Dimensionless Machine Vibration S-Discriminants as a Mean to Improve Monitoring and Get Fault Detection

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Abstract. As a matter of fact, practically all of algorithms utilized presently in machinery vibration monitoring and protection systems are entirely ineffective for early failure detection.
The paper outlines a new monitoring and diagnostics approach which is high-susceptible to incipient faults. Proposed method takes into account individual (inherent to a normally operating machine) features of vibration excitation and vibration specific modification due to machine degradation.
Peculiarity of the method is use of new monitoring and diagnostics algorithms based on dimensionless ratings (S-discriminants) of amplitudely clipped vibrations. Formulas for its calculation are given.
These S-discriminants being adapted to specific machine are noise-immuned, provided a threshold of clipping is chosen in a proper way, and very sensitive to machine degradation process it begins only. Besides, if we turn from wide frequency band to the definite narrow frequency bands, we get valuable diagnostic information about specific units of the machine.
Some successful discriminant technique applications for machine vibration monitoring and diagnostics under their operation conditions are cited, including so complicated objects of control as multi-stage gearboxes and gas turbine engines. Advantages of this new vibration monitoring approach are emphasized.

Introduction

One of reasons of unforeseen technogenic accidents with catastrophic aftereffects is use of ineffective methods and means of machinery condition monitoring, some underestimation of high-frequency vibration information value. The majority of rotation machinery fault detection algorithms using case measured vibration data, according to current international standards, are based on estimation of root-mean-square meaning (RMS) of amplitude vibration velocity in a frequency band of 10 … 1000 Hz. At first designed for low speed machines, they then have been spread out for other types of machines.
The paper gives somewhat different approach to condition monitoring and diagnostics in view of vibration sources specific features and machine vibration properties modifications during operational time. A distinctive feature of the approach is use of the dimensionless parameters (S-discriminants) of clipped vibration signals related to a normal (reference) state of the concrete machine [1-3]. The S-discriminants good noise immunity and high sensitivity to machine vibration amplitude and its fluctuations growth under machine condition degradation allows to detect an incipient fault, to diagnose its type and to trace its evolution up to the moment a control system will make note of it. Investigations and

numerous diverse applications prove the discriminant analysis effectiveness, which is shown here by the examples of a complex gearbox and a gas-turbine engine.

1. The dimensionless S-discriminant and its properties

The basic idea of machinery condition monitoring version with adaptation to the machine reference "normal" condition is to monitor the certain dimensionless amplitude discriminant along the machine operational time. The discriminant is formulated as a ratio of measured parameter current value, for example, vibration velocity RMS, to the basic one, matching the normal machine condition. Typically, the discriminants are changing from 1.0 through big values when the machine condition is deteriorating.

To increase the discriminant sensitivity to machinery faults some operation is applied, namely, vibration signal amplitude undergoes clipping, i.e. the dimensionless S-discriminants form of the part of the signal only exceeding the given threshold ***P***. Thus, the individual machine "normal" intrinsic vibration noise is put away from consideration. One can better watch slight signs of incipient defect in vibration signal after such its processing. Additionally, for magnification of sensitivity the ratio is introduced into a discriminant mathematical expression ($\boldsymbol{K_{(t)}}$ / $\boldsymbol{K_{(n)}}$) of signal amplitude pulses amounts exceeding a clip-threshold (***P***) in current ***(t)*** and normal ***(n)*** condition. The formulas of S-discriminants $\boldsymbol{I_s}$ and $\boldsymbol{I_d}$ most often used are given below:

An index of clip-threshold (***P***) exceedings by a signal, calculated for average amplitude of pulses clipped

$$I_s = \frac{\frac{1}{N}\sum_{i=1}^{N}\left[(x_i)_{(t)} - P\right]}{\frac{1}{N}\sum_{j=1}^{N}\left[(x_j)_{(n)} - P\right]} \cdot \left(\frac{K_{(t)}}{K_{(n)}}\right) \qquad (1).$$

