rotation system. We propose to use several stages or levels of processing of diagnostic information, based on various methods in order to detect the faults features and increase their diagnostic value. The application of Wavelet Decomposition and Dimensionless Peak Characteristics of the vibroacoustical signals in [3], as well as Time-Frequency Analysis and Fractal Analysis in [4] showed the effectiveness of multilevel processing of vibroacoustic signals for the diagnosis of small crack-like defects in the blades of a rotation system. In this paper we propose to use Bispectrum (BS) Analysis [5] at the first level of signal processing, and Fractal Analysis [6] of BS contour images at the second level of signal processing for the diagnosis of small imbalance of rotation system.

The purpose of this work is to substantiate the possibility and effectiveness of using the proposed multi-level signal processing in order to detect informative features of small imbalance of the rotation system in steady-state and non-steady-state modes.

2. Experimental studies of rotation system and Bispectrum Analysis of vibroacoustic signals

The experimental studies of forced vibrations of the physical model (PM) of the rotation system (air starter impeller) are carried out under steady-state and non-steady-state rotation excitations. The following two technical conditions of the PM are investigated: the absence and the presence of a small imbalance (additional load of small weight on one blade). The rotational speed of the PM in the steady-state mode is 3970 rpm, which corresponds to the rotating frequency of vibration excitation f_r = 66 Hz. We use a microphone connected through an amplifier to the PC for measuring the vibroacoustic signals emitted by the PM during rotation. The time interval of the measured signals is 25,6 seconds. During this time interval the following modes of operation are simulated: accelerating mode, transient mode, steady-state excitation with constant speed of rotation and running-out mode. Vibroacoustic noise is measured with a sampling rate f_{sr} = 16 kHz so that each sample contains N =409600 points. Fig. 1 shows one of the realizations of the measured signal for a PM without imbalance.

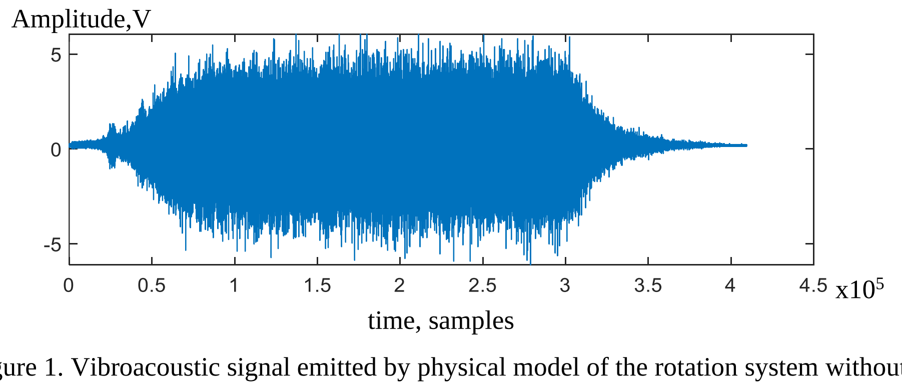

Figure 1. Vibroacoustic signal emitted by physical model of the rotation system without imbalance

We divide the measured signal into separate samples of different lengths in order to process the information separately for each mode of vibration excitation and compare the obtained results for the various technical condition of the PM. We use the BS Analysis for signal processing of the above mentioned separate samples of vibroacoustic signals. Fig.2 represents three-dimensional dependencies of the obtained estimations of BS modulus on the normalized frequencies.

The presented results show that the intensity of the BS estimations changes in presence of imbalance in all modes of the PM operation. It can be seen on Fig. 3 that the presence of small imbalance makes changes to the BS estimates presented in the form of two-dimensional contour images characterizing the dependence of BS estimates on the normalized frequencies. However, based on the obtained results, it is difficult to choose any one or more features that can be used to decide on the testing object condition.

Contour images have a complex structure and can be classified as fractal images. Therefore, we propose using the processing of the received contour images with Fractal Analysis methods in order to make the interpretation of the BS estimates easier and to determine the imbalance features of rotation system.

3. Fractal Analysis of contour images

We use Fractal Analysis to provide a diagnostic parameter that would display the differences in features of failure. The main characteristic of fractality is the fractal dimension D. The task of Fractal Analysis of images is to estimate this dimension. There are many approaches to its definition: Hausdorff dimension, Minkowski dimension, correlation dimension and others [6,7].

The basic concept is the Hausdorff dimension, but often its direct evaluation is a rather difficult task. Therefore, in practice the often-used dimension is related to the class of box counting dimension. In this paper we use the Minkowski-Bouligang dimension D_F also known as Minkowski dimension or box-counting dimension [4,7].

The box-counting dimension is one of the definitions for dimension that can be applied to fractals. The box-counting method is used for its calculation. The number of N cells of size R needed to cover the fractal set varies according to the step-by-step law:

$$N = N_0 \cdot R^{-D_F}, \quad D_F \le D, \tag{1}$$

where N_0 is the initial cell size, D is the topological dimension, and D_F is the Minkowski dimension.

