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Vibroacoustic method of diagnosing rotating machines operating under variable load

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Abstract Diagnosing machines operating under variable load using vibration signals requires the application of advanced computational methods. The variable load of rotating machinery affects their rotational speed and the amplitude of generated vibration signals. Synchronous methods are commonly used to negate the effect of speed variations, such as Synchronous Sampling, Order Analysis or Time-Synchronous Averaging. However, the problem remains with the impact of load on the amplitude values of diagnostic signals. This paper proposes new order spectra insensitive to varying load. The components of the spectra are determined from the dependence of order amplitudes as a load function. The proposed spectra are a reference to a reference spectrum determined for the correct operating condition of the machine. In order to test the effectiveness of the new method, an experiment was carried out on a laboratory bench to diagnose a planetary gearbox. The method gave unambiguous results in identifying the alignment of the driveline under test.

Keywords: vibroacoustic diagnostics, order analysis, variable load, rRMSD

1. Introduction

Using systems based on vibration signals is now standard in many industries. The energy industry has dedicated diagnosis systems for wind turbines [1] and diagnosis systems for water turbines [2]. The mining industry also uses diagnosis methods based on vibroacoustic signals [3–5]. Most of the methods implemented in industrial controllers are based on statistical parameters that perform well under fixed operating conditions. However, many machines in the industry only operate under varying load, temperature or speed conditions. These conditions affect the values of the parameters determined from the vibration signals. This influence makes it impossible to use classical vibroacoustic diagnosis methods [6,7].

This paper presents a method for diagnosing machines insensitive to varying load. The method results in new diagnostic spectra that are not dependent on changes in the load of the diagnosed machine.

The next section describes the proposed vibroacoustic method. Section 3 describes the laboratory bench and the course of the experiment. Finally, Section 4 describes the results obtained compared to classical diagnosis methods.

2. Proposal for a diagnosis method

The proposed method is based on the order spectrum, which results from applying the order analysis method [8–10]. This method is commonly used to diagnose machines that operate at the variable rotational speed [11–15]. It allows for the synchronisation of vibration signals with the rotations of the shaft of the diagnosed machine. The result of this method is the order spectrum obtained from the tested vibration signal relative to the shaft rotation marker signal. This method allows for avoiding the effect of spectrum blurring and significantly facilitates the detection of exceedances of alarm thresholds for individual characteristic components. However, this method is sensitive to changes in load, which can result in false alarms or failure to detect faults in the early stages.

The paper presents a method based on the relationship between order amplitudes and load. Firstly, the order amplitude and the load waveforms are determined. Then, these signals are sorted according to the load value. Next, a moving average is calculated for the order amplitude and load values. Polynomial curves describing the relationships between the order amplitudes and the load are then determined. As a result, we obtain the order spectrum as a load function. The processing scheme is shown in Fig. 1.

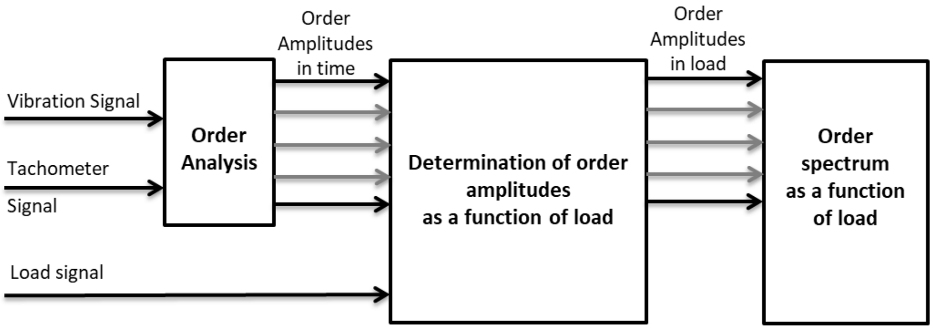

Figure 1. Schematic for determining the order spectrum as a function of load.

