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Research Paper

The Use of the Acoustic Signal to Diagnose Machines Operated Under Variable Load

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Acoustic signal is more and more frequently used to diagnose machines operated in industrial conditions where installation of sensors is hindered. Impact of background noise seems to be the major problem as part of analysis of such signal. In most cases of industrial environments, background level is high; thus, it prevents against concluding as per standard methods that have been used in diagnostic testing.

This study specifies the problem related to diagnosing machines operated under variable loads. Synchronous methods are used for diagnosing these types of machines, those include synchronisation of diagnostic signal with revolutions of the diagnosed machine. For the purpose of this study an acoustic signal was used as the diagnostic signal. Application of the synchronous method (order analysis) enables eliminating an impact of background noise derived from other sources.

This study specifies application of acoustic signal to diagnose planetary gear in laboratory testing rig in order to discover damages at early stage of degradation. This method was compared with the method basing on measurement of vibrations.

Keywords: acoustic diagnostics; vibroacoustics; order analysis.

1. Introduction

Acoustic signal is more and more frequently used to diagnose machines operated in industrial conditions where installation of sensors is hindered. Use of acoustic signal to diagnose gears with application of continuous wavelet transform can be found in the study (Baydar, Ball, 2003; Parey, Singh, 2019). Comparison of results of vibration and acoustic analyses with application of the Wigner–Ville distribution indicated usefulness for acoustic signal in the course of diagnosing damages to the gear pinion (Baydar, Ball, 2001).

The major problem in the course of analysis of such signal is the impact of background noise. In most cases in industrial conditions the background noise level is high, which makes it impossible to assess the technical condition of the machine using classical diagnostic methods. To separate acoustic signal derived from diagnosed machine, a method of order analysis was applied. This method allows for synchronisation of acoustic signal with shaft rotation marker of the diagnosed machine.

Order analysis is a synchronous method related to analysing signals applied to machines operated at variable rotational speed. Synchronous methods were applied for the first time in the eighties, relevant implementation manners can be found in the studies (Braun, Seth, 1979; Randall, 1987). Those methods include synchronous sampling of measuring signals where variable sampling frequency depends on rotational speed signal of the diagnosed machine. Currently, other methods of machine diagnosing have been developed, these are related to synchronisation of diagnostic signal at rotational speed through the decimation method (Burdzik *et al.*, 2017), the subsampling method (Cioch *et al.* 2013; Lenart *et al.*, 2008; Ottewill, Orkisz, 2013) or basing on the Gabor transform (Pan, Chiu, 2006; Shao *et al.*, 2003).

Such synchronisation allows to separate signal derived from diagnosed machine from noise derived from other sources. Signal components synchronised with rotational speed will occur within order spectrum as single spectral peaks, whereas remaining components will become blurred.

Synchronous methods allow eliminating effect of the system load in the frequency domain. However, the load itself has also impact on amplitude of vibration or acoustic signal, thus on amplitudes of determined orders. Alterations related to variation of the system load shall be considered in the diagnostic method. In the study (Pawlik *et al.*, 2016), the authors determined relationships of vibration acceleration order amplitudes as a function of rotational speed for various load levels which significantly enhanced efficiency of diagnosing. On the other hand, in the studies (Dąbrowski, 2016; Popiołek, Pawlik, 2016), the authors applied the artificial intelligence method to diagnose machines operated at variable loads. Intricate Bayes' theorem (Stępień, 2018) is also used for the purpose of detection of damages for various loads and rotational speeds (Jaramillo *et al.*, 2017). A method of separation of compounds related to variable rotation speed and load can be also found (Urbanek *et al.*, 2017).

A comprehensive review of the planetary gear diagnostic methods is included in the study (Lei *et al.*, 2014). In the work (Li *et al.*, 2019), the authors used the Vold-Kalman filter to remove irrelevant components from the vibration signal in diagnosing planetary gear. Diagnostic methods based on the Wigner-Ville (WV) distribution and continuous wavelet transform (CWT) can be found in the paper (Łazarz *et al.*, 2011). The use of the coherence function to diagnose changes in the meshing of a gear transmission is also described in the paper (Dąbrowski *et al.*, 2017). Methods for diagnosing the technical condition of the gearboxes can also be improved by using dynamic models that take into account load and geometrical parameters (Łazarz, Peruń, 2012).

