NEW MACHINERY CONDITION MONITORING TECHNIQUE BASED ON MULTIDIMENSIONAL VISUALIZATION OF VIBRATION S-DISCRIMINANTS

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1. Introduction.

Further development of specific machinery vibration monitoring technique [1, 2] based on S-discriminant analysis of vibration signal clipped so that only amplitude overshoots over some threshold were taken into account is given in the paper. The approach modified to calculate S-discriminant in parallel way for adjacent narrow frequency bands provides with exaggerated "vibroreactivity" source localization (i.e. frequency bands with signal dispersion dramatically grown in comparison with reference measurement data due to arising and then developing defects).

The present-day approach to machinery condition monitoring is built on overall level vibration velocity RMS measurement data collected for specific frequency bands and subsequent comparing them with alert and dangerous thresholds. Mainly, the algorithms that are applied in vibration monitoring systems measuring vibration velocity at stationary parts of machines use data from the frequency band of 10…1000 Hz and 2…3 first harmonics of rotation frequencies. As a rule, the common monitoring algorithms are not destined to machinery incipient fault detection and equipment parts deterioration prevention, but only for vibration protection aims. To ensure reliable and safe equipment operation it is clear (see [3…5]) that algorithms of malfunction detection, source localization and condition monitoring should be members of one team as for modern maintenance needs. There is a need in new maintenance approaches.

The application results for two modification of proposed vibration monitoring technology with discriminant analysis data [3] of clipped narrow frequency band signals within available frequency band measured which sometimes unfortunately occurs more narrow than band of excitation.

Convenient for further interpretation of the multidimensional information presentation as a matrix where array cells are S-discriminants meanings (as color image in accordance with coloured bar graph) gives a good tool for incipient fault detection, primary (initial) identification of defects and on-the-fly estimation its development rate.

Examples of the novel vibration monitoring technique practical application is given in the paper as for early damage detection of gas transportation compressor station avia- and navy-derivative gas turbine engine parts operation damages (bearing faults, damages of turbine gas generator nozzle and blade set) on GTU (gas turbine unit) case vibration measurement data. High efficiency the approach are shown in the paper, more than that the common methods do not detect these malfunctions.

2. Vibration condition monitoring version based on S-discriminant analysis

As it is, the more complex a machine the more vibration parameters dispersion within unit general totality. Due to it the specific machine features evaluation is very relevant when vibration monitoring procedure is organized. Dimensionless S-discriminant I_d (see the formula beneath) have just designed taking into account this idea:

$$I_d = \frac{\frac{1}{N}\sum_{i=1}^{N}\left[(x_i)_{(t)} - P\right]^2}{\frac{1}{N}\sum_{i=1}^{N}\left[(x_j)_{(0)} - P\right]^2} \cdot \left(\frac{K_{(t)}}{K_{(0)}}\right)$$

Here $(x_i)_{(t)}$ and $(x_i)_{(o)}$ are values of vibration amplitude components, calculated for current and reference (normal, without any faults) machine conditions; $P = \lambda \sigma_o$, (λ = 0.5 – 3.0) – amplitude clip-threshold, σ_o - standard deviation (RMS) of vibration signal for normal (reference) machinery condition; $K_{(t)}$ and $K_{(o)}$ - are numbers of spikes above the threshold P for current and reference vibration signals. For normal machinery condition, discriminant meanings are equal to 1, and became much more 1, if amplitude overshoots and their amount increases due to deterioration process development. If we get I_d within wide frequency band its growth informs us about start of deterioration process earlier than spectrums do (due to smallness spikes energy in comparison with main frequency components energy). But this information has not tied to any specific part of machine but only to unit in the whole.

For critical machinery monitoring and incipient fault detection there is proposed the algorithm based on dimensionless S-discriminant changes detailed estimation. S-discriminants should be calculated within narrow frequency bands around defect passing frequencies for only share of every vibration signal which dispersion exceeds threshold of clipping.

