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ANALYSIS OF DYNAMIC BEHAVIOR OF ROTATING MACHINES

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Abstract: Operating supervision and the condition monitoring of the rotating machines, deploying exact diagnostic methods, can be considered as a good insight into the current state of a technical system and exact assessment of maintenance necessity. In this way, one can survey a large scale of machines and processes, without loss of reliability, as well reducing the costs of maintenance and increasing system profitability. This is the paramount demand of the modern production philosophy. The paper, consideres importance of data selection and implementation of appropriate diagnostic techniques with particular emphasis on the analysis of the dynamic behavior of rotating machinery. Shown are some of the results of diagnostic analysis that have been conducted on machines in a real operation, applying advanced methods of technical diagnostics.
Keywords: rotating machines, monitoring, diagnostics

1. INTRODUCTION

The progress of computer and measurement techniques and the appearance of powerful software associated with the constant price reduction, provided a significant step forward in monitoring and protection of rotating machines. Regularly, such configurations became very affordable and available. Achieving the goal of inexpensive and efficient device for monitoring, all the rotating systems of major importance will be equipped with it, in less than 40 years. Thus would be age of error free operation in the long term. Machinery set up would be automaticaly conducted for different operating modes, aimed on identifying the causes of malfunction and archiving the specific events, important for machine record. Such devices are already deployed to monitor large number of industrial plants around the world, and will remain indispensable equipment for both new and rebuilt plants [1].

The most common deficiencies of rotating machines that can be promptly identified by the use of control–diagnostic system are: unbalance (asymmetry of rotor mass and inertia), misalignment, damaged roll/sleeve bearing, faulty inclination, resonant behaviour, disturbances of electrical and magnetic origin, aerodynamic and hydrodynamic influances, malfunction in gearing/belt drive, loose parts, mechanical impacts, rotor to stator scrub, mechanical rotor anisotropy.

2. PARAMETERS AND METHODS OF ROTATING MACHINES SURVEY

Monitoring parameters of the rotating machines are usually related to the structural parameters (frame and machine vibration, process and casing temperature, clearance in the bearing, oil pressure, etc.). All the parameters can be divided into severalgroups:

- The parameters of the dynamic machine motion: absolute and relative vibration.
- The parameters of the position: the position of the rotor in the bearing sleeve, the relative motion of the shaft (axial displacement), relative elongation of the shaft, absolute elongation of the housing.

– Other diagnostic parameters: rotational speed, temperature, shaft eccentricity, electrical parameters, the acoustic parameters and the technological parameters.

In general, approximately 90% of all deficiencies that appeared at the rotating machines, affected the vibration response.

Occurrence of certain faults on the machine produce a stable excitation which generates a specific oscillatory motion. The outcome of the vibration response analysis reveals the character of the excitation force and determine the cause of machine malfunction Figure 1. [2]

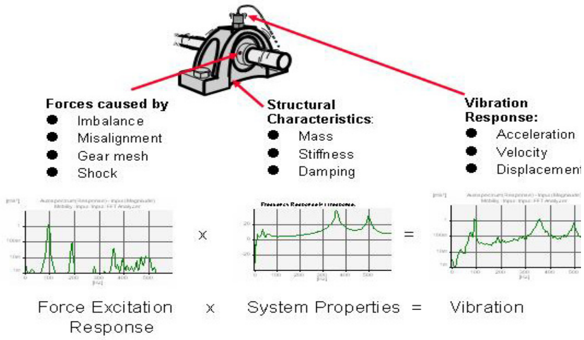

Figure 1. Dependence of system response to the excitation force

Commonly used Vibrodiagnostic methods are: simple vibration severity detection, spectral analysis, phase analysis, real–time vector analysis, orbits, DC analysis, record trends, SPM analysis, energy analysis, Zoom FFT analysis, CPB analysis, cepstral analysis, SED detection, HFD, LFD, SEE technology, modal analysis. It is possible to extract major causes of dynamical disorder by early detection. [5]

There are some other methods which contribute to a proper identifying of real causes of malfunction. They are: Monitoring and analysis of air gap, analysis of the magnetic flux, analysis of partial discharge, monitoring of parts wear, detection of combustion products, monitoring of system fluids (oil and lubricants, gases, coolants...), corrosion monitoring (visual methods, gravimetric and electrochemical methods)

3. DYNAMIC PROBLEMS CLASSIFICATION AND OPTIMAL DIAGNOSTIC MODEL

Dynamic problems are usually typical for certain group of machines, depending on their power, speed, size, foundation, etc. Standard ISO 10816 classifies all the machines into 4 categories. Each category is determined by the permitted level of vibration severity, disposition of measuring points, measuring axis and the recommended measuring parameters (Figure 2).