An index of clip-threshold (***P***) exceedings by a signal, calculated for energy of pulses clipped

$$I_d = \frac{\frac{1}{N}\sum_{i=1}^{N}\left[(x_i)_{(t)} - P\right]^2}{\frac{1}{N}\sum_{j=1}^{N}\left[(x_j)_{(n)} - P\right]^2} \cdot \left(\frac{K_{(t)}}{K_{(n)}}\right) \qquad (2),$$

where x_i, x_j – signal samples of current *(t)* and "normal" *(n)* machine vibration, exceeding a threshold $P=\lambda\sigma_n$, λ – coefficient of proportionality, σ_n - standard deviation of a reference ("normal") signal, *N*- total of samples.

It is known that the machine deterioration goes to some distortion of vibration signal observed: growth of amplitude glitches with simultaneous growth of their number in time unit, growth of noise component. Beneath, the vibration parameters common used and S-discriminants behavior having got with using of mathematical modeling the vibration signal property modifications under deterioration machinery conditions are compared. Plots of common vibration statistical performances (coefficient of excess $\boldsymbol{E_k}$, peak-factor $\boldsymbol{X_p / \sigma_s}$ and the normalized signal RMS - $\boldsymbol{\sigma_t / \sigma_n}$) and amplitude discriminant $\boldsymbol{I_d}$ (are figured at the clip-threshold $\boldsymbol{P=1.5\,\sigma_n}$) dependences on amount of glitches (over the threshold) ***m*** in a signal (which length is ***N***=1024 samplings) are presented at Fig.1 and Fig.2.

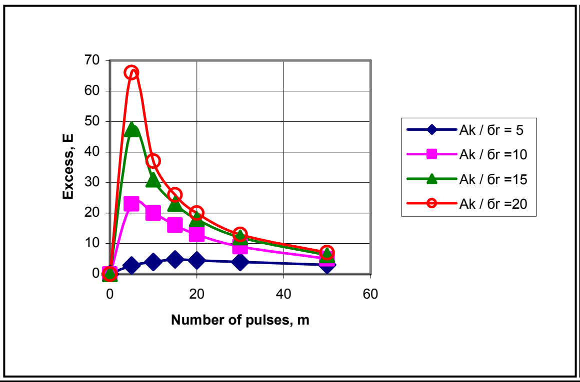

Fig.1. A family of dependences E_k on m.

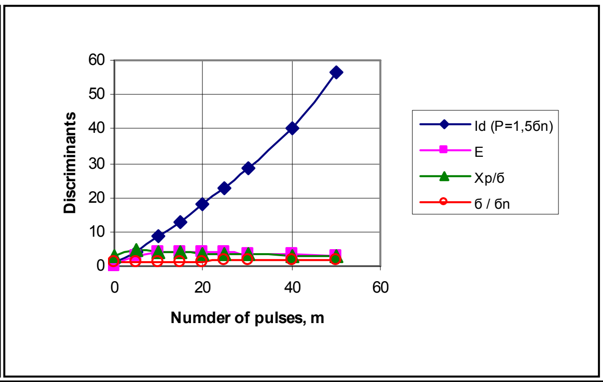

Fig..2. Curves of dependences I_d, E_k, X_p / σ_s, σ_t / σ_n on m.

Here $\boldsymbol{\sigma_s}$ - a standard deviation of "white" noise in sum sequence of equidistant impulses of amplitude $\boldsymbol{A_k}$, $\boldsymbol{\sigma_r}$ - a standard deviation of "white" noise. The amount of glitches ***m*** in the model signal imitates a local fault development degree.

The plots show essential advantage of the amplitude discriminants over other examined parameters because their high sensitivity and monotonous dependence on unit condition.