The load-dependent spectrum is initially determined for the undamaged machine and treated as the reference spectrum. In the diagnostic phase, the procedure presented in Fig. 1 is re-evaluated, and the rRMSD(r) and rΔAmax(r) parameters are determined separately for each order according to the dependencies [16]:

$$\text{rRMSD}(r) = \sqrt{\frac{1}{N}\sum_{s=1}^{N}\left(\frac{A(r,l) - A_G(r,l)}{A_G(r,l)}\right)^2}, \quad (1)$$

$$\text{r}\Delta\text{Amax}(r) = \left|\frac{A(r,l) - A_G(r,l)}{A_G(r,l)}\right|_{\max}, \quad (2)$$

where $A(r,l)$ is the order amplitude for order r at load l, $A_G(r,l)$ is the order amplitude for the undamaged state for order r at load l, and N is the number of load cases. The parameter rRMSD(r) is the mean of the squares of the normalised differences between the actual vibration amplitude and the vibration amplitude for the undamaged condition. The parameter rΔAmax(r) is the maximum normalised difference between the component amplitudes for the current state and the undamaged state. These differences are determined for all load values so that the effect of load on the vibration amplitudes is considered. A change in the vibration amplitude for at least one load value will change the proposed parameters rRMSD(r) and rΔAmax(r), as opposed to the values of the classical order spectrum. Since the order spectrum represents values averaged over time.

As a result, we obtain the spectrum of the rRMSD(r) parameter and the spectrum of the rΔAmax(r) parameter. The parameters obtained are related to the values for the correct operating state of the machine, indicating the ratio of the component amplitude to the amplitude for the undamaged state. In this case, the change in the amplitude of the components of the vibration spectrum will be due to damage since the effect of load on the amplitude of vibration is known and taken into account.

3. Diagnostic experiment

To verify the performance of the method, an experiment was carried out on a laboratory bench for diagnosing a planetary gearbox (Fig. 2). The bench consists of an electric drive motor, a planetary gearbox and a braking motor. The rotational speed of the motors is controlled by frequency converters, allowing any speed and load function to be assigned.

In the experiment, a load function corresponding to the planetary gear load of the KWK 1500s wheel excavator was used. The waveforms of speed changes in the main gearbox of the excavator were measured under industrial conditions using a monitoring system [5]. This waveform was then scaled to the dimensions of the laboratory bench and implemented as a function of changes in the current frequency of the braking motor. As a result, variable load conditions were obtained with a function shape corresponding to the load in real conditions. Figure 3 shows the changes in the rotational speed of the gearbox output shaft caused by the set variable load torque.

The vibration acceleration signals on the gearbox body were measured using a PCB 356B08 triaxial sensor, and the rotational speed using a DT-2234C digital tachometer. Measurements were carried out for a fixed gearbox oil temperature of 37°C. Changing the oil temperature also influences the values of the vibration signals, especially the mesh components [17]. The temperature was measured using an LM35 sensor.

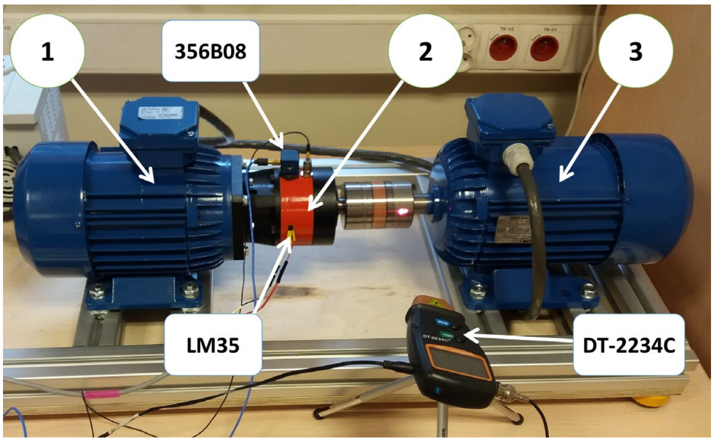

Figure 2. Laboratory bench, 1 - driving motor, 2- planetary gearbox, 3 - braking motor.