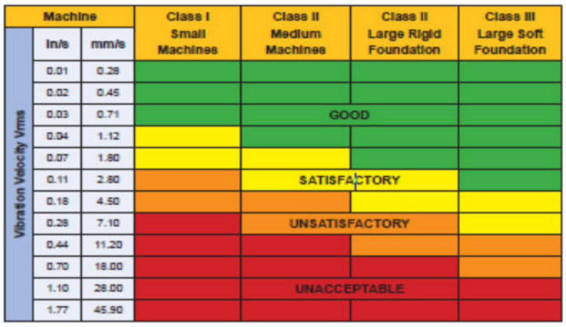

Figure 2. Vibration Severity Per ISO 10816–1

Some causes are typical for some machines. Therefore the two families of machines are recognized:

– *GROUP 1*, running with rolling–element bearings

Machines classes I, in accordance with ISO 10816

Machines classes II, in accordance with ISO 10816

– *GROUP 2*, running with journal bearings

Machines classes III, in according ISO 10816

Machines classes IV, in according ISO 10816

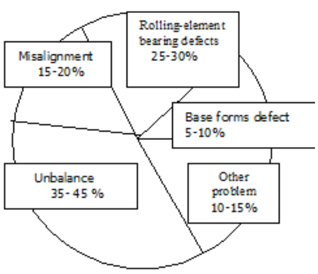

Figure 3. Probability of certain defect appearance in machines Group 1

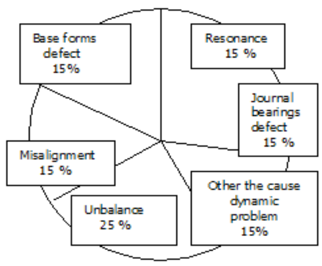

Figure 4. Probability of certain defect appearance in machines Group 2

A true study of possible causes of disturbed machine operation, brought us to conclusion that the optimal model of fault detection must be based on [7]:

1. Identifying the cause of dynamic problem
2. Simplicity for use and performance
3. Early detection
4. Economy aspect

The optimal set of methods, which satisfy the criteria, involeves: vibration severity detection, spectrum analysis, polar trend of the signal. Additionally the machines belonging GROUP 1, should be observed by HFD method, while the machines from the GROUP 2 need Bode chart and orbit analysis.

4. CONFIGURATION OF THE MONITORING–DIAGNOSTIC SYSTEM

In order to provide the appropriate data record, necessary for the evaluation and analysis, the monitoring system must be configured to collect all the relevant data. As well the device should arrange the data in a relevant form (format), appropriate for instant decisions of possible machine trip, and maintain recommendations. System must be restrictevly conseived, allowing only authorized persons to access data record, and alarm settings.

Regularly, monitoring system consists of: 1) Transducers (sensors), 2) Data collect unit, and 3) Diagnostic system for data record, analysis, alarm raise and data transfer.

Signal from the sensor undergoes amplifcation and raw filtering in order to present properly vibration level, all spectral components, phase lag, etc.

Some modern instruments use a computer facility for data record, data presentation and data transfer. Moreover, the computer is capable of detailed spectral analysis and data archiving in different forms, Figure 5.

Besides the ability of signal conditioning and analysis, PC can communicate with the expert systems, transferring to them both data and responsibility for the proper decision. This is applicable either in the long term operation or in transition stages like start up and machine coast down.

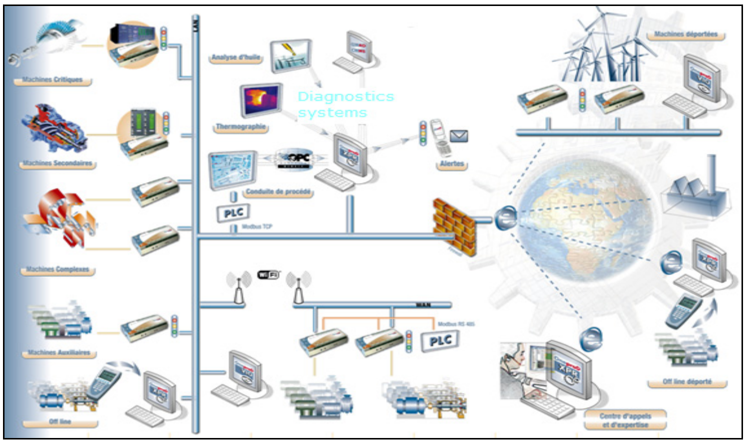

Figure 5. Data collect, data transfer and archiving with modern diagnostic systems

Most of the built–in diagnostic systems are equipped with the adaptable knowledge base. That is the memory space where the user knowledge is stored, in order to expanded system expertise. When set, the whole diagnostic process develops automatically, securing an optimal diagnosis always at hand [8].

