ON SOME CRITICAL MACHINERY VIBRATION MONITORING ALGORITHM AND ITS APPLICATION FOR INCIPIENT FAULT DETECTION AND LOCALIZATION

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Summary

Further development of proposed earlier [1] critical machinery vibration monitoring algorithm intended for faults early detection, unlike standard monitoring techniques, is propounded. The algorithm is founded on nondimensional S-discriminants, calculated from current amplitude-clipped vibration signal parameters referred to the ones for the machine being in good (normal) condition. These parameters have an inherent high sensibility to amplitude spikes magnitude and amount growth, which takes place at vibration signal under the machine degradation, due to suppressing intrinsic machine vibration hash. The paper shows that really effective high speed machinery condition monitoring technique based on using casing vibration data should mandatory take into account the acceleration parameters calculated both in wide and narrow frequency bands.

Keywords: vibration condition monitoring, non-dimensional discriminant, machine defect.

1. INTRODUCTION

To assure technical, ecological and human safe machinery exploration one needs to use condition monitoring and diagnostics algorithms which enable to detect operational malfunctions at the very early stage of their development, i.e. algorithms based on specific methods which detect even week changes of vibration signals originated from the incipient faults. It is the well-known fact that vibrations carry all information about machine dynamic behavior, including defects manifestation as well. The wider frequency range we use for machine problem analysis and the more diagnostics algorithms take into consideration the main specific features of machine dynamic model, the better are results. It is well-known also another fact, that generally most of machinery monitoring and protection system algorithms are based on the estimation of the RMS (root mean square) value of vibration velocity over the range of 10 to 1000 Hz, or amplitude divergence (for wide or narrow frequency band) from base line meanings under good machinery condition.

The conventional vibration velocity range (10- 1000 Hz) of high-speed-rotation machinery contains merely several first shaft rotation frequency harmonics affected only by rough machinery condition changes, for example due to unbalance, eccentricity, misalignment, part breakage, and so on. But technique of incipient fault detection (such as erosion, corrosion, pitting, scuffing, and so on) bases on some other principles, because their symptoms are situated in high frequency vibration range [1-3]. The paper gives evidences of the necessity of combined approach with incipient fault detection and diagnostics methods as its foundation. The paper presents some investigation results on the subject of safe machinery operation ensuring in atomic applications and on early detection of gas turbine engine (GTE) rolling bearing developing defects at a gas pipeline compressor station.

2. A NEW APPROACH TO THE VIBRATION MONITORING OF HIGHSPEED MACHINERY

As it is seen from practice, the more complicated is a machine unit, the more dispersion of measured parameters within general scope of similar machines proves. Due to that it is important to use the individual approach when vibration monitoring is applied.

One feasible way for the early malfunctions recognition is preliminary "passportization" of vibration spectrums and posterior comparison of measured current spectra with the passport spectral data to estimate changes derived from machine condition degradation during its exploration. The point is that the procedure is not effective enough because these changes are small and due to the procedure is not automatic.

There was suggested another way with using some non-dimensional vibration characteristics (S-discriminants) which values are independent either on machine type or vibration units, but only on type (kind) of defect and its severity. Such well-known discriminants as peak-factor X_p/σ, excess $E=\left(\mu_4/\sigma^4\right)-3$ (or kurtosis), indexes of amplitude or frequency modulation, prof. Cempel dimensionless discriminants, and so on, often have been used for this aim [1]. However above-mentioned nondimensional parameters have an essential demerit, namely – when a numerator growing along with defect development (due to the number and amplitude of vibration overshoots enlargement), a denominator behaves similarly and dependences of these characteristics on machinery time operation are nonlinear as a rule. It is known [1], that such sensitive vibration parameter to overshoots appearance as excess coefficient, having high sensitivity to any damages at an early stage with small amount of overshoots per time unit, lost its sensitivity to well-developed damage with overshoots quantity growing on.. Dependence of excess (and other standard dimensionless parameters) values from pulses number (which is modeling the machinery parts degradation degree along the operational time) is nonlinear function that means non-single-valued nature of these parameters, in contrast to S-discriminant I_d (see Fig. 1).

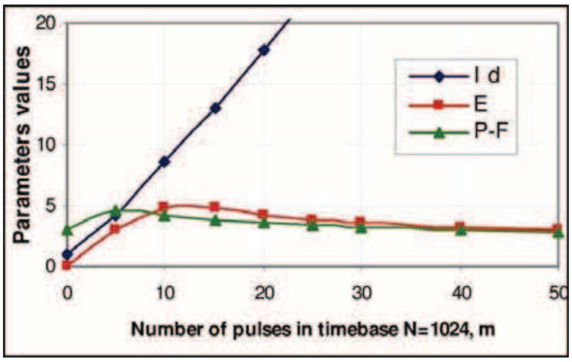

Fig. 1. Influence of pulse quantity **m** (within time realization *N*=1024) on excess *E*, peak-factor *P-F*, normalized amplitude deviation σ_t / σ_n and S-discriminant I_d values for meaning of relative pulse amplitude A/σ_s=5, where σ_s, σ_n – are standard amplitude deviations of random noise signal and reference summary noise and pulses sequence

All that is the foundation for suggestion such kind of monitoring and protective algorithms which would be more sensitive to early fault events and besides have monotonic dependence from machinery degradation state during operational time. To properly realize the "critical" machines condition monitoring and incipient fault detection techniques was proposed the algorithm of estimation of some dimensionless S-discriminant magnitude declining from the value equal to an unit that is placed in correspondence with machinery normal condition.