To realize heightened vibroreactivity source localization this way it is necessary to evaluate dimensionless vibration (displacement, velocity, or acceleration) S-discriminant upgrowth within any frequency bands specified a priory by expert. When machinery conditions deteriorate the S-discriminants demonstrate high susceptibility to amplitude spikes and amplitude meanings growth in the specific frequency narrow bands.

Several type of discriminant presentation are suggested for the novelty conditional monitoring approaches.

3. The first way of machine heightened vibroreactivity source identification on max S-discriminants in narrow frequency bands.

It consists in detection of the frequency bands with max vibroreactivity increasing in comparison with reference one ($\mathbf{I_d}\approx1$) for normal technical condition taking into account results of measurement point vibration parallel discriminant analysis within different frequency bands narrowing in ratio 1:2. It is convenient to display the results for some operation time term as a table where discriminant magnitudes are shown not merely as digital values but and as differently colored cells accordingly with associated scale bar.

As a practical example there is the Table 1 with vibration velocity S-discriminants peak values colour presentation for case measurement point TGG-Hor (in narrow frequency bands) within operational dates Dec 26, 2006 through Jul 27, 2007 when nozzle set of HPT got burning up. It worth to be mentioned to underline use of this approach that now maintenance staff monitors the vibration velocity RMS in frequency bands of 30…200 Hz, 1.0…4.0 kHz, and amplitudes of the first and second rotation frequencies harmonics (mainly of gas generator GG and power turbine PT)

Table 1. GTU heightened vibroreactivity sources localization when second stage HPT nozzle set of engine PS-90 was burning up.

(1-2)	(3-4)	(5-8)	(9-16)	(17-32)	(33-64)	(65-128)	(129-256)	(257-512)	513-1024	1025-2048

ΔF	S-discriminants peak value for case measurement point TGG-Hor within different frequency bands in time lag Dec 26, 2006 through Jul 27, 2007							
4.0 kHz	4.8							
2.0 kHz	2.2				23.9			
1.0 kHz	2.7		3.3		2.0		185	
0.5 kHz	9.8	2.1	5.4	5.3	2.1	4.3	802.2	38.0
Date	20.05.07	17.04.07	04.07.07	05.05.07	15.07.07	25.04.07	13.05.07	31.05.07

F (kHz) 0.1 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0

As it could be seen from the table a nozzle burning (the stationary part of HPT) essentially affects 3.0 … 4.0 kHz frequency band vibration features with maximum discriminant value Id=185. To be exact the most vibroreactivity shows within more narrow frequency band of 3.0 … 3.5 kHz. In that band we have Max Id=802.2 yet May 13, 2007, i.e. 2.5 months beforehand the engine final breakage. Presumably, with regard to the vibration spectrum data, the real source of the vibration is self-excitation oscillations generated by high pressure flow going by reach-through hole due to whirls arising at their edges and producing something similar a whistle. It could be well seen at bottom half of Figure 1 where are presented wave forms and corresponding spectrums for wide frequency band (0…4.0 kHz) - upper and for narrow frequency band (3…3.5 kHz) – lower respectively.

