Vibration diagnostics of rotating equipment with non-stationary speed mode

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Abstract

Rotating equipment vibration analysis is currently the most common method of determining its technical condition. For this purpose, in the vibration spectrum the harmonics levels, associated with the defect magnitude, are determined at the defects frequencies. To improve the diagnosis accuracy and reliability the analysis should be carried out not by the instantaneous spectrum, which has a significant statistical straggling, but by the average spectrum. However, if the equipment speed mode is non-stationary, a direct averaging of the spectrum will lead to recognition errors due to the defects frequencies dependence on the rotation speed.

The paper considers diagnostics of rotating equipment with non-stationary operating mode by the example of a rolling mill diagnostics. To obtain the averaged spectrum, a scale transformation in frequency, which ratio depends on the mill speed mode, has been used. Thus an ordinal average spectrum in rotation frequency terms has been received. To determine accurately the speed mode two independent channels are used – a hardware speed sensor and a software channel of an automatic rotation frequency recognition according to the case vibration.

Using the ordinal average spectrum and two independent channels for the rotation frequency determining has provided an accurate and reliable system for the mill technical condition diagnostics.

1. Introduction

Rotating machines are the most common type of equipment used in various industries. Pumps, compressors, fans, mills, engines of diverse types - all of them are based on the rotating shaft, performing a job. To determine the technical state of machines, various methods of non-destructive testing are used, but the most effective is the vibration method, which provides the vibration signals analysis of rotating equipment casing. The basic method of determining the technical state of the signal is a vibration spectrum analysis, since various rotating equipment defects appear as increased levels of one or another frequency components of the spectrum.

The vibration signal of the machine casing in addition to periodic components (due to the presence of defects, operational mode) also includes an informative random component [(8)]. With a significant level of the random component, an instantaneous spectrum analysis can be difficult because of the periodic components, hidden by the noise spectrum, which has a considerable dispersion in the instantaneous spectrum. To increase the spectrum ability to detect defects while the vibration analysis of machines,

averaging is used. The spectra averaging reduces the dispersion of the spectrum random component, thus providing analysis of periodic components.
The spectra averaging gives excellent results in the vibration analysis of machines with a stationary operating mode. However, the direct spectra averaging in the vibration analysis of rotating machines with non-stationary speed mode leads to poor results as compared with the instantaneous spectrum.

2. Connection between defects and rotation frequencies

Most frequencies of the machine rotor part defects are connected with the rotating frequency and in general the frequency value is determined by the formula:

$$F_d = K_d \cdot F_r \text{, where} \tag{1}$$

F_d – a defect frequency
K_d – a ratio, determined by the defect type
F_r – a rotating frequency

From the formula (1) we obtain a stating for the frequencies calculation of the so-called serial spectrum:

$$K_d = \frac{Fd}{Fr} \tag{2}$$

The serial spectrum is widely used for the analysis of machine vibration as there is no need to attach to the frequency of rotation in order to search for the defect frequencies - the spectrum is presented in the form of its coefficients (series).
However, to obtain the serial spectrum the accurate information on the rotation frequency is required. Even a slight change in the rotation frequency with the spectrum averaging and subsequent calculation of the serial spectrum will lead to significant errors.
Typically, the machines defects appear in the vibration signal in the form of pulse signals. As well as the pulse signal spectrum has a form of harmonic components series, the defects occur in the signal spectrum as a series of harmonic components. A stating 1 for the harmonic components can be written as:

$$F_d = N \cdot K_d \cdot F_r \text{, where} \tag{3}$$

N – the harmonic number

A stating 3 shows that the rotating frequency change is proportional to the defects frequencies changes. The absolute change of the defect frequency with the rotating frequency change is determined by a stating:

$$\Delta F_d = N \cdot K_d \cdot \Delta F_r \text{, where} \tag{4}$$

ΔF_d – absolute variation of the defect frequency
ΔF_r - absolute variation of the rotating frequency

As seen from the stating 4, even small fluctuations in the rotating frequency with large values of K_d and N can lead to significant absolute changes in the defect frequency,

which will greatly exceed the spectrum resolving ability and with the spectrum direct averaging will lead to a drastic decrease of the detecting ability instead of its increasing.
The stating 4 will help to determine the necessary accuracy of the rotation frequency measuring in order to get the serial spectrum of the required range. Assuming that the resultant error of the uppermost frequency of the spectrum range does not exceed the bandwidth of the spectrum, i.e.:

$$\Delta F_d = F_w = 1/T, \text{ where} \tag{5}$$

F_w – the bandwidth of the spectrum, Hz
T - sampling time, s

Thus, the maximal absolute uncertainty of the rotation frequency measuring will be determined by a stating:

$$\Delta Fr = \frac{1}{N \cdot Kd \cdot T} \tag{6}$$

As we can see, the required uncertainty of the rotation frequency determining is inversely proportional to the maximal coefficient of the defect (series), the number of analyzed harmonics and sampling time.

