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ESTIMATION OF CHANGING VIBRATION CONDITIONS OF COMPLICATED MECHANISMS USING VIBRATION CHARACTERISTICS OF START-UPS AND RUN-DOWNS

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In many cases, when possible, the technicians dealing with operation and maintenance of multi-seat rotary aggregates analyze the vibration characteristics, obtained during rundowns (free breaking of the running shaft) when the mechanism is being stopped, or during startups. This is essential when evaluating the technical condition of the operated object and planning the routine maintenance and repair works. The start-up and rundown vibration characteristics are the key features widely used to evaluate the technical condition of the mechanisms and aggregates that use friction-type bearings (turbo machinery, powerful pumps and drives). These characteristics are remarkable, since the vibratory excitation at frequencies take place during the transition period, referred to the changed shaft rotation frequency. Therefore the parameters of the vibration harmonic constituents, calculated in these operation modes, make it possible to evaluate the frequency values, the shaft misbalance, as well as to reveal a number of other defects. The paper considers the automation strategy for the comparative analysis procedure of the startup and rundown vibration characteristics. A number of parameters have been selected that describe the amplitude factors and distinctive features of these characteristics' shapes. The decision functions are proposed to conclude regarding similarity or difference of the comparable characteristics. The paper discusses the practical examples of estimating the vibration conditions of the bearing assemblies in some turbo machinery are presented. In the considered cases, while the changes in the vibration intensity in the stationary mode were relatively insufficient, the rundown vibration characteristics varied substantially.

1. Introduction

Vibration-based diagnosis is needed to continuously improve operating strategies and maintenance of equipment. Such diagnosis is based on modern technologies, monitoring, and analysis of technical conditions as well as generalization of practical operating experience.

The operating states of equipment can be characterized by many parameters that have different physical characteristics. However, one of the most important parameters is the level and spectral composition of vibration, which requires continuous monitoring and tracking of its vibratory state [1–3] during extended non-stop operation of a technical object.

One of the major problems of vibration control of large machines with rotary motion is to determine the amplitude and phase of vibration parameters in real time in multichannel mode. The resulting solution of this problem is to use vibration data for comprehensive assessment of a vibrating condition (including balance) of flexible shafting, especially in the process of performing balancing operations. In addition, the amplitude and phase parameters of vibration bearings and their changes over time are key in technical condition assessment and in building diagnosis systems for machines with rotary motion.

Specialists involved in the operation and maintenance of complex multi-support units with rotary motion must make decisions on changing the technical condition of operated objects as well as regarding the planning of preventive and repair work. In many cases, with adequate opportunities, specialists must analyze the vibration characteristics obtained when coasting (free braking of the rotating shaft) during the stop or start mode of a mechanism. The vibration characteristics of the start-run process can be used to evaluate the technical condition of machinery and units with sleeve bearings (turbines, high-power pumps, and motors). These characteristics are the focus of the fact that vibration excitation occurs at natural frequencies during the transition process associated with a change in frequency of shaft rotation. Thus, the vibration parameters of components are calculated in these modes, thereby enabling the estimation of the magnitude of imbalance shafting as well as identifying other defects [4–5].

However, a software process is required to automatically analyze changes in the technical condition of the control object based on a study of vibrating characteristics of the start-run-receive tasks over a certain period, to improve the efficiency and reduce the complexity of repair work [6].

2. Presentation of vibration characteristics

Vibration characteristics in the starting stage show the dependence of the amplitude of vibro at the point of shaft speed. These characteristics can be obtained with the help of modern vibration control systems, with a start or stop in the turbine unit or some other mechanism. Figure 1 presents an example of such characteristics.

The vibrating characteristics in the starting stage vary. In many cases, significant differences are observed even for the same name that bears different arrangements of the same type. However, certain vibration characteristics can be identified; patterns such as presence of peaks (global and local) that are shaped like a parabola, as well as smoothness characteristics, change, at least to a certain frequency zone.

For experts in the field, the change of vibration characteristics obtained for the same bearing at different times is of interest, for example, offset in the frequency domain values of natural frequencies or change in the rotor imbalance degree.