The development of communication allows remote monitoring of the machines regardless their location against the location of control staff. Also, the machine producer can be involved in the monitoring process, contributing by its expertise to the competent reaction on any alert/alarm event. As well by such producer oriented monitoring the data base of systematic equipment faults is promptly updated.

5. DIAGNOSTICS ON SITE

Here follows some examples of site diagnostics, conducted at the Thermal Power Plant Gacko, implementing COMPASS,Bruel & Kjaer diagnostic system.

5.1. Electric feed pump (machinery GROUP 1)

Location: Thermal Power Plant Gacko, Plant: Feed Pump

Technical data: electric three–phase AC motor, rated power P = 630 kW, 750 RPM.

Multistage pump, 6 impelers. Rolling bearing tyupes: L1–6326, N326–L2, L3 and L4–6318

Process parameters: water pressure at the pump inlet 1.7 [bar], water pressure at the pump discharge 6.2 [bar], motor current, 62 [A].

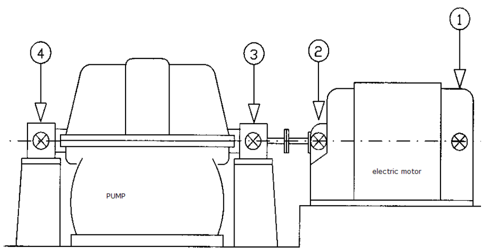

Figure 5. Feed Pump

Inspection Methodology:
1) measurement of vibration severity of all bearings in either of three main axis
2) spectral analysis at each point
3) HFD bearing detection.

The results – vibration severity

MACHINE assessment, in accordance with ISO 10816 standard: *permissible.*

Table 1. Overall vibration levels

Bearings	Horizontal $\sum v_{RMS}$ [mm/s]	Vertical $\sum v_{RMS}$ [mm/s]	Axial $\sum v_{RMS}$ [mm/s]
1	1,6	1,2	1,8
2	1,2	1,1	1,3
3	1,9	2,1	1,5
4	3,2	3,1	1,2

– Spectral analysis

Beneath is the spectral plot of the horizontal vibration at the outer, 4–th bearing.

In order to identify the main causes of faulty behaviour, the characteristic frequencies are needed. Fundamental tone of rotation is 1X = 12.5 Hz. Frequency signature for SKF6318 is: BPFO= 38,6 Hz, BPFI=61,2 Hz; BSF=26,1 Hz; FTF=4,75 Hz, Vane pass frequency of impeller is 12.5 x 6 = 75 Hz (BPF)

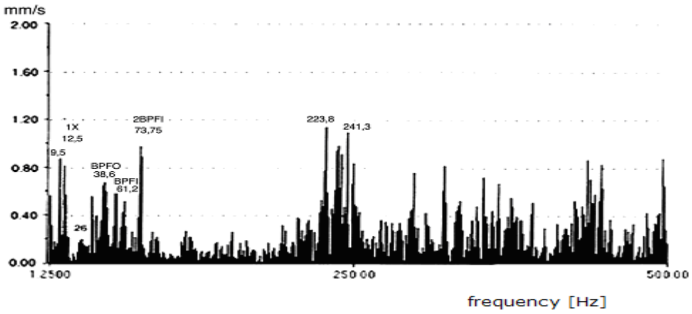

Figure 6. Spectrum plot horizontal vibration at outer 4th bearing

Spectrum plot indicates damaged rolling–element in outer 4–th bearing, Figure 6.

– HFD overall value

HFD equals 9,2 g. This is a high value.

5.2. Turbine (machinery GROUP 2)

Location: Thermal Power Plant Gacko, Plant: Steam Turbine

Operating mode: Active power P = 262 MW, reactive power Preah = 40 MVAr.

Steam parameters inlet: t = 520 ° C, p = 235 bar, primary steam flow Q = 750 t / h. Secondary steam parameters: T = 525 ° C, p = 34 bar.

Level of condensate 120 cm, Vacuum level in condenser p = 0.86 bar.

Oil temperature at turbine bearings discharge (°C): t1 = 68, t2 = 60, t3 = 60, t4 = 56, t5 = 56, t6 = 64, t7 = 71 , t8 = 58, oil pressure at bearing discharge p = 1.55 bar.