2. Some of research neutron reactor IBR-2 vibration monitoring results

Some outcomes of the S-discriminants application for research reactor PO-2 [2] mobile neutron reflector parts fault detection are presented below. It is just the case when vibration condition monitoring is almost the only way to define though indirectly the real operational state and ability of critical machinery.

Plots of amplitude discriminant $\boldsymbol{I_d}$ (for $\boldsymbol{P=2\sigma_n}$) dependences on operating time ***T*** for wide frequency band vibration acceleration signals (over the frequency range of 16 … 12500 Hz) are presented at Fig.3. The accelerometers have been located in four measurement points of case construction PO-2. The reflector fore-support vibrations were measured at points ***k-1*** and ***k-2*** in vertical and horizontal directions, of the multistage gearbox vibrations were measured by transducers installed on a gearbox housing at points ***k-3*** and ***k-4*** in vertical and horizontal directions as well.

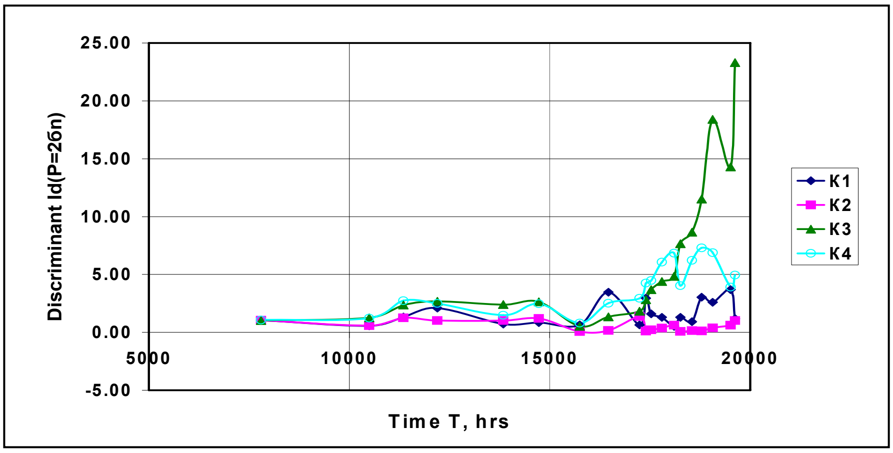

Fig. 3. Amplitude discriminant I_d curves for different measurment points (k-1, k-2, k-3, k-4) of MR-2 in wide frequency band (16 … 12500 Hz).

It can be seen from data of the wide frequency band vibration acceleration signal discriminant analysis presented at Fig.3 that the plant PO-2 condition remains practically almost the same as normal one ($I_d \approx 1$) up to total operation time value of ***T=17000*** hours. Then process of inner disturbance of the gearbox began to develop and corresponding to it vibration parameters behavior changed (amplitude discriminants grew up to 8-10 at the point ***k-4*** and up to 24 at the point ***k-3***). The discriminant I_d for the reflector fore-support measurement points ***k-1*** and ***k-2*** did not exceed of value 4. The fault detection method based on an envelope analysis within high-frequency mechanical system resonance region (Δf = 5.0-6.3 кГц) allowed to reveal the unit ball bearings damages [2] that are incompatible with the further maintenance of it. Index of an amplitude modulation (AM) has come up nearer to critical meaning of 0.2 due to a wear of the unit ball bearing elements. The important notice: the discriminant I_d calculated for the same narrow band high-frequency signal component (see Fig. 4) is growing up to 700 times in a comparison with the normal unit condition which demonstrates this approach much more sensitive than amplitude demodulation method.