However, the starting time or run-out is not fixed and depends on many factors; thus, the raw data obtained by vibration monitoring systems require pre-normalization for further analysis in the common coordinate axes.

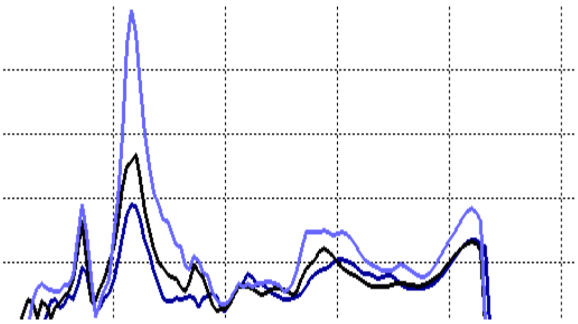


Figure 1: Vibration characteristics overrun for vertical direction of bearing in turbine unit.

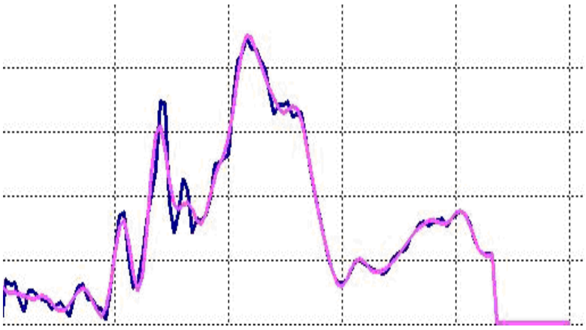


Figure 2: Approximation of vibration characteritics of run-twenty harmonic components.

3. Approximation of vibration characteristics at starting stage

Comparing transient vibration characteristics obtained by direct instrumentation or systems can be difficult; these characteristics involve interfering components and instrument errors. Therefore, approximating the original features is appropriate, as is conducting a comparative analysis of the approximation characteristic.

The vibration characteristics of the stick out, which are presented in Figure 1, enable the assumption that the characteristics can successfully be approximated by a certain number of harmonic components with parameters that are computed using discrete Fourier transform. The initial vibration characteristics approximated by the stick out are assumed to be stored in the data array, and the approximation can be performed for all the characteristics or for a certain portion of them.

Discrete Fourier transform is applied to determine the approximation coefficients. The approximated starting characteristic is calculated as

$$A_a\left(k\right) = A_0 + \sum_{j=1}^{L} A_j \cdot \cos\left(\frac{2\pi \cdot j \cdot k}{N} - \phi_j\right), \qquad (1)$$

A_0 represents the constant component; A_j, ϕ_j are the amplitude and the initial phase of j th approximating harmonics; L is the number of approximating harmonics; N is the dimension array of data to approximate; and k varies from 0 to $N-1$.

Further analysis is applied to approximate the characteristics at starting stage. This application eliminates random perturbations that can occur in the measurement process, and this process enables the analysis of a smooth function.

Figure 2 shows an example of such an approximation of 20 harmonics.

Visually, an approximated curve is apparent and is obtained with the help of 20 harmonic components. From a practical point of view, the curve indicates the initial vibration characteristics of the machine, as observed by their close agreement on the value of the frequencies and amplitudes at the points where the majority of the local maxima are fixed and only minor amplitudes of deviations peak for local extrema.

However, in cases with a sufficient degree of accuracy for comparison of vibration characteristics, we can focus on a small number of approximating harmonics.

4. Comparative analysis of vibration characteristics at starting stage

Given the continuous monitoring of vibration signals, the vibration characteristics of the start-up and coasting over a long period can be determined. At this stage, pre-processing is performed. Normalization vectors and relevant parameters are calculated. A specialist in vibration diagnostics conducting visual analysis of these characteristics can make conclusions regarding the technical condition of the mechanism of change. However, the actual task is the automation of processes of such analysis.

When comparing the characteristics (functions), one of the functions is taken as the base and the second is considered for comparison.