3. Algorithm of the serial spectra averaging with the variable rotating frequency

To eliminate this effect in the non-stationary operating mode of the machine, the technique of the spectrum synchronous averaging is used - a measuring device has a special clock input connected to a speed sensor, a sampling frequency is assigned by a phase locked loop (PLL) system. Thus, the resulting spectrum of this signal is hardware attached to the rotating frequency. However, such measurement circuits are much more complex and expensive than ordinary analog digital converters (ADCs) with the sampling fixed frequency, which are widely used in the signal digital analysis. . This principle based construction of multi-channel systems with the optimal cost-parallel-to-serial architecture is becoming a very difficult problem.
To solve the problem of obtaining the averaged serial spectrum without the use of complex and expensive hardware, it is necessary to use one of the principles of monitoring systems construction - the principle of programmability (1,2).
According to this principle, the tasks, being solved by hardware techniques, can be transferred to the computing device. Due to constantly improving performance of computing devices, this principle is increasingly being used.
Figure 1 shows an algorithm for software implementation of the serial spectrum averaging with variable rotation frequency.

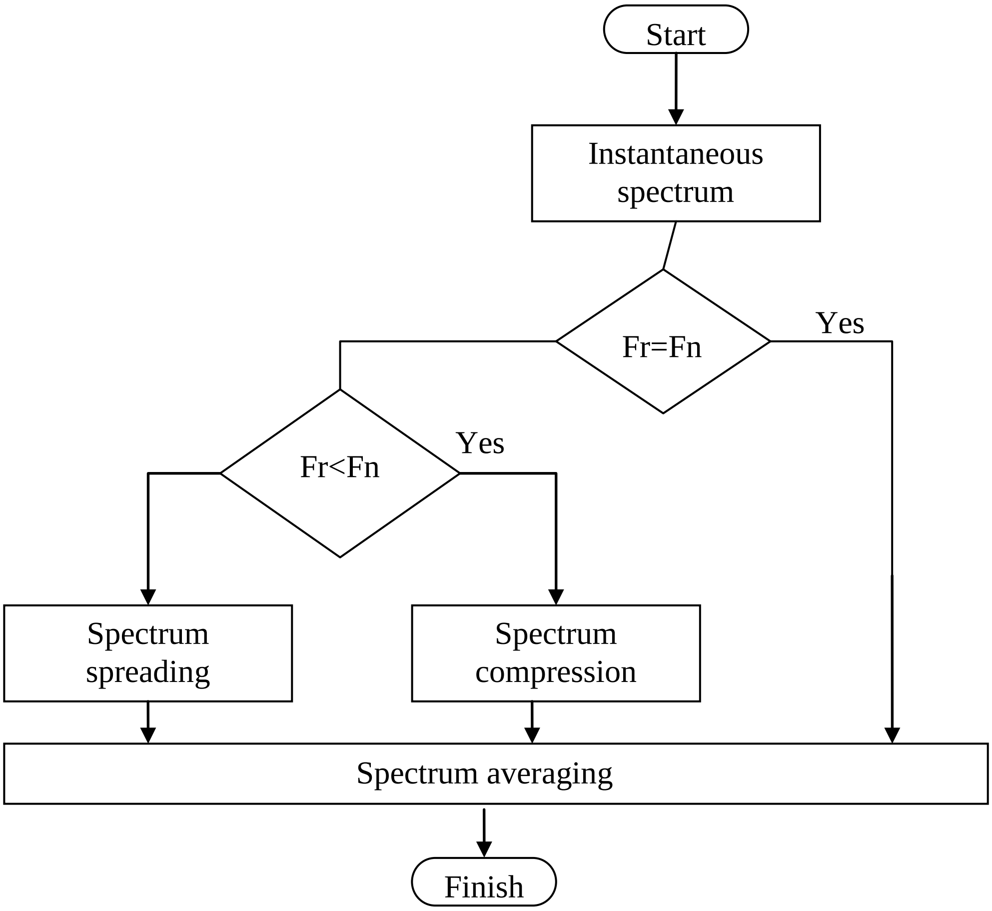

Figure 1. The serial spectrum averaging algorithm at variable rotation frequency

The algorithm is based on the spectrum scaling at the frequency axis - the spectrum is compressed or spread depending on the rotating frequency value, next it is lead to some standard value, and then is converted into a serial spectrum.
The algorithm basis is the calculation procedure of the spectrum new components , when it is compressed or stretched.The main problem here is the algorithm for the new components calculation when the spectrum is compressed or spread. One should be guided by the main principle - the signal power should remain invariable in compression, as well as in spreading of the spectra.