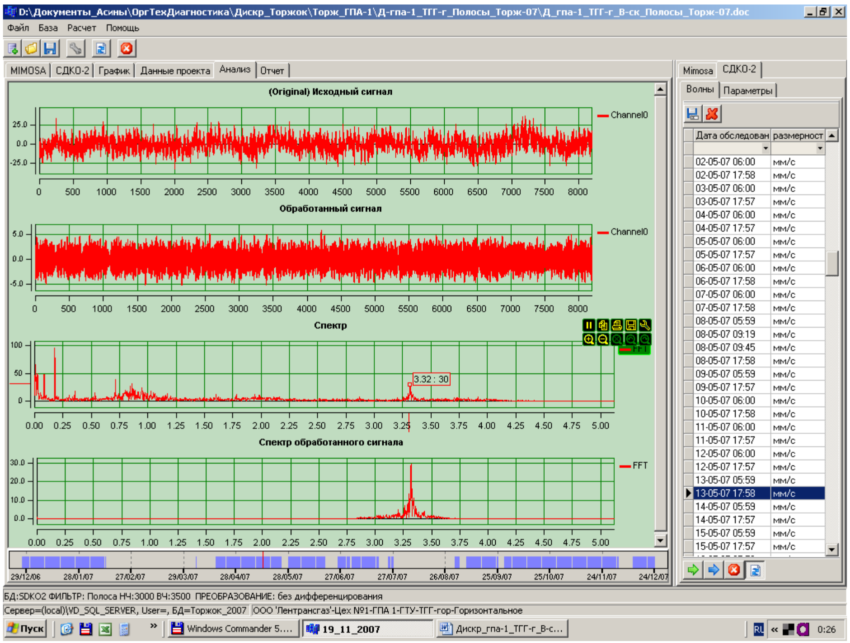


Figure 1. A couple wave forms (up) and corresponding spectrums (down) for wide frequency band (0…4.0 kHz) - upper one of couple, and for narrow frequency band (3…3.5 kHz) – lower one respectively. Measurement date is 13.05.07, defect – the second stage HPT nozzle set of engine PS-90 is burning up. (**Max I_d** =802.2).

4. The second way of data view for heightened vibroreactivity source localization consist in three dimension presentation of vibration discriminant values trends as a table in coordinates as follows: frequency, time, amplitude. To find max vibroreactivity frequency bands, trace vibroreactivity changes in every measurement point along the unit operational time and understand its roots it is advisable to monitor this parameter within fixed narrow frequency bands in parallel. The vibroreactivity tables allow to appreciate the present machinery condition at a glance and decide what maintenance should be provided. The example of three coordinates (measurement date, frequency band, and amplitude band by way of colour) presentation is given beneath as a coloured Table 2 with discriminant values for GTU PS-90 vibration within wide frequency band (0…4.0 kHz) and several narrow frequency bands of **ΔF**≈500 Hz width under unit condition deterioration.

Table 2. S-discriminant values for GTU PS-90 case vibration velocity within wide frequency band (0…4.0 kHz) and narrow (**ΔF**≈500 Hz) frequency bands for different measurement dates within operational term of 26.12.2006 - 27.07.2007 under the nozzle set of HTP burning development.

(1-2)	(3-4)	(5-8)	(9-16)	(17-32)	(33-64)	(65-128)	(129-256)	(257-512)	513-1024	1025-2048

Frequency band	**ΔF ≈ 4.0 kHz**	**ΔF ≈0.5 kHz**							
Dates	**0-4.0**	**0.1-0.5**	**0.5-1.0**	**1.0-1.5**	**1.5-2.0**	**2.0-2.5**	**2.5-3.0**	**3.0-3.5**	**3.5-4.0**
26.12.06_18.02 - Reference	1	1	1	1	1	1	1	1	1
Out of operation (13.02-15.04.07)									
16.04.07_18.00 – Defect rise	2	2	1	2	3	1	1	45	2
17.04.07_18.02	1	4	2	1	1	1	1	382	2
18.04.07_18.00	1	2	1	2	2	1	2	106	1
27.04.07_18.00	1	2	1	2	4	1	2	428	2
10.05.07_06.00 – Full-blown defect	1	2	1	2	1	1	1	742	1
13.05.07_06.00	1	2	1	3	1	1	1	350	1
13.05.07_18.00 – Max defect	2	3	1	2	2	1	1	802	1
14.05.07_06.00	2	3	1	3	1	1	1	249	1
14.05.07_18.00	2	4	1	2	4	1	1	560	1
20.05.07_18.00 – Secondary damages	1	10	1	2	2	1	1	282	5
24.05.07_06.00	1	2	1	1	1	1	1	150	2
Out of operation 25 .5 thru 27. 05.07									
28.05.07_08.32 – Secondary damages	1	5	0	2	2	1	1	107	17
29.05.07_06.00	1	2	0	3	3	1	1	122	33
31.05.07_18.00	2	4	1	2	3	1	1	20	39
06.06.07_18.00	1	1	1	3	1	1	1	465	1
12.06.07_06.00	1	1	1	3	1	1	1	16	2
12.06.07_18.00	1	1	1	2	1	1	1	195	1
14.06.07_18.00	1	3	1	2	1	1	1	598	3
Out of operation 19.06 thru 24.06..07									
25.06.07_18.00	1	1	1	4	1	2	1	29	9
07.07.07_18.00	1	1	1	3	1	1	1	278	1
11.07.07_06.00	1	1	1	2	1	1	1	6	1
11.07.07_18.00	1	1	1	2	1	1	1	240	1
18.07.07_18.00 – Multiple faults	1	1	1	1	1	1	1	4	1
Out of operation 19.07 thru 23.07.07									
27.07.07_18.00 – Engine shutdown	1	1	1	1	1	1	1	1	1