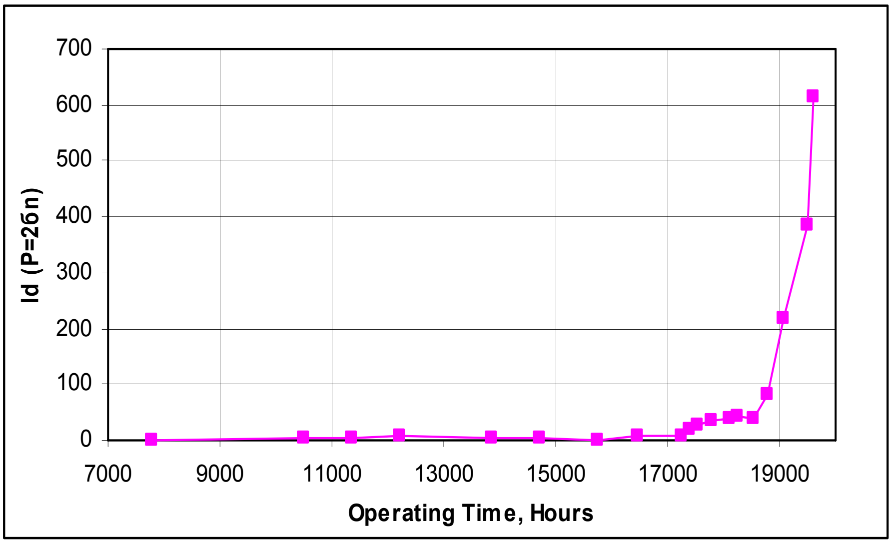

Fig.4. Dependence of amplitude discriminant I_d ($P = 2\sigma_n$), calculated in high-frequency resonance region (Δf = 5.0 … 6.3 kHz) of the multistage gearbox, on total operation time T.

In spite of the fact that fault type definition with using of S-discriminants technique in a wide frequency band is not obviously possible (only well-sensitive monitoring of condition changes in general), combining this approach and narrow frequency band S-discriminant analysis [2] ensures not only incipient fault detection, but also diagnosing local malfunctions of machinery parts.

3. Use of discriminant analysis for gas turbine engine incipient fault detection.

In this section a case history is given which demonstrates such an approach advantages for the purposes of critical machinery vibration monitoring. Data gained with online monitoring and diagnostic system SDKO (corporation Orgtechdiagnostika) and S-discriminant analysis application made possible a fore-support bearing defect detection of the three-shaft gas turbine unit (GTU) DG-90 low-pressure compressor (LPC) of a compressor station. The point was that the engine had to put out of operation because of sudden failure discovered due to monitoring of engineering (non-vibration) parameters.

However, the unit vibration parameters under control having been measured in regular points of LPC case (vibration velocity RMS in the frequency band specified by a manufacturer and comprised the engine rotation frequencies) have not fallen outside the limits acceptable values. Obviously, that for early fault detection of the GTU it is expedient to use more sensitive, than RMS, performances of vibrations, and wider frequency band, than it is accepted now.
As a result of the thorough analysis of DG-90 vibration signals available the failure development scenario was clarified.
Vibration acceleration spectrum data in vertical and horizontal directions and the analysis of the basic statistical performances (a variance, a standard deviation, the peak-factor, a kurtosis) trends along the unit exploration time ***T*** has showed the essential GTU vibration processes instability. Noteworthy that unlike common regularities in rotor machinery when the deterioration plant condition is accompanied by its vibration activity growth, in this case the overall vibration energy of GTU had a paradoxical trend with an operating time: not to grow but to lower.
Graphs of GTU vibration vertical and horizontal components energy change within a wide frequency band (0 … 9.0 kHz) in due course operating time from Apr 1, 2004 through Aug 19, 2004 are shown at Fig.5. Contrary to the generally accepted notion the plant vibration activity before breakage tends a slope down and only before the breakage small up rise is observed.