For any characteristic coasts, considering it either as a normal functional relationship or as a function of the probability density, we can determine certain parameters, each reflecting some properties. To reduce the influence of random confounding factors that occur in determining the characteristics of run-down, such a reduction can be represented in the form of approximating the expansion over a number (12–20) of harmonic components, and then the informative parameters for approximating function are calculated.

For a comparative analysis of algorithms for vibration characteristics of overrun, an array of informative parameters must be formed to determine the specific characteristics of overrun. When the parameter types are selected, important differences occur in the amplitudes and shapes of the run-down characteristics. Therefore, we propose the use of the following parameters [7]: a constant component; maximum vibration displacement amplitude (both fixed data array $j_{R_{\max}}$ index A that corresponds $R_{\max}$); shaft speed that corresponds to the maximum amplitude of vibro; amplitude ratio (crest factor); weighted average shaft speed; initial (first to fourth) times; central (from first to fourth) times; standard deviation of shaft speed from average value; skewness; peak factor; values of local maxima and minima.

To find the local maximum and minimum value of the characteristics, the first and second derivatives of the approximate characteristics of overrun are used. In comparative analysis of algorithms, considering the values of the three or four local maximal values and two or three local minimum values is appropriate. The most informative parameters are the amplitude and phase of the first three or four approximating harmonics.

The amplitude characteristics of the properties that were proposed to be evaluated were examined using the following parameters: amplitude of the first three (highest) peaks approximating function (local maxima), amplitude of the first four harmonic components approximating decomposition, and main peak.

Form function is characterized by the following parameters: maximum frequency function, frequency of approximating function of the first three peaks, phase four of approximating decomposition of the first harmonic components, peak factor, skewness, and peak ratio.

Conclusion of the similarity of the compared characteristics of the base and the current is taken based on decision functions, which, for example, may be as follows [8]:

$$FR(x)=\begin{cases} 0, & x \le X_1; \\ 0.25, & X_1 < x \le X_2; \\ 0.5, & X_2 < x \le X_3; \\ 0.75, & X_3 < x \le X_4; \\ 1, & X_4 < x; \end{cases} \qquad (2)$$

where x is a parameter related to the determined value of the decision function; X_j is value threshold; and $X_1 < X_2 < X_3 < X_4$. Their quantitative knowledge is selected based on the expertise and accumulated experimental data.

Application of the decision function (2) to the parameter enables the sensing of the output-hole on the degree of similarity of compared characteristics.

If $FR(r) < 0.25$, we must conclude "very similar;" if $0.25 \le FR(r) < 0.5$, then "are similar, but differences occur;" if $0.5 \le FR(r) < 0.75$, then "significantly different;" if $0.75 \le FR(r) < 1$, then "very different;" and if $1 \le FR(r)$, then "quite similar."

As a synthesis, comparing the coasting characteristics can offer a parameter that is calculated as the ratio of the distance between the base in Manhattan and the current characteristics to the RMS basic characteristics.

Table 1: Values of thresholds of decision function.

Parameter name	Ур. 1 X_1	Ур. 2 X_2	Ур. 3 X_3	Ур. 4 X_4
Distance between Manhattan features	0,12	0,22	0,3	0,45
Deviation in frequency of maximum amplitudes	0,12	0,22	0,3	0,45
Rejection frequency peaks, rev/min	70	140	210	270
Deviation of amplitude ratio	0,5	1,0	1,5	2,0
Deviation of asymmetry coefficient	0,12	0,25	0,35	0,5
Deviation ratio peaked	0,15	0,3	0,45	0,6
Deviation of amplitudes of spectral components	0,2	0,35	0,5	0,65
Deviation of spectral components of phase degrees	30	50	70	90

The conclusions on the degree of similarity of compared characteristic coasts require clarification in terms of the ratio of their amplitudes; such a ratio can judge the intensity of the vibration change and the similarity of their forms. The deviations can draw conclusions on the possible structural and technological changes. To this end, each information parameter is determined by an argument corresponding to the decision function, and then by the value of the decision function.