As it seen from the table a vibroreactivity maximum Id=802.2 is in 3.0…3.5 kHz frequency band for given example.

There is worth to point to the specific vibration feature of engine **stationary** part damage, namely closeness discriminant values to normal ($\mathbf{I_d} \leq 10$) in a wide frequency band (0…4.0 kHz) and a low frequency band (0.1…0.5 kHz), where rotation frequencies and its harmonics are located. So, it is clear that it is impossible to detect such kind malfunctions with only using conventional methods.

Next example deals with **rotary** part damage of navy derivative GTU DG-90. The Table 3 presents vibration S-discriminants data acquisited when damages of CLP 1-st stage blades and CLP front support ball bearing were in progress.

Table 3. Heighten GTU DG-90 vibroreactivity frequency allocation when condition of CLP 1-st stage blade set and CLP front support ball bearing kept worsened within operational term of 14.10.08…17.12.08.

(1-2)	(2-4)	(4-8)	(8-16)	(16-32)	(32-64)	(64-128)	(128-256)	(256-512)	512-1024	1024-2048	Out

Frequency band	ΔF ≈4.0 kHz	ΔF ≈0.5 kHz								
Date	0-4.0	0.1-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5	3.5-4.0	Comments
14.10.08_15.01	1	1	1	1	2	4	1	1	1	Reference
15.10.08_03.01	1	1	1	1	1	5	3	2	1	
21.10.08_15.01	1	1	1	1	4	23	1	1	1	Full-blown defect of
22.10.08_03.01	1	2	1	1	4	35	1	1	1	LPC 1-st stage rotor blade
22.10.08_15.01	1	1	1	1	3	28	1	1	1	(band 2.0-2.5 kHz)
24.10.08_03.01	1	1	2	1	1	4	1	1	1	
30.10.08_15.01	1	1	1	2	2	14	21	3	1	
31.10.08_15.01	1	2	1	1	2	36	1	1	1	
01.11.08_03.01	3	2	2	1	2	27	7	1	1	
02.11.08_03.01	1	1	2	2	1	1	3	6	1	
02.11.08_15.01	1	1	1	5	1	1	4	4	1	
05.11.08_15.01	1	1	1	2	1	11	5	1	1	
06.11.08_15.01	1	1	1	1	2	24	7	3	1	
08.11.08_15.01	1	1	1	1	1	1	3	10	1	
09.11.08_15.01	1	1	1	4	1	1	5	5	1	
16.11.08_03.01	1	2	3	2	3	5	1	1	1	
18.11.08_15.01	1	1	1	1	3	45	1	2	1	
20.11.08_03.01	2	2	2	2	2	2	3	1	1	
21.11.08_03.01	1	1	2	2	1	63	1	2	1	
24.11.08_03.01	1	1	3	3	4	40	1	6	3	
24.11.08_15.01	1	1	2	3	7	61	1	3	1	
25.11.08_03.01	1	1	2	5	8	74	1	1	1	Spikes rising within inner race
27.11.08_15.03	1	1	1	8	6	41	4	10	1	ball passing frequency band
28.11.08_15.03	1	1	1	5	4	12	1	13	5	(1.0-1.5 kHz) of LPC fore
29.11.08_15.03	2	1	3	12	4	7	1	14	8	support vibration
30.11.08_15.01	1	1	3	6	6	36	1	5	1	
02.12.08_03.03	2	1	4	8	7	3	1	10	1	
02.12.08_15.03	1	1	2	6	10	44	1	3	2	
05.12.08_15.01	1	1	1	3	2	33	2	8	1	
06.12.08_03.01	2	1	2	4	6	90	1	5	2	Max damages of
06.12.08_15.01	1	1	2	9	13	101	1	7	1	LPC 1-st stage rotor blade
07.12.08_15.01	1	1	1	7	9	71	1	13	7	
09.12.08_03.01	1	1	3	4	5	14	1	4	1	
10.12.08_03.03	1	1	1	4	5	2	1	2	17	
10.12.08_15.03	1	1	3	4	5	1	5	13	1	
11.12.08_03.03	1	1	6	7	5	22	7	2	1	
11.12.08_15.03	1	1	3	8	2	27	9	2	1	
12.12.08_03.03	1	1	8	30	3	37	9	1	1	Development of inner race
13.12.08_03.03	2	1	4	51	3	24	7	7	1	defect of the ball bearing
13.12.08_15.03	1	1	4	68	5	8	1	14	2	
14.12.08_03.03	3	1	6	42	5	39	5	3	1	
14.12.08_15.03	3	1	4	35	7	40	1	1	1	
15.12.08_03.03	6	2	4	632	5	14	11	3	1	Rough damage of the ball
15.12.08_15.03	6	4	3	206	2	3	2	2	1	bearing inner race
16.12.08_03.03	5	4	4	132	2	8	3	1	1	
16.12.08_15.01	16	5	8	388	11	17	2	28	2	High vibration level in freq.
17.12.08_03.01	20	10	11	295	11	5	1	17	3	band around rot.frequencies and
17.12.08_15.01	100	89	14	145	10	9	4	27	3	in wide band