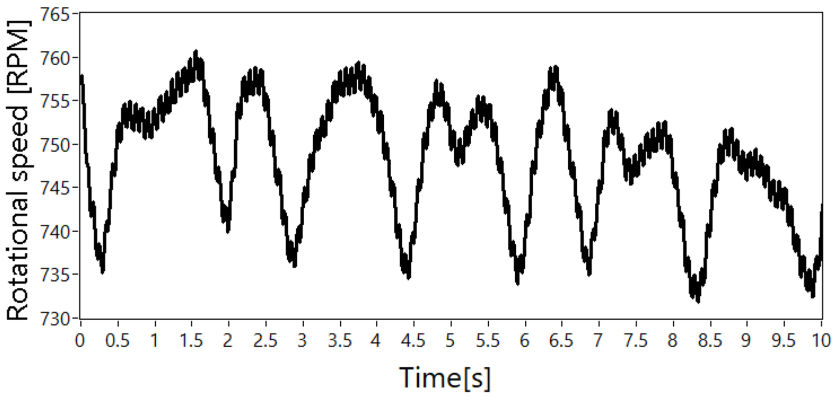

Figure 3. Variations in rotational speed caused by varying loads on the planetary gearbox.

A driveline failure in the form of gearbox output shaft misalignment was introduced by shimming a 0.5mm thick shim under the drive motor feet. Five signals of 60 seconds each were recorded for the no-damage condition and five signals for the misalignment condition.

The misalignment of the shaft lines results in a second harmonic of the shaft frequency in which it occurs. However, in the case of a connection using a claw coupling, the misalignment will be visible in the amplitude of a harmonic corresponding to the number of claws [18]. Misalignment equally causes gear skewing, which will be visible in gear meshing band and the harmonics. The characteristic orders of the planetary gear located in the diagnosed drive system are shown in Tab 1. The clutch was located on the output shaft of the gearbox, on which the speed was measured. With four claws of the coupling, misalignment should be visible for the 4th order.

Table 1. Characteristic orders of the tested gearbox.

System component	Order [-]
The output shaft of the gearbox	1
The input shaft of the gearbox	4
Gearbox meshing	72
Claw coupling	4

4. Result analysis

Analysing the spectrum of vibration acceleration orders recorded on the body of the gearbox operating under varying load, no symptoms of misalignment are visible (Fig. 4). The amplitude variations for the order corresponding to the number of claws (No. 4) are not apparent when damage occurs. Also, the amplitude values for the mesh order (No. 72) and harmonics do not change significantly when misalignment is introduced. This is because the order spectrum represents the averaged values of the vibration amplitudes, which change due to loading. The monotonicity of these changes may vary due to damage, while the average value may remain the same.

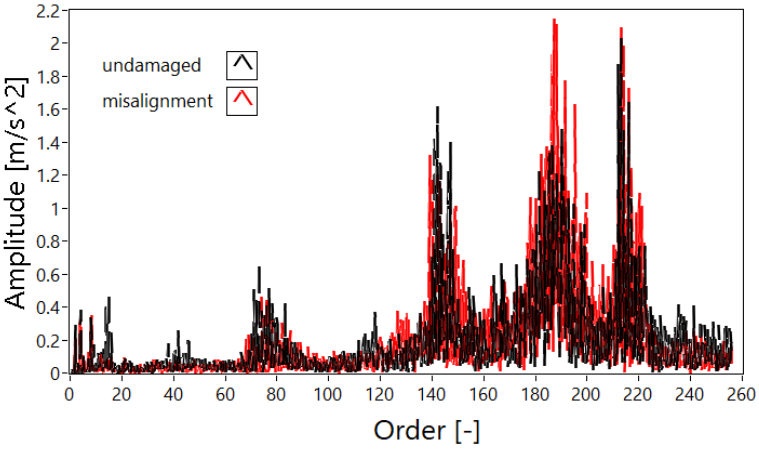

Figure 4. Order spectrum of vibration acceleration measured on the gearbox body in the transverse direction.

