

Приборостроение, метрология и информационно-измерительные приборы и системы

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AN APPROACH TO FAULT DIAGNOSIS OF GEARBOX BASED ON AN INSTANTANEOUS ANGULAR ACCELERATION. EXPERIMENTAL STUDY

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Introduction. Gears are important parts of almost every operating mechanism in many industries. The gear condition monitoring is an important unit of condition monitoring of a mechanism as a whole. The vibration is one of the most used sources of information for equipment technical diagnostics. Traditionally, vibration is measured by accelerometers which are fixed on the mechanism body. Analyse of the measured data from the accelerometers requires applying the special methods and the staff with developed analytical skills. On the other hand, a novel approach to the accelerometer fitting location allows receiving extra diagnostic information and facilitating diagnosis. **Aim.** The present study shows the application of the novel approach to the accelerometer fitting location and the analyse of extra information for gearbox diagnosis. **Materials and methods.** The novel accelerometer fitting location is a rotating shaft of the mechanism. The extra diagnostic information is an angular acceleration of the rotating shaft. The theoretical base for the angular acceleration as diagnosis information is shown in the study. **Results.** The study contains experimental results of fault detecting such as the 'chipped tooth' and 'broken tooth' of a pinion. In addition, the study contains the proposed criteria for the detection of the local fault. **Conclusion.** The experimental results and the applied criteria show that the proposed approach allows detecting the pinion local defect on the first pinion rotation frequency clearly at various rotation frequencies.

Keywords: diagnostics, accelerometer, wireless acceleration sensor, rotating shaft, rotating machinery, angular acceleration.

Introduction

Gears are widely used in operating mechanisms in many industries. Variable loads and speeds lead to gear wear. Moreover, the growth of the defect rapidly evaluates and can be a factor of irreparable harm. In addition, the diagnosis of the gears is highly important but it is a difficult problem because of non-steady-state operations, as previously mentioned.

The most common method of gears diagnosis is vibration diagnostics [1, 2]. Nevertheless, even a defect-free gear pair has some work vibration, which has a wide frequency band. The vibration is the result of key factors: cyclic variation of gear teeth stiffness in a meshing phase and manufacturing and assembly errors [3]. The cyclic variation and constant meshing tooth error excite oscillations on a gear-meshing frequency f_z

$$f_z = z_1 f_1 = z_2 f_2,$$

where z_1, z_2 are teeth number of pinion and gear, respectively. The f_1, f_2 are rotation frequencies of the pinion and gear, respectively [4]. The variable meshing tooth appears on the rotation frequencies kf_1, kf_2 ($k = 1, 2, 3, \dots$), and the modulated frequencies $mf_z \pm nf_1, mf_z \pm nf_2$ ($m, n = 1, 2, 3, \dots$) [5]. At the same time, the frequency spectrum has components that are associated with cutting error of pinion and gear f_d

$$f_d = kz_d f, \quad k = 1, 2, \dots,$$

where z_d is the number of teeth of the gear wheel of the gear cutting machine. Operating defects of gears

mating surfaces (such as wear, microchipping, sticking, crack, chipping, broke and related) are an additional consideration of frequency spectrum change. Moreover, a broken tooth is the most dangerous type of defect in view of rapid growth from crack to broke. Operational defects of gear at an early stage have a low energy contribution in the frequency spectrum that makes more complicated detecting them. Furthermore, commonly gearboxes are operated with other mechanical nodes, which also make high-level noises [6, 7]. That fact is challenging to methods of gearbox diagnosis and successfully fault detection [8, 9].

Traditional source of information about condition gearbox is accelerometers which are fixed on the gearbox body. Moreover, various methods, criteria, and indicators are used for gearbox diagnosis in the time-domain, frequency-domain, and time-frequency domain. The time-domain diagnosis is the poorly-successful and problematic approach. That fact was shown in studies [10–12]. On the other hand, diagnosis in frequency-domain and time-frequency domain are more successful approaches. The commonly conditional indicators in the frequency-domain are the kurtogram [13, 14], kurtogram with TSA [15], adaptive SK filtering method on the grounds of Morlet wavelet [16] et alii. The commonly conditional indicators in the time-frequency domain are Hilbert-transform based methods [17, 18].

The author in study [19] describes the 8-DOF dynamic model of a gearbox in detail with a local defect of the pinion. The function of gear tooth meshing stiffness varies according to the modelled defect type (chipped or broken tooth). The pinion has $z_1 = 19$ teeth; the gear has $z_2 = 48$ teeth. The frequency of pinion rotation is $f_1 = 30$ Hz. The result shows a spectrum changing of gear linear accelerations with various local defects, which corresponds to the “canonical” non-monotonic behaviour described in the literature. However, focusing on the traditional measurement methods, the author considered the behaviour of only the linear acceleration spectrum. On the other hand, analysis of the spectrum of an angular acceleration gear allows for increasing possibilities of a gearbox diagnosis.