The values of generalized functions to solve amplitude parameters and shape parameters are determined as a weighted sum of the crucial functions of individual parameters:

$$FR(t) = \sum_{i=1}^{n} a_i \cdot FR(x_i) \Bigg/ \sum_{i=1}^{n} a_i \,, \tag{3}$$

where t is the parameter type; n is the number of parameters; $FR(x_i)$ is used to define a generalized decision function; a_i is the value of the decision function for the *i*th parameter; and i is the weighting factor for the parameter.

Considering the values of these critical functions, we specify the findings of the similarity of the compared characteristics of overrun. Based on expert assessments that selected the thresholds for individual parameters or groups of parameters for critical functions (2), each informative parameter is calculated (Table 1).

5. Field example of vibration characteristics at starting stage

In this case, damage to the blades of the turbine unit of 100 MW occurred at the initial stage of operation of the unit after overhaul. Concurrently, the impossibility of fixing the damage can be attributed to slight changes in the standardized RMS vibration frequency range of 10–1000 Hz. Although short-term data are recorded, slight vibration bursts for several minutes occurred in the vertical direction of the second and fourth bearings.

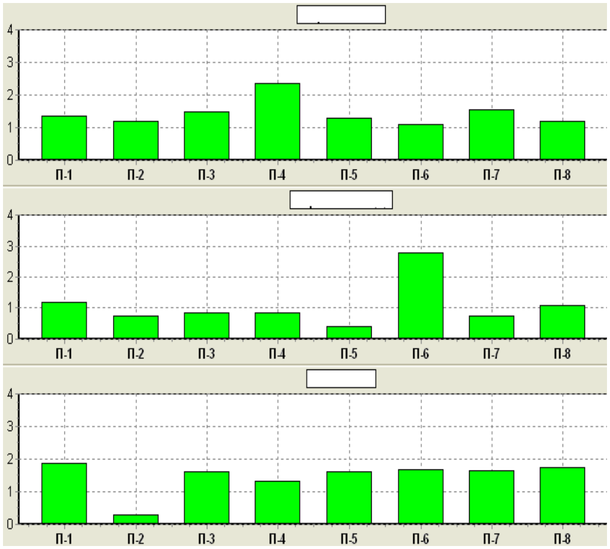


Figure 3: Vibration condition turbine unit after running of turbine unit.

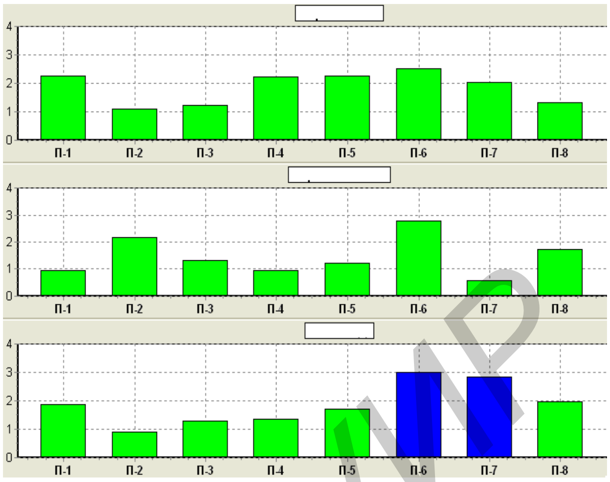


Figure 4: Vibration condition turbine unit at stopping stage.

Vibration condition of bearing supports turbine unit was normal (Figures 3 and 4 present RMS vibration velocity diagrams). The diagrams show green RMS vibration levels up to 2.8 mm/s as well as blue RMS vibration levels from 2.8 mm/s to 4.5 mm/s. However, during the run-down on the first bearing support, RMS vibration equal to 18 mm/s was recorded; such a value is much higher than the alarm level of 11.2 mm/s. Thereafter, the high-pressure cylinder of the turbine was opened and damage to blading was found.

Analyzing the situation is interesting in terms of changing the vibrational characteristics of overrun. Figures 5 and 6 present the vibration characteristics of the run-bearing turbine unit recorded after entering the pump set to damage the blades (shown in dark blue), after injury (shown in black), and after repeated repair work (shown in light blue).