The image analysis software is developed using the software realized in Matlab environment [8]. Minkowski dimension was obtained for each image of the same size presented in Fig. 3, for four vibration excitation modes of a PM of the rotation system without imbalance and with a small imbalance. The obtained results are presented in Table 1.

Parameter V is the relative rate of change of the imbalance feature (fractal dimension), it is calculated by expression:

$$V = \left| D_F - D_{Fimb} \right| / D_F, \tag{2}$$

where D_F is the Minkowski dimension for an image without imbalance, D_{Fimb} is the Minkowski dimension for image with imbalance.

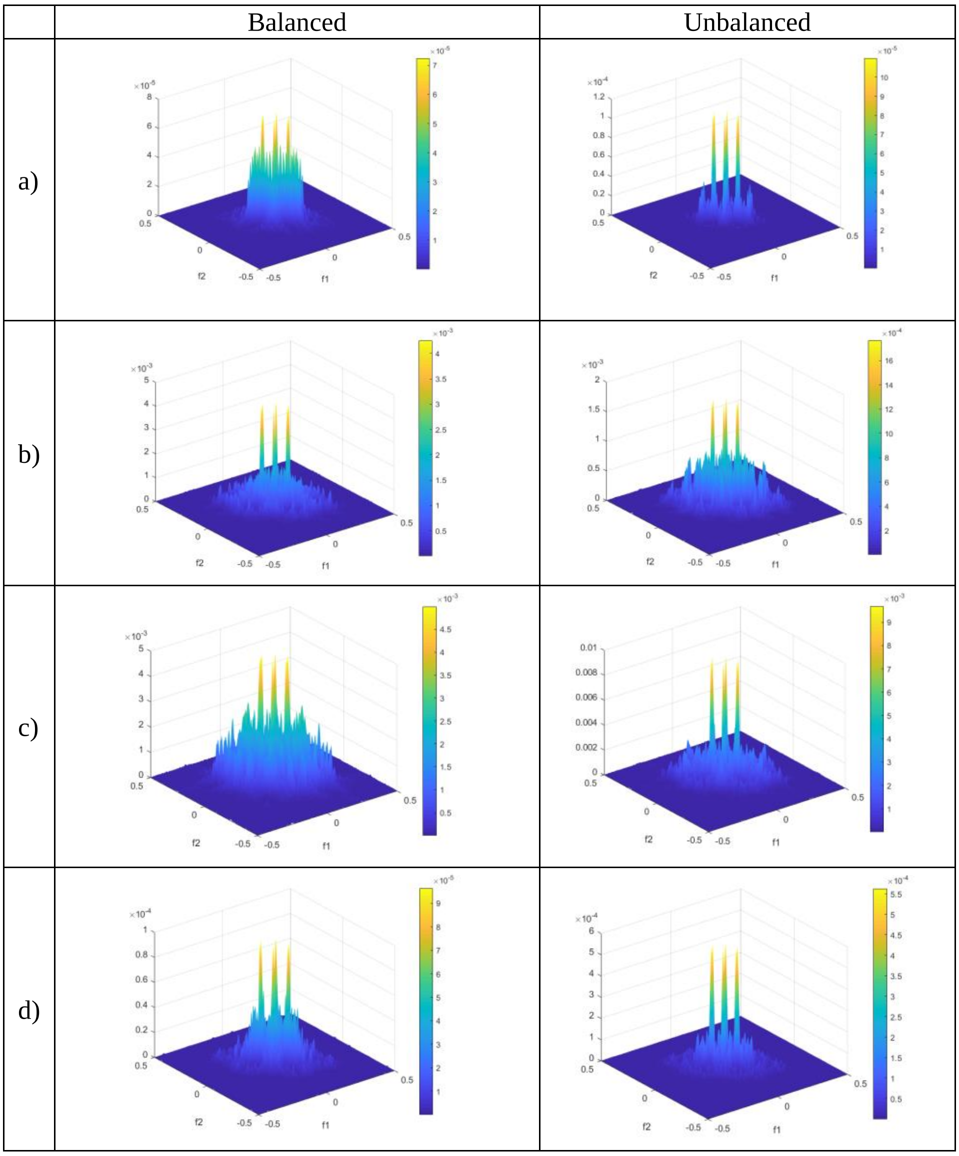

Figure 2. Three-dimensional dependencies of obtained estimations of BS modulus at the modes: (a) accelerating mode; (b) transient mode; (c) steady-state mode; (d) running-out mode