This study suggests application of the parametrisation method for relationships between order amplitudes of acoustic signal and the drive system loads. This method has been applied in the analysis of the vibration signal in the study (Pawlik, 2019). This method includes determination of relationship between order amplitude and load in a form of polynomial and then determination of single-number statistical parameters that specify departures from the model registered during the machine operation.

Usefulness of acoustic signal was tested for the purpose of diagnosing the planetary gearbox including incorrectly installed output shaft on which the planetary carrier was mounted. Such damage can occur in the course of replacement of the gear bearing.

2. Laboratory testing rig

Laboratory testing rig consists of planetary gear TRAMEC EP 90/1 (ratio 4:1), drive motor, and braking motor. Frequency of voltage supplied to motors is provided through frequency inverters which are controlled with a measurement card. Application of the measurement card with analogue outputs (supported by the application designed for LabVIEW environment) enables defining rotational speed as well as any function of gear load torque.

GRAS 46AE measuring microphone was used to diagnose the gear. To control correctness of diagnosing, PCB 356B08 acceleration sensor was used. To control operational conditions, LM35 temperature sensor was used, all measurements were carried out at the same temperature of the gear, that is 40°C. Measurement of output shaft rotational speed was carried out with a tachometer DT-2234C+ including analogue output. For the purpose of data recording, NI PXIe–8133 controller located in NI PXIe-1062Q chassis along with the check cards was used: NI PXI-4472B – measurement of acoustic pressure, vibration acceleration, and rotational speed, NI PXIe-6361 – measurement of temperature. The testing rig including arrangement of sensors is specified in Fig. 1.

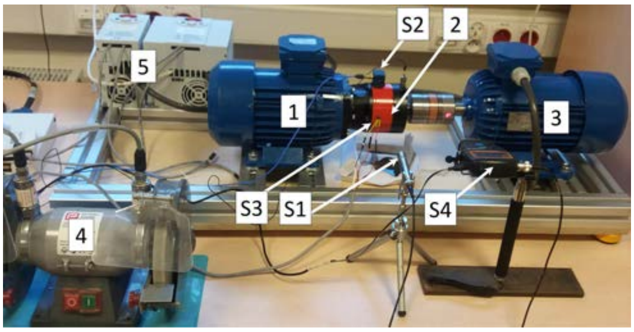

Fig. 1. Testing rig: 1 – drive motor, 2 – planetary gear, 3 – breaking motor, 4 – bench-grinder, generating interference (background noise), 5 – frequency inverters, S1 – measuring microphone, S2 – acceleration sensor, S3 – temperature sensor, S4 – tachometer.

The damage introduced was incorrect assembly of the output shaft on which planetary carrier was mounted. The carrier was chaffing against the sun wheel. Final results can be observed on the photographs that were taken upon completion of the test (Fig. 2).

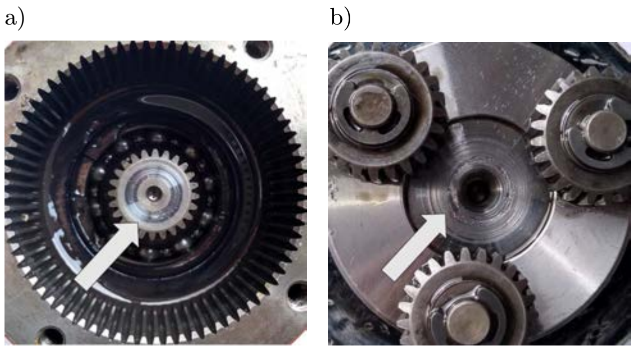

Fig. 2. Damages resulting from operation of incorrectly installed bearing in the gear output shaft: a) scratches on sun wheel of the planetary gear, b) scratches on carrier of the planetary gear.

In order to implement analysis of effects of operational conditions on the tested configuration, variable sinusoidal load was introduced, its maximum value was 3.9 Nm and its minimum value was 1.8 Nm. Figure 3 shows course of rotational speed of the output shaft along with sinusoidal load.