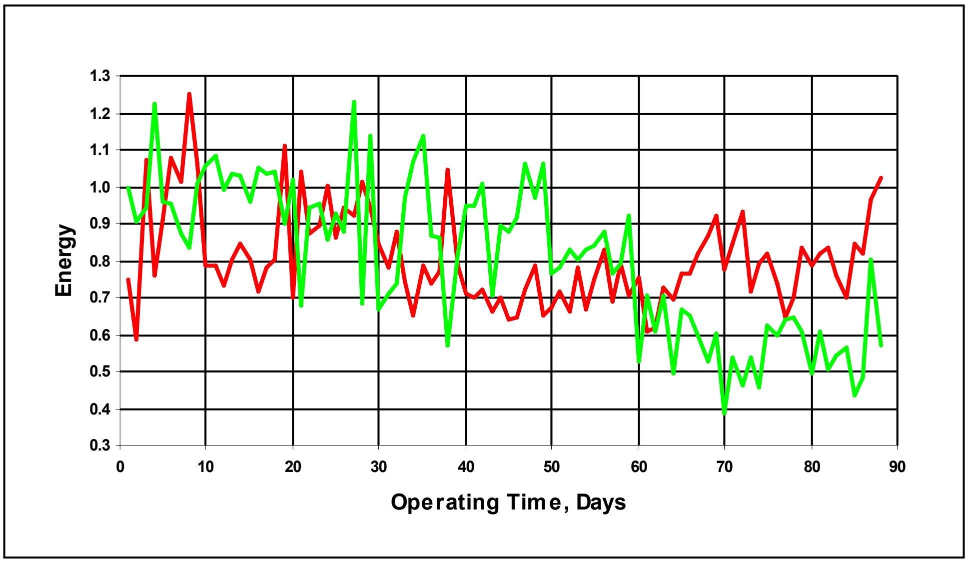

Fig.5. LPC vibration energy trends in a wide frequency band (0 … 9.6 kHz). Green curve is for vertical vibration, red line - horizontal vibration

Calculation of GTU fundamental excitation frequencies (and its harmonics) has been yielded, founded on the plant kinematics' configuration, its blade numbers and parameters of ball bearings. Then narrow frequency bands for the dimensionless S-discriminants analysis were selected for reliable incipient fault detection of the LPC fore-support bearing and tracking a course of their evolution. The means of post processing synchronization ("comb" filtering) of the measuring information was applied to simplify comparison of forced vibration amplitudes (because of plant rotation frequency instability from one measurement to another).
To learn all of LPC vibration activity behavior along an operating time the discriminant analysis has been done in wide (0 … 9.6 kHz) and narrow frequency bands:

- In the bands including various combinations of blade frequencies harmonics of LPC stages, formed with using a comb filtering;
- In the bands including various combinations of blade frequencies harmonics of the high-pressure compressor (HPC) stages and the supercharger turbine (ST), formed with using a comb filtering as well;
- In the standard frequency band I (0 … 1000 Hz);
- In a narrow frequency band II (f_r ± 5 Hz) around the shaft CLP rotation frequency;
- In a narrow frequency band III (≈ 1.1 … 1.7 kHz) around frequency of the LPC fore-support bearing inner race defect (f_i ≈ 1400 Hz).

Results of the discriminant analysis in band I and bands including blade frequencies of LPC, HPC and ST stages have displayed the discriminant values relative independence on the train operating time, i.e. vibration due to the troubleshot fault is related to other frequency bands.

Data of the discriminant analysis made in wide frequency band, and narrow frequency bands II and III, presented at Fig.6, allow concluding that plant breakage cause is the bearing elements fracture inside LPC fore-support. The fault of the bearing was clearly exhibited since the measurement # 76, after which with small delay (namely from # 80) growth of amplitude on a rotation frequency of CLP has followed due to increase of shaft CLP unbalance. The unbalance evident cause is a slackness expansion in the bearing due to intensive outwearing the inner bearing race.