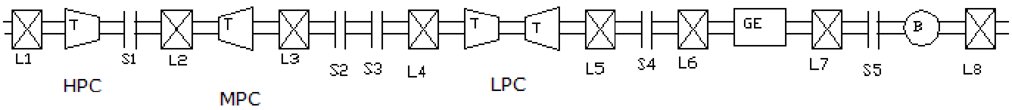

Figure 7. Steam turbine Power train

Other parameters: Speed n = 3000 RPM, axial displacement 0.30 [mm], relative elongation HPC 1.96 [mm], absolute spread HPC 30.7 [mm], absolute spread of MPC 20 [mm], relative elongation MPC –1.65 [mm], relative elongation of LPC 3.26 [mm].

Table 2. Overall vibration levels

Bearings	HOR $\sum v_{RMS}$ [mm/s]	VER $\sum v_{RMS}$ [mm/s]	AX $\sum v_{RMS}$ [mm/s]
1	3,4	1,8	1,8
2	2,1	1,8	2,1
3	1,4	3,6	2,2
4	2,0	1,9	2,3
5	3,2	2,7	2,1
6	3,3	4,6	6,5
7	3,8	5,8	9,3
8	6,4	5,2	4,1

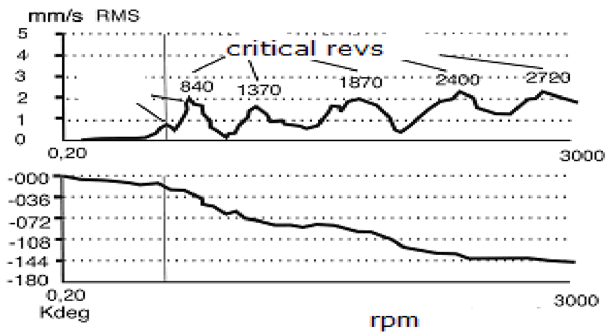

Figure 8. Bode plot

Temperature in bearing body: t1 = 54, 55 (two measurement points), t2 = 53, t3 = 68, t4 = 61, t5 = 62, t6 = 67, t7 = 68.

Test methodology: vibration severity on all turbine bearings. Spectral analysis at each measuring point of increased vibration where needed, polar trend graph 1X and 2X fundamental.

The results – Bode plot

1X fundamental at start–up, 1–st bearings.

Turbine critical are at (RPM): 1– 840; 2– 1370; 3– 1670; 4– 2400; 5– 2720, Figure 8.

– vibration severity

Assesment in accordance with ISO 10816 standard: permissible.

– Spectral analysis

Spectral plot clearly verifies that the unbalance and misalignment of the generator are the main causes of increased vibrations. Additionally, spectral plot at the 8th bearing indicates slack, while the 7th bearing suffers of reduced stifness in the axial direction. Note: More illustrative picture of deficiency origin is delivered with polar trend plot of 1X and 2X fundamental in radial and axial bearing of the generator, Figure 9,10,11,12. In order to identify the real cause of the problem it is necessary to correlate the diagnostic parameters with the parameters of the process.

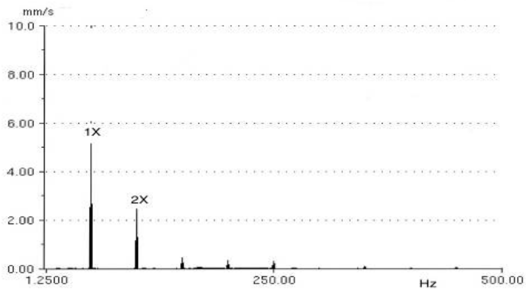

Figure 9. Spectral plot at 6th bearing (V)

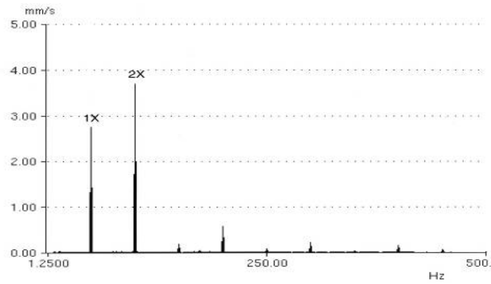

Figure 10. Spectral plot at 7th bearing (V)

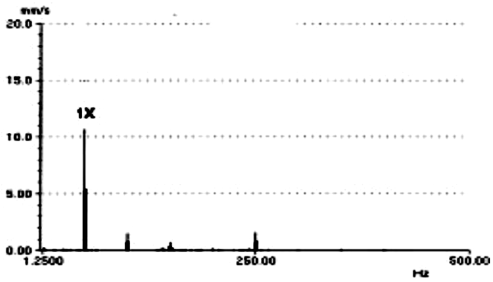

Figure 11. Spectral plot at 7th bearing (A)