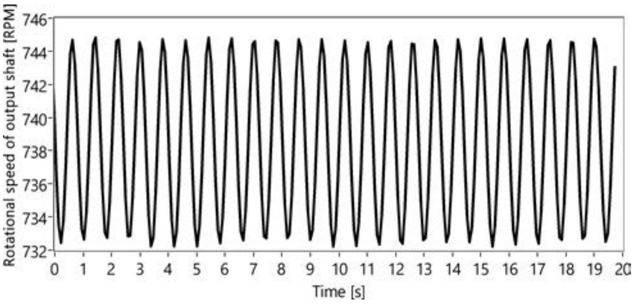

Fig. 3. Course of rotational speed of the output shaft including sinusoidal load.

3. Diagnosis method

Measurement of acoustic pressure was carried out within 0.4 m distance from the gear body. To verify the diagnosis method, a measurement of vibration acceleration on the gear body was carried out. Signal from the tachometer was used for the purpose of synchronous analysis that is discussed hereafter.

The order analysis method was used for the purpose of signal analysis, one of its results includes order spectrum. It is determined as per the method basing on resampling of acoustic pressure time signal and vibrations against input shaft rotational speed. Figure 4 shows a diagram related to algorithm of the order analysis. Firstly, a signal from the tachometer is subject to interpolation through cascaded integrator-comb CIC. Then, basing on filtered signal from the tachometer, vibration signal, the resampling procedure is carried out in order to determine vibration signal relative to Even Angle Signal. Such tested signal may be subject to fast Fourier transformation (FFT). Upon implementation of such transformation, order numbers are obtained instead of frequency, these correspond to multiplicity of rotational frequency of the shaft on which measurement of rotational speed was carried out (National Instruments Corporation, 2005). In this case, such measurement was carried out on the output shaft, order numbers correspond also to multiplicities of the output shaft frequency.

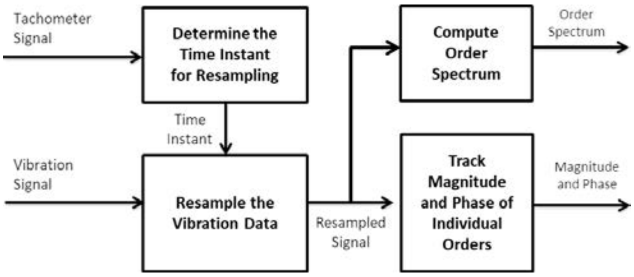

Fig. 4. Diagram of algorithm of order analysis (National Instruments Corporation, 2005).

Application of the order analysis significantly facilitates diagnosing conditions of machines operated under variable load as instead of observation of the entire variation band related to a given component a single parameter can be observed, such parameter is an amplitude of a given order which is synchronized with machine rotations. The synchronous method enables also eliminating components that aren't synchronised with rotation of the shaft of diagnosed machine.

The process of monitoring amplitudes of specific orders allows obtaining information related to technical condition of tested facility. However, alteration of amplitude values may be caused also by alteration of load on the set (Pawlik *et al.*, 2016). As a result, it is necessary to monitor values of specific orders as a function of load (Pawlik, 2019). In this case, alterations of rotational speed are inversely proportional to value of load torque, as the drive motor is supplied with constant-frequency voltage, alterations in load are defined through decreasing value of supply voltage frequency of the braking motor. This study is focused on the analysis of amplitude alterations into acoustic signal orders as a function of load. Figure 5 shows the amplitude of order no. 72 (meshing order of the planetary gear) as a function of rotational speed of the output shaft.

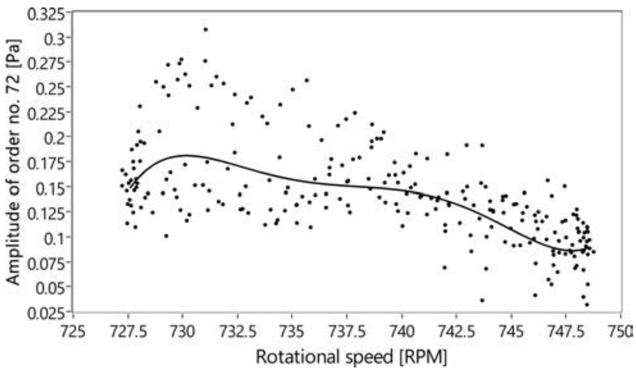

Fig. 5. Order no. 72 amplitude of acoustic signal as a function of rotational speed altered under the influence of load – the set is efficient.