The approach of the shaft acceleration measuring from the rotating shaft, including angular acceleration, studied in [20]. Moreover, the mathematical model one of the design versions of the WAS-Technology sensor described in [21]. That design allows measuring angular acceleration, two linear accelerations in the diametrical plane and the turning angle of the shaft.

1. Method for processing of angular acceleration

An analysis of the gear angular accelerations changing (dynamic model from Ref. [19]) under the influence of local defects shows that the changes of the spectrum discrete components are associated with harmonics of the gear frequency is close to monotonic (Fig. 1).

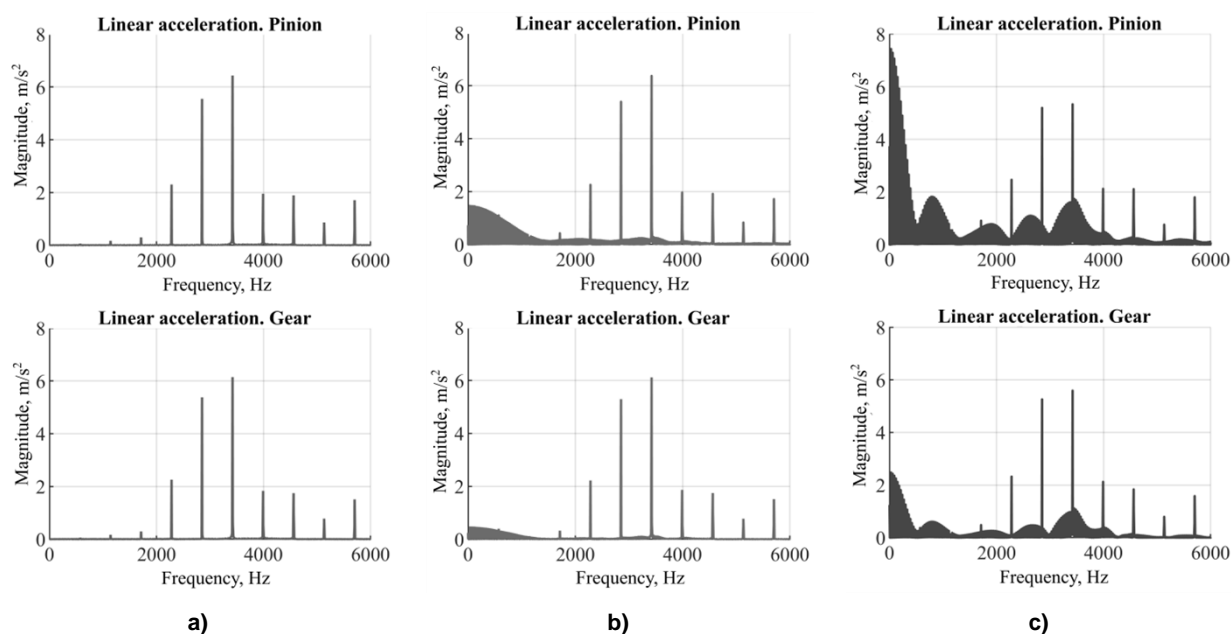


Fig. 1. Frequencies spectrum of the gear angular accelerations with a local defect:
a – without defect; b – chipped tooth; c – broken tooth

At the same time, a modulation index of the angular acceleration spectrum around harmonics of the gear frequency increases in the same way as the linear acceleration spectrum. Moreover, defects detection based on a comprehensive analysis of discrete components, which are associated with harmonics of the gear and rotation frequencies, by the Prism-method was studied in [22, 23]. On the other hand, the first pinion harmonic f_1 of the gear angular spectrum increases by increasing local defect, in other words, the level of harmonics of the frequency meshing defected tooth increases (Fig. 2).

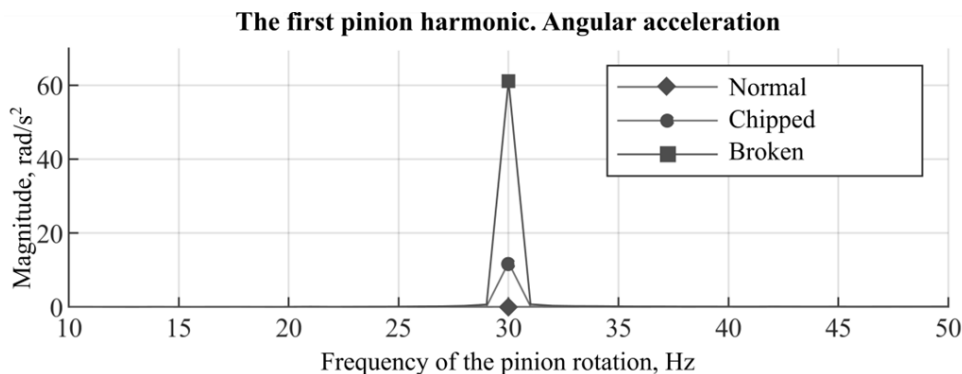


Fig. 2. The first harmonic angular acceleration of defected pinion with various defects

Thus, the level of the first pinion harmonic can operate as a criterion for the detection of local defects, such as a chipped and broken tooth.