4. Determining of the rotation frequency by the vibration signal

The above mentioned algorithm for the spectra averaging requires an accurate value of the rotating frequency, which is usually determined by the speed sensor. To improve the system reliability in case of the speed sensor failure, they have set and successfully solved the problem of determining the rotating frequency directly from the original signal spectrum, using the certain information about the machine construction and its defects frequencies. For example, if a machine has a gearing, the vibration spectrum will have a series of tooth harmonics. When these harmonics are recognized, the actual rotating frequency can be accurately determined by a stating:

$$F_{\kappa} = \frac{F_Z}{N_Z}, \text{ where} \quad (7)$$

F_Z – a tooth harmonic frequency,
N_Z – number of teeth

Recognition of harmonics in the spectrum is performed by using search algorithms and maximization of function of the spectrum harmonics total power [7]. The software module for the rotation frequency operates in the system with the speed sensor, thus ensuring the reliability of the system measurement channel

The full redundant algorithm of determining the rotating frequency both by the speed sensor and the vibration spectrum is shown in Figure 2.

With a correct speed sensor the rotating frequency equals the sensor readings. When the sensor is faulty, the system receives information on the vibration spectrum at a certain point of the unit (for example, on the gearbox with gear teeth), on a parameter, determining the calculation - from the equipment database (number of teeth) and evaluates the rotating frequency according to the vibration spectrum F_s, which is taken as basic for the spectra averaging algorithm.

It should be pointed out that the necessity for the speed sensor with a block for an autodetection of the rotating frequency from the spectrum is conditioned by its greater accuracy.