Analysis of machine vibration waveforms with operational damage in progress shows that vibration becomes unstable and mandatory feature of an incipient fault is an appearance of single or multiple signal overshoots (Fig. 2) deriving from interaction conjugate parts format changes due to erosion, corrosion, pitting, contact surfaces welding and scuffing, and so on.

To raise the sensitivity of the vibration features to incipient faults and minimize the influence of uninformative regular machine vibration (i.e., noise), there were suggested stochastic dimensionless characteristics (amplitude discriminants) to be formed for vibration signals, clipped above the specified amplitude clipthreshold *P* (see for example the red lines at Fig. 2 which are drawn here at amplitude values of ±2σ_n). Thus it is possible to get rid of the own machine vibration which is intrinsic in absence of any malfunctions, and due to it improve the parameters sensitivity.

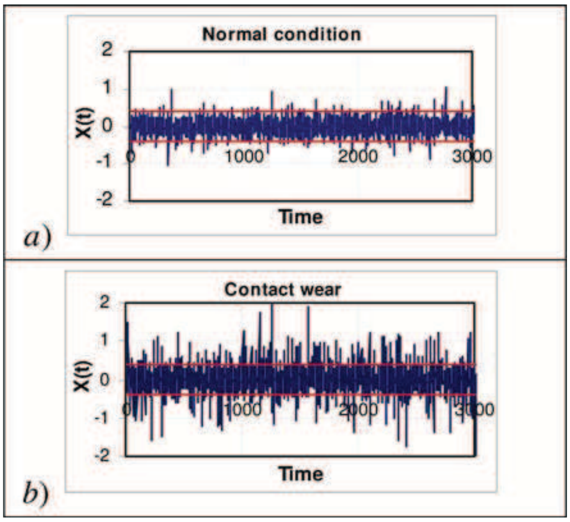

Fig. 2. Examples of vibration acceleration time histories: a) for machine in good condition, b) for machine with injured elements (scuffing in contact zone)

As a result there were formed the relative indexes from some statistical parameter of the clipthreshold exceeding for current vibration signal divided by the same characteristic of reference signal, measured under machinery normal condition. One of them is dispersion index $\mathbf{I_d}$ of threshold exceeding, formulated as follows:

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

Here $(x_i)(_t)$ and $(x_i)(_n)$ are values of vibration amplitude components, calculated for current and reference (i.e. normal, without any faults) machine conditions; $P = \lambda \sigma_n$, (λ = 0.5 – 3.0) – amplitude clip-threshold, σ_0 – standard deviation (RMS) of vibration signal for normal (reference) machinery condition; $K_{(t)}$ and $K_{(n)}$ – are numbers of overshoots above the threshold *P* for current and normal vibration signals.

An amplitude discriminant significance equals to 1, when the machine is under its good condition, but becomes >1 or >>1, if any kind of damage would take place. Thus there were formed dimensionless amplitude discriminants, featuring high sensitivity to instability, caused by machinery operational imbalance, resulted from any fault, and noise immunity to internal machinery masking interference. Some practical (experimental) examples of S-discriminant successful application for incipient detection of multistage gearbox parts defects and of gas turbine unit rolling bearing faults are given below.

2. VIBRATION ANALYSIS RESULTS OF GAS TURBINE ENGINE (GTE) AND GEARBOX

The example below is given to clearly prove that standard monitoring technique is not effective to evaluate changes of complex high speedy machinery and is not applicable to incipient faults detection and recognition (malfunctions of bearing supports, tooth gears, compressor and turbine blades, and so on) due to practically absence of information of these machine parts operability in vibration velocity signals. Really, plant's limiting values of vibration velocity RMS within 10…1000 Hz frequency band (overall level) could be exceeded only under great machine degradation that distorts of its shaft line (bearing breakage, blade breakaway, and so on).

Accordingly with GTE failure statistics there about 80% breakdowns are the result of bearing malfunctions. Typical plot of lateral vibration acceleration spectrum being acquired at one of navy GTE type DG-90 casing measurement points is given in Fig. 3 for front support of low pressure compressor (LPC) in vertical direction [2].