This study suggests parametrisation of acoustic signal order amplitude – load relationship. Such parametrisation includes determination of functional dependence between rotational speed and specific orders. Synchronous measurement of vibrations and rotational speed make a condition for effectiveness of the method. Amplitude values related to specific orders are recorded along with corresponding values of rotational speed. This method was applied in the analysis of the vibration signal in the study (Pawlik, 2019).

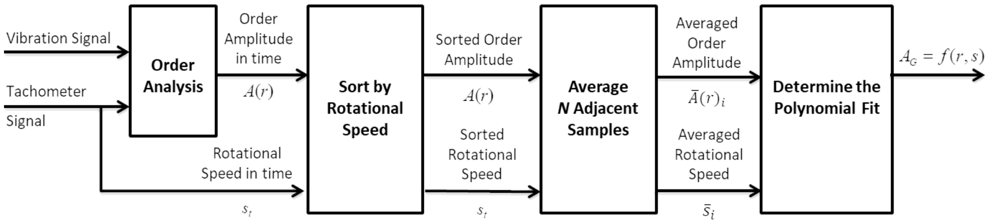

Fig. 6. Diagram of algorithm related to determination of functional relationship between rotational speed and specific orders (Pawlik, 2019).

As a first step of the algorithm, pairs of samples measured at a given time (rotational speed and order amplitude) are arranged in terms of rotational speed – ascending. The subsequent step includes determination of average values related to rotational speed and order amplitudes related to vicinal samples. Then, fitting by order n-tuple polynomial is determined. Due to such operation, a functional relationship between rotational speed and order amplitude is obtained. A diagram related to the foregoing algorithm is shown in Fig. 6. Detailed algorithm can be found in the study (Pawlik, 2019).

Equation of a polynomial curve determined for machine correct operation can be used as a reference. For the purpose of this study, a curve deviation measure was implemented, it is determined during machine operation with reference to analytical curve. In order to determine differences between the curves, the Root Mean Square Deviation (RMSD) was applied, which is regulated by the following relation:

$$\mathrm{RMSD}(r) = \sqrt{\frac{1}{N}\sum_{s=1}^{N}(A(r,s) - A_G(r,s))^2}, \tag{1}$$

where $A_G(r,s)$ – reference amplitude for current rotational speed (s), of r-th order, determined from functional dependence [Pa]; $A(r,s)$– current amplitude for current rotational speed (s), of r-th order, determined from functional dependence [Pa].

The other suggested parameter is the maximum difference for the entire range of rotational speed:

$$\Delta A(r)_{\max} = |A(r,s) - A_G(r,s)|_{\max}. \tag{2}$$

Normalized measures were implemented, where differences between the current amplitude and the reference amplitude are divided by the value of the reference amplitude (Pawlik, 2019):

$$r\mathrm{RMSD}(r) = \sqrt{\frac{1}{N}\sum_{s=1}^{N}\left(\frac{A(r,s) - A_G(r,s)}{A_G(r,s)}\right)^2}, \tag{3}$$

$$r\Delta A(r)_{\max} = \left|\frac{A(r,s) - A_G(r,s)}{A_G(r,s)}\right|_{\max}. \tag{4}$$

4. Analysis of results

The major problem in machine acoustic diagnostics is elimination of background noise impact on diagnostic parameters. Acoustic interference can be generated by other machines operated in the vicinity of diagnosed machine. In the course of analysis of acoustic signal, components derived from other machines can be incorrectly identified. Figure 7 shows acoustic signal spectrum recorded within 0.4 m distance from the gear. Black mark represents acoustic signal recorded during operation of the gearbox itself (excluding background noise), whereas grey mark represents signal recorded during the gearbox and jamming machine (bench-grinder) operation. Additional components derived from the jamming machine can be observed in signal with background.

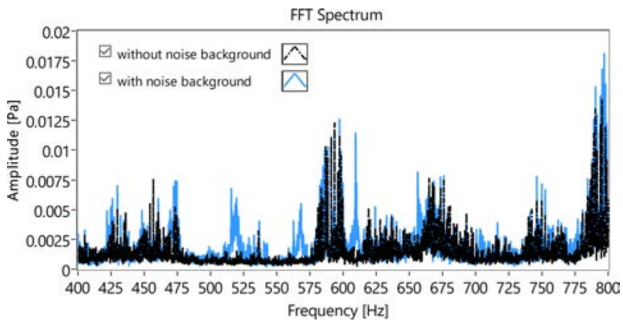

Fig. 7. Spectrum of acoustic pressure signal for undamaged gearbox (sinusoidal load).