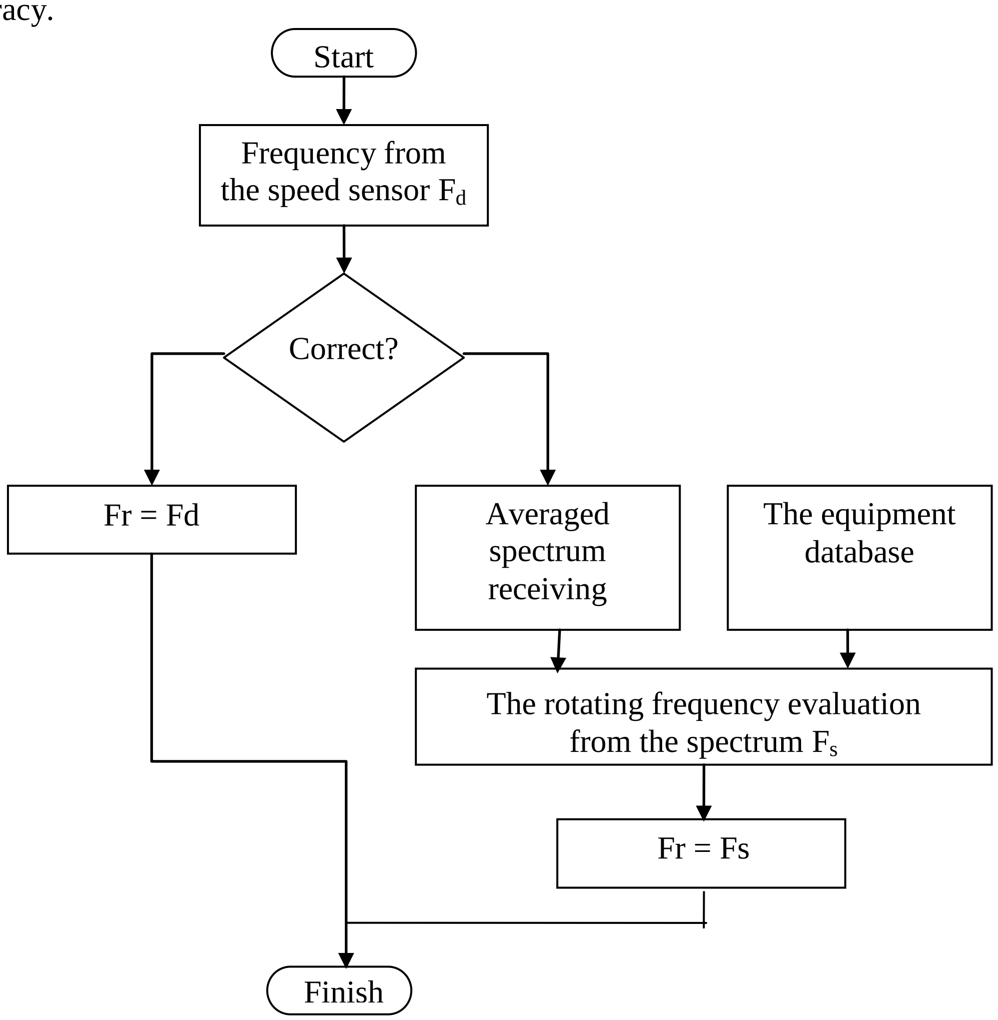

Figure 2. Redundant algorithm to determine the unit rotating frequency

5. Practical implementation at the automatic diagnostics of the wheel-rolling mill

In 2005 at the wheel rolling mill (WRM) in a press-rolling sector of a wheel rolling complex (WRC) at "Vyskunsk metallurgical works" JSC a technology ACS SMS™ COMPACS® (1-5), based on the stationary computer monitoring system for accidents prevention and state monitoring COMPACS® , has been implemented.

WRM consists of upper and lower edging shafts, driven by direct current motors via 2-stage reducers, as well as a junction of thrust shafts and a carriage, controlled by the hydraulic system.

The system COMPACS®-WRM, installed at the wheel-rolling mill, monitors its technical state: 22 vibration channels, 4 temperature channels2 rotational speed channels, 3 channels of fluid pressure in the hydraulic system of WRM, as well as controls a wheel block temperature. The enterprise diagnostic network Compacs-Net® has been developed on the system basis; it transmits information on the mill state to the WRC specialists: mechanics, technicians and technical diagnostics laboratory of the "Vyskunsk metallurgical works" JSC.

The system is based on the automated expert system, which by making analysis of the casing vibration signals draws a conclusion about the wheel-rolling mill technical state and issue recommendations to the maintenance service specialists. Analysis of the vibration spectra signals has been performed under conditions of the mill unsteady operation. Figure 3 shows a typical random process of changing the edging shaft rotation frequency for the rolling cycle. Cycle-to-cycle view of the curve changes, although the general nature of it remains the same. It is seen that in the beginning of the cycle there is the rotation frequency growth, and a relatively stable section with irregularity up to 10 % and duration of less than 8 seconds is observed in the mid-cycle. The cycle rolling time varies with each cycle, keeping the appearance shown in Figure 3, and the main influencing factor is a blank temperature.