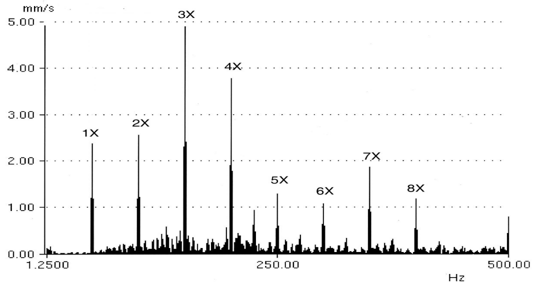

Figure 12. Spectral plot at 8th bearing (V)

Polar trend plot

Polar trend plot 1X and 2X fundamental is made for bearings 6 and 7. Polar trend 1X fundamental (V) at the 6th and 7th bearing is collected while:

– Operating at rated speed (3000 RPM), without excitation on generator

– Machine at rated power

– Machine coasts down after power cut of the generator excitation.

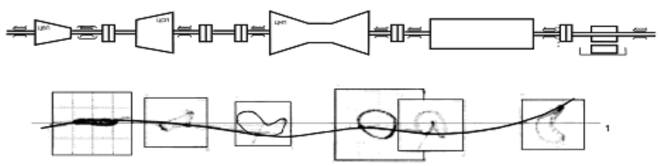

Figure 13. Orbit analysis for the turbine bearings

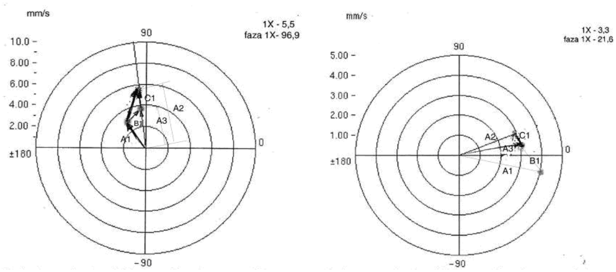

Figure 14. Polar trend plot at 6th and 7th bearing

Polar trend plot clearly shows that there is a change in amplitude and phase of 1X Fundamental with power increase. This fact indicates the mass asymmetry of the rotor mass, possibly change in rotor geometry, which may be due to thermal distorsion or impact of asymmetric magnetic field. Further analysis of the polar trend 1X Fundamental indicate also some other effects, such as:

– Vector at A1– 1X intensive component, while cold

– Vector at A2– 1X intensive component, on full a full power
– Vector at A3 – 1X intensive component after power cut.

It is obvious that the vector B1 (Figure 14) indicates thermal unbalance, also has a minor influence on the overall dynamic state (vibration severity slightly changes). On the other hand vector C1 indicates asymmetric magnetic field vector, which significantly affects the dynamic state of the machine, because its phase coincides with the residual unbalance at the seventh bearing.

6. CONCLUSION

Recent development of the microprocessor technology and digital signal processing, allows outstanding progesss in conceiving on–line monitoring systems. Nowadays bundles of signals are processed practically in real time. Therefore modern methods in technical diagnostics provide a deep insight into the following issues:

– When and where the damage occurred (technical diagnostics)
– How the damage progresses over time,
– How soon comes the final failure (technical prognostics)
– What is the cause of failure (technical genetics)

Substantial goal of the condition based maintenance is to recognize timly the possible threats for smooth and restles operation. The set of properly configured measurements, composed with the monitoring concept and signal analysis lead to a reliable technique of early fault detection. Dynamic behaviour of the machine is thus constantly observed with the high degree of proactive protection and deep understanding what occures under the machine cover.

In this way, machines are managed properly, resulting with increased availability and improved utilization. Maintenance costs are reduced to the minimum while the profitability of the machinery increases to an almost theoretical level.

A humble contribution of this paper is addressed to those who still compromise between full capacity of modern monitoring systems on a valuable machinery and usually traditional low cost diagnostic techniques with a poor performance.

NOTATION

FFT – Fast Fourier Transform; BPFO – Outer Race Frequency; SEE – Spectral Emitted Energy; BPFI – Inner Race Frequency; CPB – Constant Percentage Bandwidth; BSF – Ball Spin Frequency; SPM – Spectrum Pulse Method; FTF – Fundacion Train Frequency; HFD – High Frequency Domain; SED – Selective Envelope Detection; BPF – Blade Pass Frequency; LFD – Low Frequency Domain; CVP – High Pressure Cylinder; CDS – Computer Diagnostic System; MPC – Medium Pressure Cylinder; RPM – Revolution Per Minute; LPC – Low Pressure Cylinder

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