To separate acoustic signal derived from diagnosed machine from signal derived from other sources, a method of order analysis was applied. Synchronisation of acoustic signal with variable rotational speed of the output shaft provokes components derived from other sources to be blurred. Figure 8 shows order spectrum of the same signal which was described previously. In case of output shaft rotational frequency that equals 12.5, order no. 32 corresponds to 400 Hz frequency. The noise that occurs within 512.5–525 Hz band does not occur in case of corresponding 41–42 order. Similar cases can be observed for component 610 Hz that occurs within signal spectrum which was not synchronised with rotations. However, in case of order spectrum, such component is blurred and occurs within band of order 48–49.

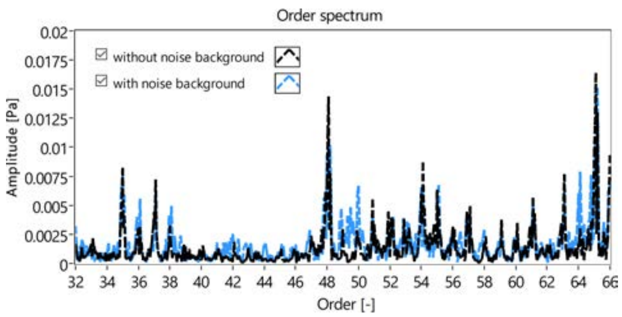

Fig. 8. Order spectrum of acoustic pressure signal for undamaged gearbox (sinusoidal load).

In the next step, the order spectrum of the acoustic signal for varying degrees of gear degradation was analyzed (Fig. 9). Successive curves were recorded at intervals during gearbox degradation. Slight changes can be observed in the vicinity of the gear meshing order (no. 72). Clear differences can be observed in the order spectrum of acceleration signal (Fig. 10).

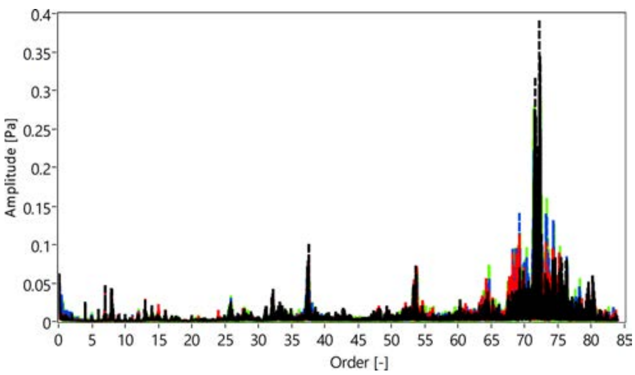

Fig. 9. Order spectrum of acoustic pressure signal for the set with sinusoidal load in the first minute of degradation (black marking); for the set in the tenth minute of degradation (red marking); for the set in the 43 minute of degradation (blue marking); for the set in 75 minute of degradation (green marking).

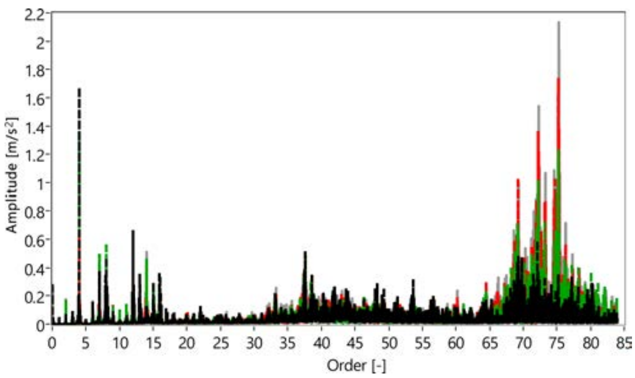

Fig. 10. Order spectrum of acceleration signal for the set with sinusoidal load in the first minute of degradation (black marking); for the set in the tenth minute of degradation (red marking); for the set in the 43 minute of degradation (blue marking); for the set in 75 minute of degradation (green marking).