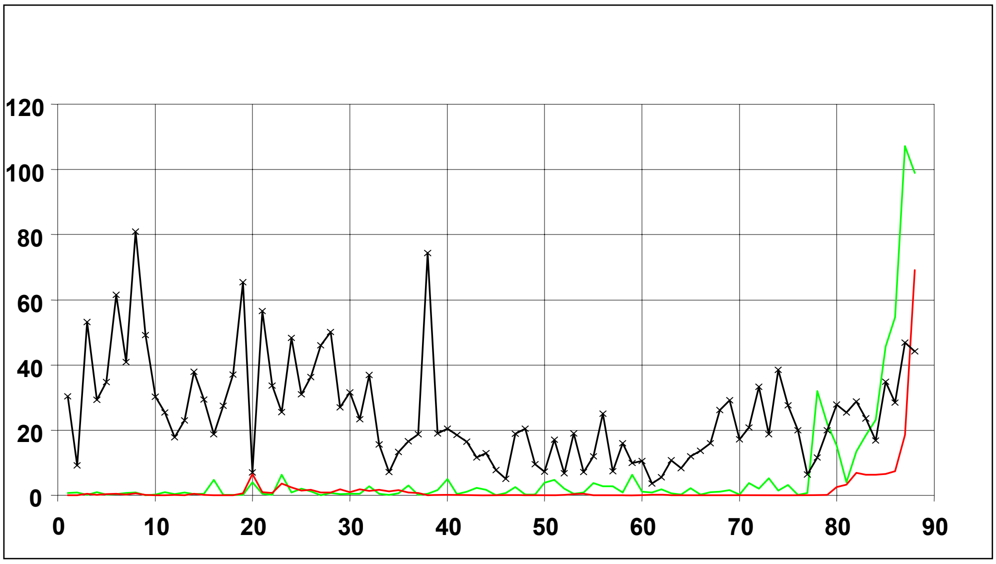

Fig.6. Plots of S-discriminants dependencies on GD-90 operating time. CLP vertical vibration discriminants in different frequency bands: black curve – wide frequency band (amplitude scale is 25:1); green curve – inner race defect frequency narrow band (amplitude scale is 1:1); red curve – shaft speed narrow band (amplitude scale is 25:1).

It is well seen from Fig.6, that there is different degree of sensitivity to plant condition changes of the discriminants, calculated in different frequency bands. The wide frequency band vibration discriminant dependence on the plant operating time shows high vibration parameters instability and lack of the reliable reference information on normal unit condition (in this data complete set). The intense vibration level fluctuations and its falling down before the bearing breakage do not promote a reliable discernment of the gas turbo plant defect with using of wide frequency band analysis. At the same time the narrow-band

discriminant analysis in the definite frequency bands, which include all physically stipulated frequencies of possible exploration faults of machinery parts, really ensures the early detection and diagnostics of these inaccuracies.
It is useful to compare diagnostics value of amplitude discriminant I_d and common dimensionless probability performances such as peak-factor ***P-F***, the normalized RMS (i.e. deviation of signal amplitude) σ_t / σ_n, and a coefficient of excess E_k (see Fig. 7). All this parameters are taken for CLP case vertical vibration acceleration in a frequency band 1.0 … 1.75 kHz as a function of operating time ***T*** in the same (see Fig.6) interval of observation.