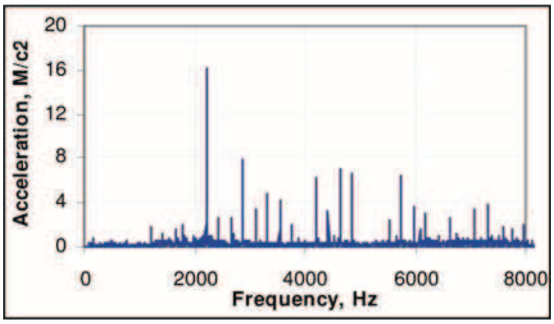

Fig. 3. GTE casing vibration acceleration spectrum

It is clear, that frequencies of bearings generated vibration lay, as a rule, exceed 1000 Hz and as a matter of fact the deterioration of LPC front support ball bearing in question had not been detected timely with the conventional on-line monitoring system because of no one vibration velocity threshold had not been exceeded.

In Figure 4 the several non-dimensional vibration parameters plots are shown under degradation process in ball-bearing of front support of low pressure compressor (LPC) of navy gas turbine engine DG-90 during operation time 01.06.04 to 19.07.04, when machinery was stopped due to metal chips appearance in lubrication.

All parameters were measured for narrow band (1.0÷1.75 kHz) case vibration acceleration – around of the inner race frequency (BPFI) [2]. The discriminant I_d actually has *max value* of _ 100, but Figure 4 scale (0 to 25) was chosen for purpose the other parameters (peak-factor *P-F*, normalized standard deviation σ_t / σ_n, excess *E*) – to be recognizable. The first significant discriminant overshoot which corresponds to dramatic change condition of ball-bearing one could see at 25.06.04 point, i.e. three weeks before the train has been stopped.

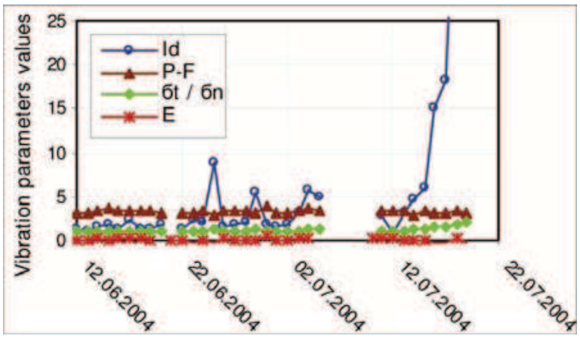

Fig. 4. Narrow band (1.0-1.75 kHz) case vibration various parameter behavior during ball bearing damage development in LPC of gas turbine engine DG-90 front support.

Some practical examples of S-discriminant application for multistage gearbox parts malfunctions are described below. Wide-band vibration discriminant analysis permits to detect informative measurement point for consequent detailed narrow-band signal analyses. In Fig. 5 there are given the dependences of discriminants from operation time of research reactor IBR-2 movable reflector-modulator [3], that are calculated for narrow frequency band (5.0-6.3 kHz) casing gearbox vibration, measured in points #1-4.

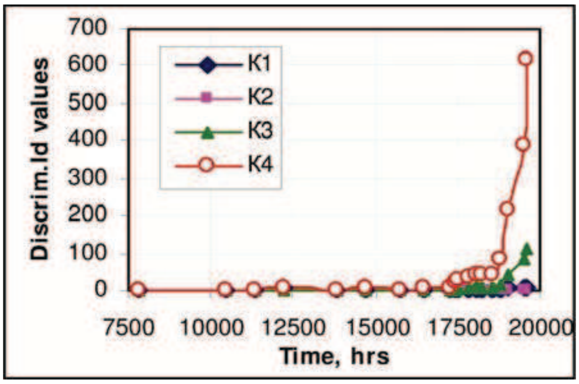

Fig. 5. Narrow-band gearbox casing vibration discriminant trends for measurement points (#1-4)

In Fig. 6 are given the amplitude modulation indexes, calculated for informative measuring point #4 on the ball bearings defect passing frequencies.

In such a way it's possible to realize the procedure of machinery deterioration development detection generally, and after that – specific malfunction localization by means of frequency identification. For objective estimation of operating machinery condition it is reasonably to estimate both wideband and narrowband vibration parameters evolution during machinery service life such as S-discriminant.

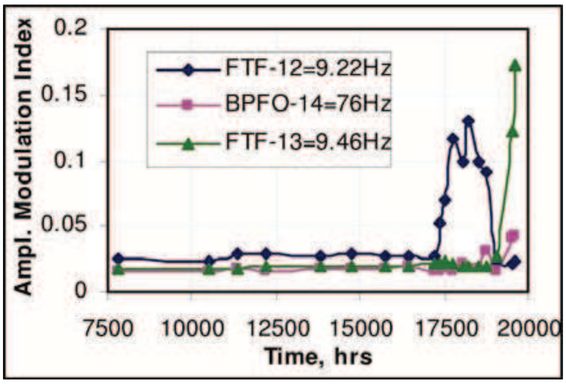

Fig. 6. Trends of ball bearings defect passing frequencies amplitude modulation indexes

Only combined utilization of a set different methods and algorithms for operating condition monitoring of critical machinery, leaning on the information, obtained with incipient failure detection methods can give a reliable estimation of its condition.

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