The spectra shown are determined from a 15 s window and then averaged with the next signal windows, the whole signal is 120 seconds long. Changes in the amplitude due to sinusoidal load with a frequency of 1 Hz will not be visible in the spectrum of the signal. Therefore, the amplitude dependencies of selected characteristic orders as a function of rotational speed changes were presented. Figure 11 shows planetary gear meshing order amplitude (no. 72) of sound pressure as a function of sinusoidal load measured in the course of operation of bearing that had been installed incorrectly. Succeeding curves were recorded at time intervals during gear degradation. When analysing the amplitude of this component only for the highest load (rotational speed equal to 725.5 RPM) damage would not be detected, similarly for the lowest load (747.5 RPM). However, for a rotational speed corresponding to 735 RPM the differences are significant. It is worth noting that the amplitude for this value decreases with damage.

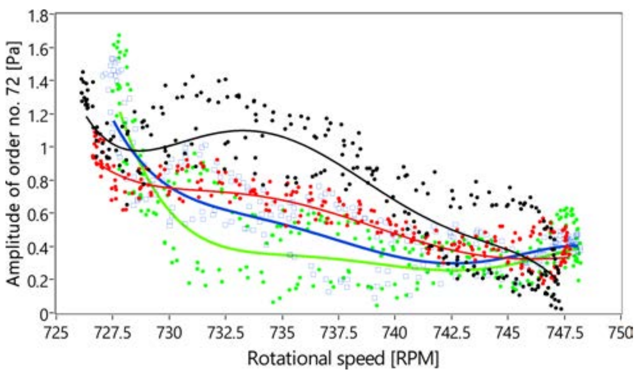

Fig. 11. Amplitude of order no. 72 related to acoustic pressure signal as a function of rotational speed which was altered under sinusoidal load for the set in the first minute of degradation (black marking); for the set in the tenth minute of degradation (red marking); for the set in the 43 minute of degradation (blue marking); for the set in 75 minute of degradation (green marking).

Analyzing the meshing order amplitude of the vibration acceleration signal, noticeable differences can be observed between successive curves determined during machine operation. Amplitude values change up to five times for the least loaded system (rotation speed equal to 745.5 RPM) (Fig. 12).

Analysis of signal envelope spectrum (Randall, Antoni, 2011) is the tool that has been widely used in machine diagnostics. Such a tool is perfect for analysis of signals in which amplitude modulation occurs.

As part of this study, an analysis of the signal envelope using a bandpass filter in the band 630–1130 Hz was carried out. This is a band containing the planetary gear meshing frequency and its modulations related to average value of output shaft rotation frequ-

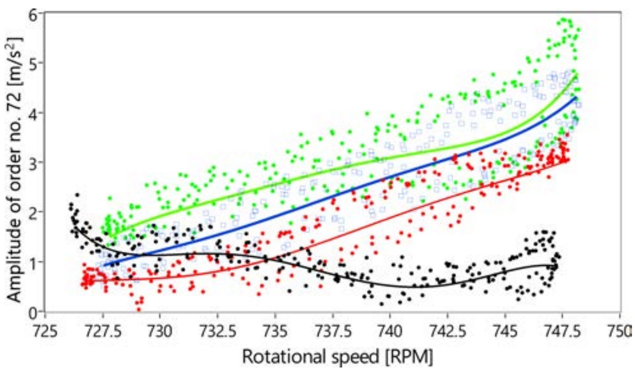

Fig. 12. Amplitude of order no. 72 related to vibration acceleration signal (direction transversal to the shaft) as a function of rotational speed which was altered under sinusoidal load for the set in the first minute of degradation (black marking); for the set in the tenth minute of degradation (red marking); for the set in the 43 minute of degradation (blue marking)); for the set in 75 minute of degradation (green marking).