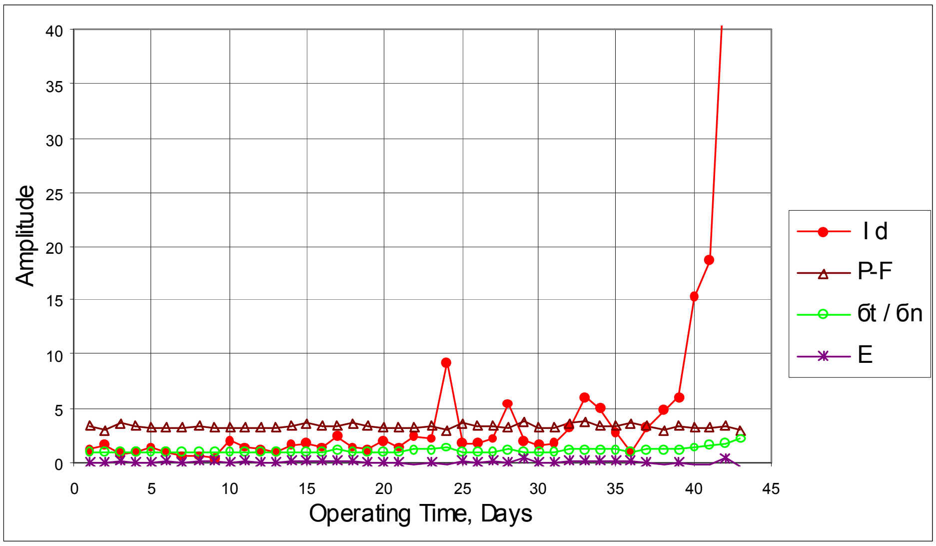

Fig.7. S-discriminant I_d at a clip-threshold $P=1.5\sigma_n$ and common dimensionless parameters (P-F, σ_t/σ_n, E_k) in a frequency band 1.0 …1.75 kHz as functions of GTU DG-90 operating time.

The behavior of graphs with all conspicuity shows advantage of the S-discriminant with its high sensitivity to the fault in comparison with common statistical performances. Maximum value of discriminant I_d run up to magnitude 100 (outside the full scale range specified by the graph) when the ball bearing fails.
Despite of wide use peak-factor and a coefficient of excess for rotation machinery fault detection, the given dimensionless vibration parameters have some shortages essentially restricting their diagnostic value, especially for plants of such type as GTU. These shortage are, for example: non-linear and nonmonotonic dependence of the parameters on a degree of fault evolution and a low noise-immunity to the "native" plant vibration.
Note, that only the relative standard deviation σ_t / σ_n from all performances of narrow-band signals reacts to ball bearing failure though growth of amplitude of this parameter (when machine condition changes from a normal one to critical) does not exceed value of 2,3. Nevertheless, the given parameter is also possible to use for developed fault detection.

Conclusions

The results of investigations and applications aimed to elaboration of individual machinery condition monitoring algorithms with high sensitivity to even small deviations of technical state parameters from normal ones are presented in the paper. Use in existing monitoring systems the vibration parameters (as a rule, a level of vibration energy in some frequency band) which are feebly sensitive to incipient defects sometimes is ineffective. Now and then it is impossible to timely make decision about the further unit maintenance only founding on such monitoring system operative information. The key difference of an offered machinery condition monitoring technique from the common ones is use of the dimensionless amplitude-clipped vibration signal S-discriminants with its adaptation to a specific reference machine state.

The produced instances of the discriminant analysis method practical use for complicated machinery condition monitoring show its high sensitiveness to operation faults and apparent advantages against the standard methods oriented on use of energetic vibration performances.

References

[1] Sokolova Asja, Balitsky Felix, Sensitive and Noise-immune Vibration Discriminants for Instability Phenomena Detection caused by Incipient Machinery Deterioration. - Proceedings of "The 1st International Symposium on Stability Control of Rotating Machinery - ISCORMA-1", 20-24 August 2001, South Lake Tahoe, California, USA.

[2] Sokolova A G., Balitsky F.Ja., Sizarev V.D. Detection Technique for Faults Perturbing Rotor Stability, Illustrated by Means of an Example of the Movable Reflector-Modulator of the Pulsed Research Reactor. Proceedings of "The Second International Symposium on Stability Control of Rotating Machinery-ISCORMA-2", 4-8 August 2003, Gdansk, Poland.-p.170-179.

[3] Sokolova A.G. Algorithm of Machinery Vibration Condition Monitoring with Adaptation to a Reference State / Publishing house "Machinostrojenije", «Monitoring. Diagnostics», v. 11, 2005. p. 30-40 (in Russian).