Polynomial functions depicting order amplitudes as a function of rotational speed, changes of which are caused by varying load, are shown in Fig. 5 and Fig. 6. It can be seen that the load has a clear effect on the values of the order amplitudes, especially for the order in the gear mesh band for the undamaged condition (Fig. 5). The shape of the curves changes in the event of damage for the orders responsible for alignment (No. 4) and the orders in the gear mesh band (No. 72). On the basis of these curves, new order spectra of the parameters rRMSD(r) and rΔAmax(r) proposed in Chapter 2 were determined. These spectra allow a single-number representation of the distance between the curves for each order. Fig. 7 shows the spectrum of the parameter rRMSD(r), which rearranges the normalised RMS value of the deviation between the curve for the machine with damage and the curve for the machine without damage. A clear peak can be seen for the gear mesh band orders (Nos. 68 and 76) (Fig. 7); this is the sideband of the amplitude modulation of the mesh order [19]. The parameter value represents a multiple of the change in the parameter concerning the reference curve. A fivefold increase in the case of a constant load in diagnostic theory indicates damage. Observing the spectrum of the rΔAmax (Fig. 8), it is worth noting that this parameter for order 68 reaches a value above 10. This parameter illustrates the maximum ratio of order amplitudes concerning the reference value. For at least one load value, the amplitude of this order increased by a factor of 10. According to diagnostic theory, a 10–fold increase in component amplitude unambiguously indicates a fault [18]. In the proposed spectra, peaks are visible for order No. 3, corresponding to the number of satellites on the planetary gear yoke. In the rΔAmax spectrum, the value for this order is almost 3, while in the rRMSD spectrum, the value is more than 1.6.

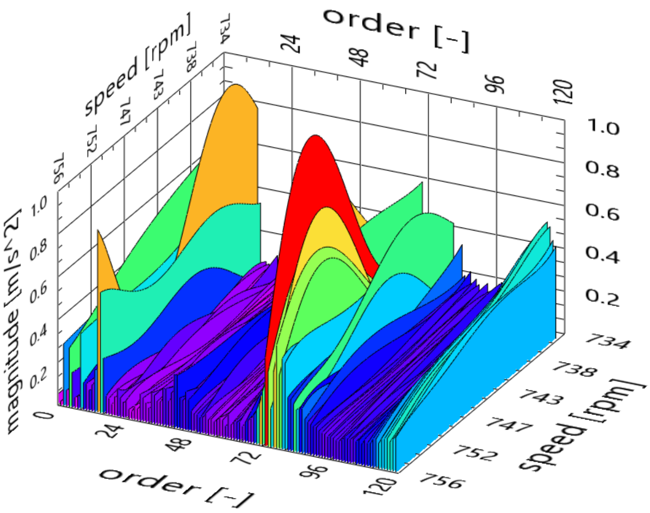

Figure 5. Polynomial functions for each order obtained using the algorithm shown in Fig.1 - undamaged system.

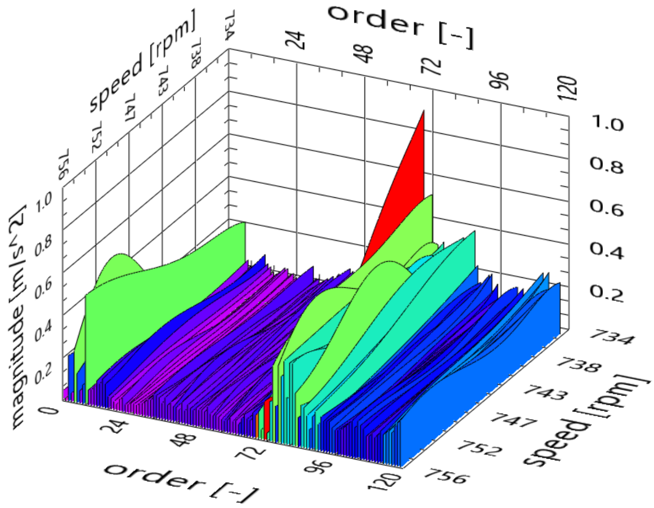

Figure 6. Polynomial functions for each order obtained using the algorithm shown in Fig.1 - misalignment system.