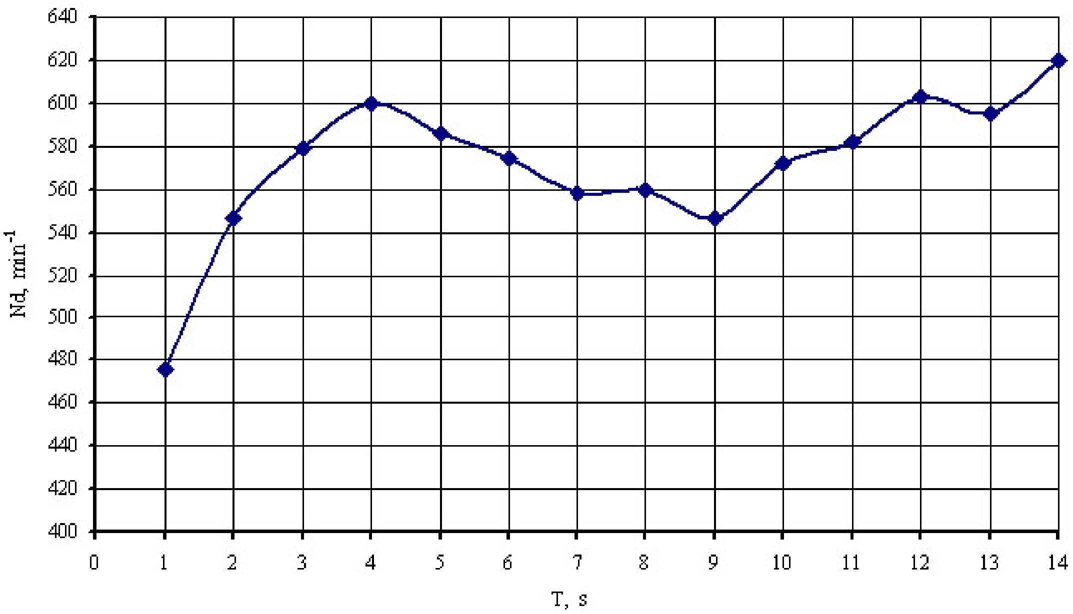

Figure 3. The rotation frequency trend of an edging shaft

For the spectra averaging and their further analysis the above described algorithms have been used. Figure 4 shows the averaged serial spectrum of a vibroacceleration signal of a defective edging shaft bearing. On the spectrum, along with circulating harmonics, there are low-frequency components with the serial frequency value of the less than 1, which are associated with a fastening weakening of the edging shaft screw.

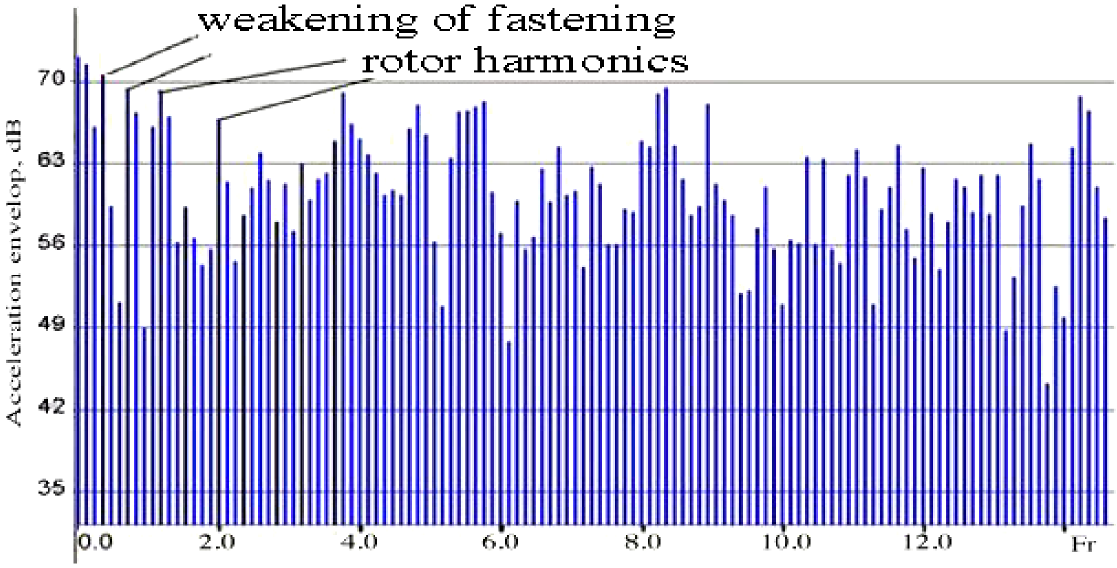

Figure 4. Averaged serial frequency of the vibroacceleration envelope signal, which are with a fastening weakening of the edging shaft screw

As the system operation example Figure 5 shows the trend of a multimodal exponential destruction of an edging shaft. Three stages of the edging shaft fatigue destruction are strongly marked (Sections 1-3).

As a result, they have decided to operate the shaft to failure, i.e. to use the inherent resource to the full extent. A repair team has been timely assembled, and the edging shaft has been timely replaced, which has reduced the mill downtime for more than 3 hours, thus allowing to produce over 300 wheels.

Thanks to the developed algorithms for the vibration signals analysis in the non-stationary speed mode, the real-time technical state monitoring system has been successfully implemented. This has allowed to shift the wheel-rolling mill failures from a sudden to a gradual category at the expense of early detection and the personnel warning about developing malfunctions.

Figure 5. The trend of a multimodal exponential destruction (cut) of the wheel-rolling mill edging shaft:
Sections 1-3 – multistage destruction of an upper edging shaft;
Section 4 – the mill repair according to the actual technical state

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CM2013/MFPT2013 CONFERENCE TOPICS/ABSTRACTS

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