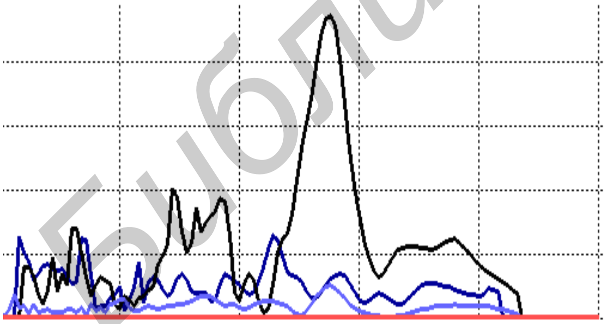


Figure 5: The vibration characteristics overrun for the first bearing.

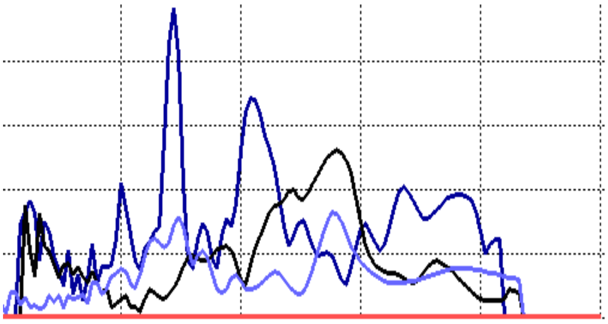
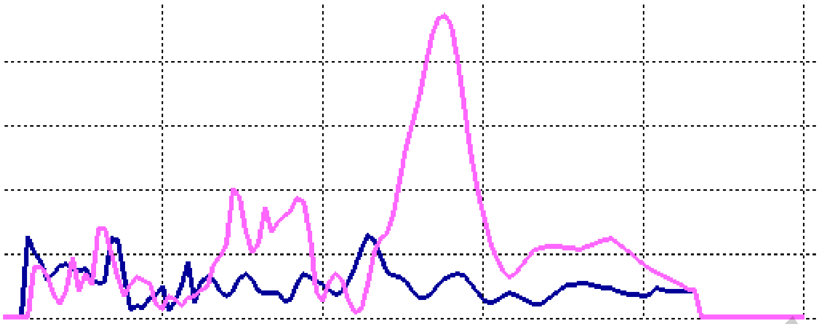


Figure 6: The vibration characteristics coasting to a second bearing.

Visual analysis of Figures 5 and 6 indicate that the vibration characteristics of the coasting received after the injury blade were noticeably different from the vibration characteristics obtained in the normal turbine unit.

Comparative analysis of the normal and emergency vibration characteristic coasts (Figure 7) are performed by a computer program that works in accordance with the proposed algorithm that automatically diagnoses the appearance of damage.



Results of comparative analysis
Criterion - relative distance between functions:
Basic and current characteristics are significantly different.
Generalized decision function:
Basic and current characteristics are significantly different.
where
shaped base and current characteristics are significantly different,
and amplitude parameters of the basic and current characteristics are significantly different.
Value of total for Russian Federation (RF) in the form 0.8155
Value of total RF amplitude 1.0
Value of decisive function of distance 1.0
Value of generalized decision function 0.911

Figure 7: Comparison of run-vibration characteristics obtained at normal state.

6. Conclusion

Vibratory start-coasting characteristics can be used to detect several incipient defects (e.g., rotor imbalance) even in normal conditions in accordance with standards [9]. Such characteristics include the vibration state of turbine bearings when operating in a steady state.

Comparative analysis of the vibration characteristics of the start-up and run-down in certain situations enables the detection of changes in a technical condition of the controlled object even with a slight change in vibration parameters at operating conditions.

Software tools allow the automation of the comparative analysis of the vibration characteristics of the start-up and run-down; synthesized conclusions occur in the extent of differences between the compared characteristics. Such automated analysis enables professionals to focus on the possibility of defects.

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