View of Table 3 gives us a chance to localize the frequency bands of maximum signal changes, estimate event chronology, rate of vibration temporal changes and detect cause-and-effect relations of vibration changes in different frequency bands.

As for measurement point LPC-Vert (closely to front support) the most vibration signal changeability is seen in the band of inner ring passing frequency (IRPF) of LPC fore support ball bearing ($\mathbf{\Delta F}$ =1.0…1.5 kHz). Stable discriminant growth had begun from 12.12.08_03.03 ($\mathbf{I_d}$=30), reached max value 15.12.08_03.03 ($\mathbf{I_d}$=632.3) when the ring was destroyed. After that discriminant falled down that is specifically to this stage of condition degradation. It could be seen from the Table 3 that significant changes in wide frequency band had begun from 16.12.08 only. And else later (17.12.08) - in the band of rotation frequencies (0.1…0.5 kHz). It means that ball bearing malfunctions become apparent in wide and common used frequency bands of rotation frequencies at the last stage of bearing condition deterioration. The role of vibroreactivity source localization technique becomes clearly evident on consideration of S-discriminant trend curves in mentioned frequency bands (see Fig.2).

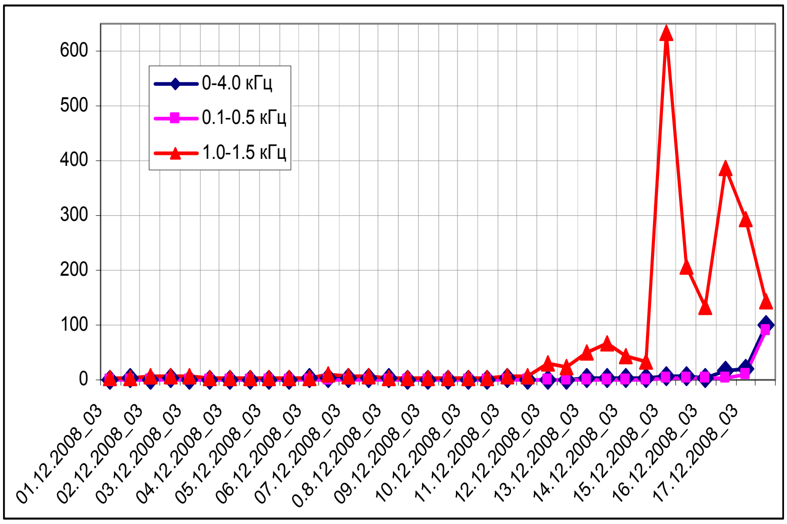
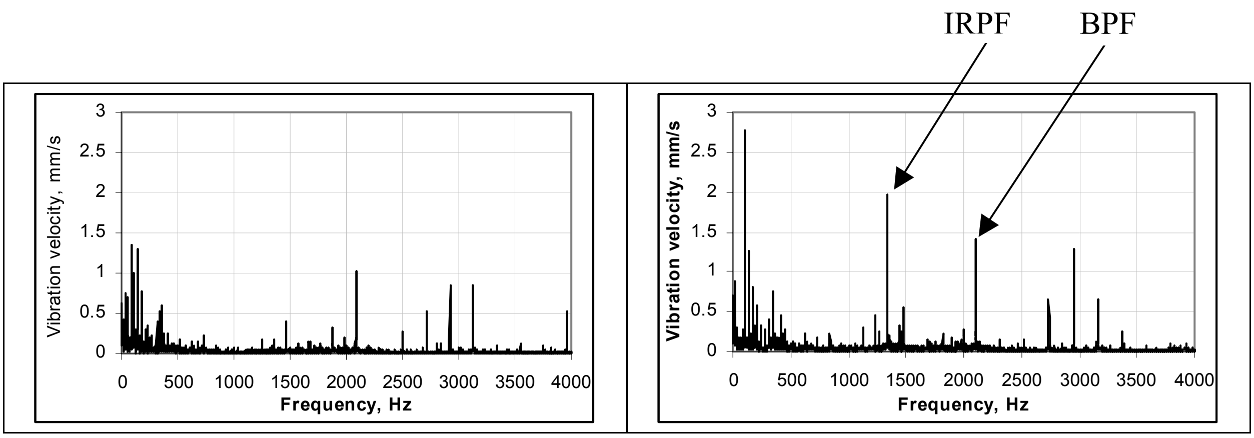


Figure 2. Trends of S-discriminants $\mathbf{I_d}$ calculated for GTU DG-90 case vibration velocity measured in point LPC-Vert (within several frequency bands: 0 … 4.0 kHz; 0.1 … 0.5 kHz and 1.0 … 1.5 kHz), caused by LPS front support ball bearing condition degradation.

As it could be seen at the Table 3 and Figure2, before bearing elements had been destroyed there were essential vibration velocity amplitude fluctuations (and discriminant values respectively) in the frequency band of 2.0…2.5 kHz (max $\mathbf{I_d}$ =101.2 of 06.12.08_15.01). Most probably, it is due to 1-st stage blade surfaces damages like spalling, cavity, corrosion or erosion wear. Such kind of slight damages reveal itself mainly at blade passing frequency (BPF) and their amplitude modulation.
It is always useful to compare different kind of data to be certain in your diagnostic conclusions. So, spectrums of the same measurement point on Figure 3 show significant growth along operational time of the inner race passing frequency level and some increase of the blade passing frequency level that is compliant to said above. Unfortunately, due to the monitoring system available frequency band limitations there are not possibility to take into account another blade frequencies and their harmonics to do the diagnose more true.



a) *b*)

Figure 3. DG-90 LPC vertical vibration spectrums for normal condition (*a*) - of 14.10.08_03.01 and under damaged inner race condition of FS LPC ball bearing (*b*) – of 15.12.08_03.03.

Conclusions

As it is shown at the paper, to effectively monitor machinery conditions, realize an incipient fault detection and localize heighten vibration reactivity sources the vibration monitoring should be based on vibration parameters which are sensitive to current amplitude changes and especially to their spikes. The suggested algorithm of vibration monitoring with estimation of S-discriminants meets to this requirements. The result representation of its application as a coloured table is very convenient to fluently estimate said above and foreseen further development of malfunctions.

These S-discriminants presentation properties permit to use it in condition monitoring systems not only for emergency protection aim, but for heightened vibroreactivity sources localization, caused by incipient faults influence, and for early machinery operational damages detection.

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