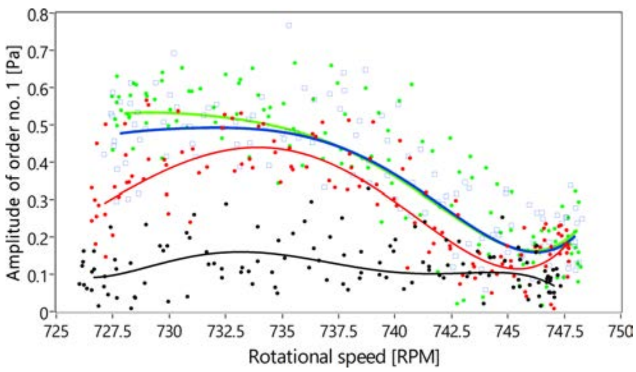

Fig. 13. Amplitude of order no. 1 related to acoustic pressure envelope signal as a function of rotational speed which was altered under sinusoidal load; for the set in the first minute of degradation (black marking); for the set in the tenth minute of degradation (red marking); for the set in the 43 minute of degradation (blue marking); for the set in 75 minute of degradation (green marking).

ency – equal 12.3 Hz. Subsequently, order analysis was carried out on filtered signal and then the algorithm (specified in Sec. 3) was applied. As a result, relationships between order amplitudes and loads obtained from signal envelope order spectrum were determined.

Damage to the output shaft can be expected in the acoustic signal of the amplitude modulation with a modulation frequency equal to the output shaft frequency (Zhang *et al.*, 2018). After the envelope analysis, these changes will be visible to the order corresponding to the output shaft rotation (no. 1). Analyzing changes in the amplitude of order no. 1 of the acoustic signal envelope (Fig. 13) can observe clear shape alterations of the dependence along with the time of device degradation.

In the course of analysis of the statistical parameters specified in Sec. 3, related to acoustic signal (Table 1), growth of statistical parameters including operational time can be observed as those parameters represent deviation from the analytical curve.

In case of acoustic pressure signal envelope, increase in statistical parameters along with degradation time is more dynamic (Table 2), it proves amplified usefulness of such signal as part of acoustic diagnostics in comparison to signal that was not subject to analysis of envelope related to the case.

Table 1. Statistical parameters determined on the basis of amplitude of order no. 72 of acoustic signal.

Time from start-up of incorrectly installed gear	RMSD [Pa]	$\Delta A_{\max}$ [Pa]	rRMSD [–]	$r\Delta A_{\max}$ [–]
10 min	0.28	0.39	0.25	0.48
43 min	0.40	0.53	0.34	0.76
75 min	0.52	0.73	0.47	0.67

Table 2. Statistical parameters determined on the basis of amplitude of order no. 1 of acoustic signal envelope.

Time from start-up of incorrectly installed gear	RMSD [Pa]	$\Delta A_{\max}$ [Pa]	rRMSD [–]	$r\Delta A_{\max}$ [–]
10 min	1.15	0.20	0.13	1.83
43 min	2.40	0.38	0.29	3.38
75 min	2.43	0.40	0.29	3.52

5. Summary and conclusions

This study undertakes a problem related to assessment of technical condition of the planetary gear operated at variable loads with application of acoustic signal.

Active diagnostic experiment on the labolatory testing rig was carried out. Usefulness of acoustic signal was tested against diagnosing the planetary gear operated along with incorrectly installed output shaft on which the planetary carrier had been fixed. Measurements were carried out in the vicinity (distance 0.8 m) of the other machine (bench-grinder), which made an background noise that interfered with the measurement.

It was suggested to apply the order analysis for elimination of acoustic noise derived from other machines. The order analysis allows separating signal of diagnosed machine operated at variable load from other non-synchronised machines. Such conditions frequently occur in industrial environment, it augurs for multiple applications of the method in industrial conditions. The use of order analysis has effectively eliminated the impact of background noise for measurement at a distance of 0.4 m from the gearbox. The use of acoustic signal to diagnose gearboxes is known in the literature. However, it is very important to maintain close proximity to the diagnosed machine 0.05 m (Baydar, Ball, 2003) or conducting research at a low background noise level (Parey, Singh, 2019).

Functional quality of the suggested method basing on parametrisation of function that determines relationship of acoustic signal order amplitude and the set load was also tested. Statistical parameters which make a measure of distance of the curve – determined for diagnosed machine – from the standard curve (defined during correct operation of the machine) have been specified. The tests which were carried out at the laboratory testing rig indicated that parameters applied for acoustic signal enable diagnosing of the machines. However, application of additional methods for signal analyses, such as envelope analysis, significantly improves diagnosis efficiency.

The measurements were compared to vibration acceleration signal registered on the gear body; the signal itself confirmed occurrence of damage to the planetary gear.

This method can be also applied to other machines and damages. It is necessary to select specific orders corresponding to given damages and apply the algorithm specified in this study.

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