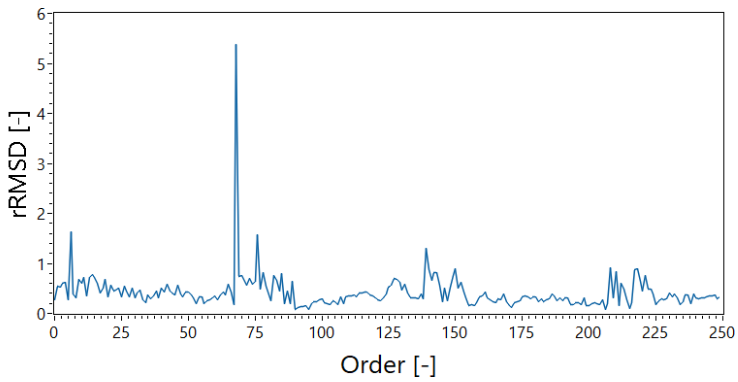

Figure 7. The rRMSD spectrum for misalignment system.

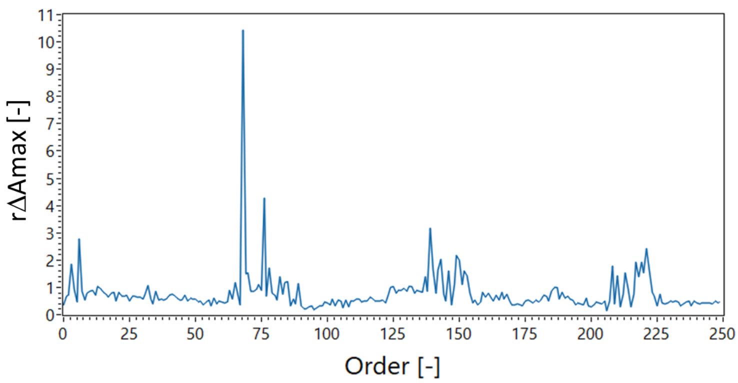

Figure 8. The rΔAmax spectrum for misalignment system.

In summary, the proposed spectra allow effective diagnosis of misalignment of drive systems operating under variable load, as opposed to an order spectrum. Since the order spectrum depicts the average amplitudes, it may not be effective when the function describing the order amplitude monotonically changes with load. Furthermore, the proposed spectra contain values normalised to a reference spectrum from an undamaged machine.

5. Conclusions

This paper presents a method for diagnosing rotating machines operating under varying loads. The results of the method are new load-insensitive spectra: the rRMSD spectrum and the rΔAmax spectrum. The first is the RMS value of the distance between the curves describing the dependence of the ordinate amplitudes on the load for the damaged and undamaged machine. In this way, we can consider the differences between the amplitude values of each order for each load value. The second type of spectrum is rΔAmax spectrum, which illustrates the maximum difference between the amplitude values for the damaged condition compared to the undamaged condition. Both types of the spectrum are relative measures relative to the amplitudes for the reference (undamaged) condition. The author's previous work presented the parameters used in the proposed spectra [16].

The diagnostic performance of the proposed spectra was tested on a planetary gear laboratory test bench. The method detected an early misalignment stage not visible on the classical order spectrum.

It is worth noting that order amplitudes are also affected by oil temperature and speed in addition to load, for which purpose order spectra would need to be considered in two additional dimensions. In order to solve this, artificial intelligence would be the solution, such an approach was presented in the paper [20] and was also based on the dependence of order amplitudes on particular factors. However, the method proposed in this work can be used assuming that the measurement is carried out for a fixed operating temperature of the machine and in the same speed range. Such conditions can often be found in industrial settings.

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Additional information

The author declares: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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