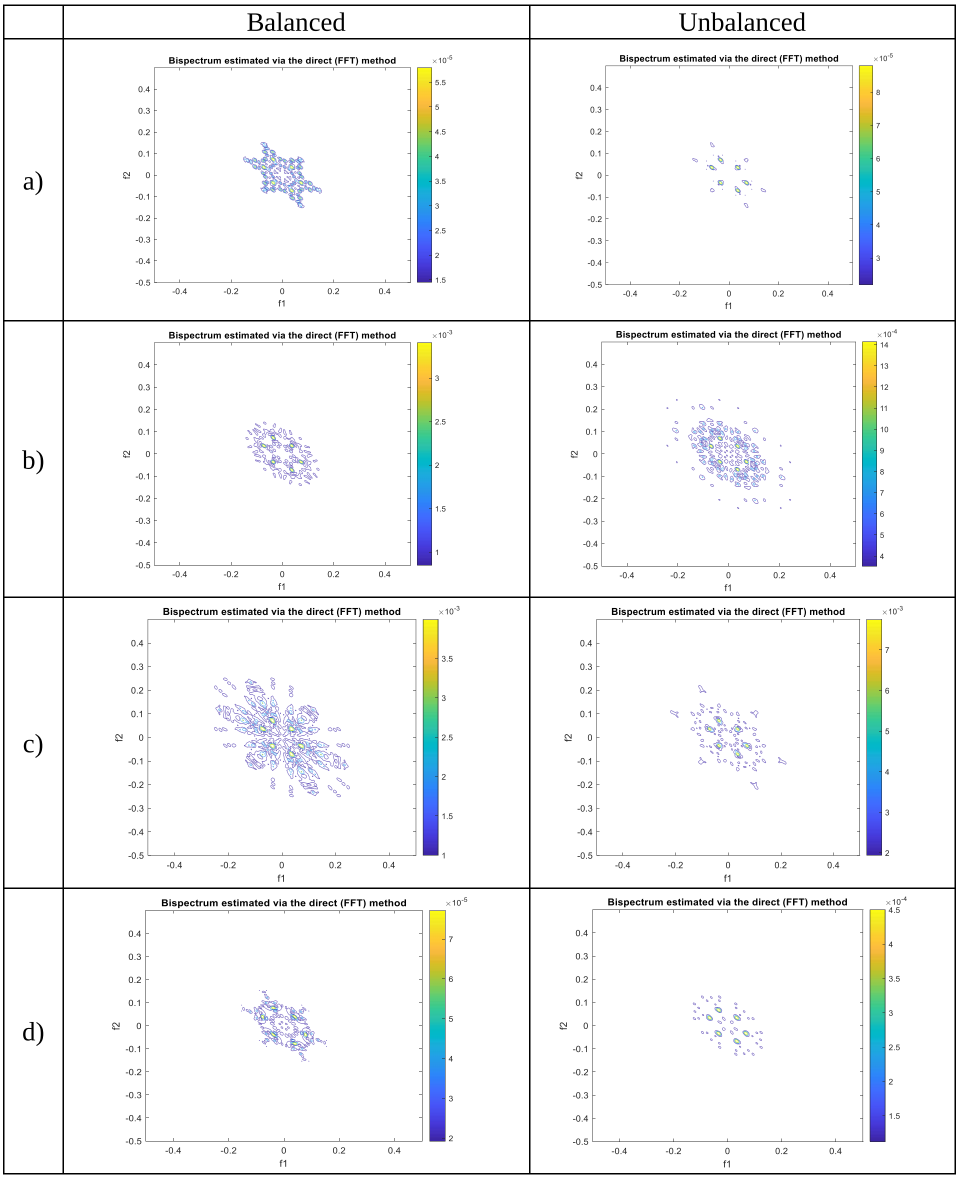

Figure 3. BS estimates in a form of two-dimensional contour images at the modes: (a) accelerating mode; (b) transient mode; (c) steady-state mode; (d) running-out mode

Table 1. The calculation of the Minkowski dimension of BS contour images

Modes of operation	Balanced PM	Unbalanced PM	*V*
Acceleration mode	1,1307	0,92097	18,5%
Transient mode	1,1244	1,2644	12,5%
Steady-state mode	1,3691	1,1401	16,7%
Running-out mode	1,1765	0,9563	18,7%

The obtained results very well illustrate the differences in technical condition of the PM of rotation system at different operating modes. Minkowski dimension is an integral numerical index that characterizes the geometry of the contour image, and allows identifying the PM conditions during operation. Thus, the Minkowski dimension calculated for contour images of BS estimates of the vibroacoustic signal can be used as a feature of a small imbalance of rotation system.

4. Conclusions

The obtained results show the efficiency of multilevel signal processing and can be used for the multiclass diagnosis of initial faults of rotation system at the steady-state and non-steady-state modes. The usage of the additional Fractal Analysis allows increasing the informative content of BS estimations of vibroacoustical signals. Therefore, we propose to use the Minkowski dimension as a diagnostic feature of a small imbalance of rotation system. The efficiency of proposed multilevel signal processing is demonstrated by results of the comparative analysis of the Minkowski dimension values in absence and presence of an imbalance in all modes of PM operation.

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