2. Test equipment

2.1. Experimental rig

The applicability of the proposed criterion for the diagnosis of gear transmission is considered on the example of a single-stage gearbox of the experimental rig (MFS-Magnum from SpectraQuest) with bevel gears (Fig. 3).

The motor of the experimental rig is operated by the frequency drive that allows setting any motor rotation frequency in the operating range.

The pinion of the gearbox has $z_p = 18$ teeth; the gear has $z_g = 27$ teeth. The design of the studied gearbox allows for the simulation of the pinion defects such as the chipped tooth (Fig. 4) and the broken tooth (Fig. 5).

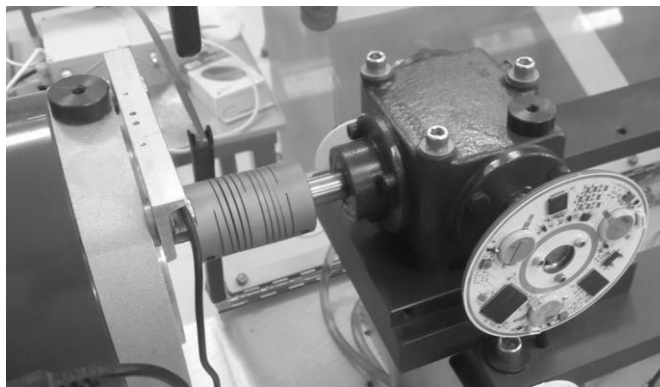


Fig. 3. Gearbox with mounted the WAS-Sensor



Fig. 4. Pinion with the chipped tooth



Fig. 5. Pinion with the broken tooth

Simulating the pinion defects due to pinion experiences more wear than the gear because pinion has fewer teeth and makes more revolutions.

2.2. WAS-Sensor

The applicability of the proposed criterion for the diagnosis of gear transmission designed the prototype of a WAS-Sensor based on WAS-Technology. The WAS-Sensor contains three MEMS-accelerometers (ADXL001-70 from Analog Devices) (Fig. 6).

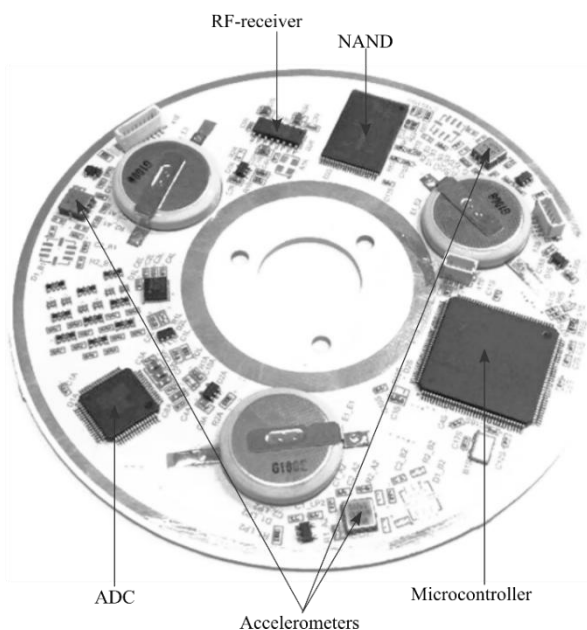


Fig. 6. The prototype of the WAS-Sensor

Each accelerometer has a measurement rate $\pm 70g$, resonance frequency 22 kHz, sensitivity 24.2 mV/g at 100 Hz. The mathematical model of the Sensor is described in the study [21]. Also, the WAS-Sensor contains ADC (AD7609 from Analog Devices) which samples of accelerometers signals at 39.4 kHz. Moreover, the WAS-Sensor contains microprocessor (STM32L476 from STMicroelectronics) which controls accelerometers and ADC, makes pre-filtering signals and writes data to NAND. Also, the WAS-Sensor has lithium batteries for power.

3. Experimental results

The WAS-Sensor was fixed on output shaft of their gearbox. The gearbox was diagnosed in a quasi-steady operation. The simulator motor rotation frequency had 12 Hz. Thus, the output shaft was rotated with 8 Hz in accordance with gear-ratio $k_z = 1.5$. The measured linear accelerations of the

output shaft by the WAS-Sensor contain periodic high-frequency vibrations for the chipped tooth situation (Fig. 7). The frequency spectra of the accelerations measured by the sensor contain many components, including discrete peaks (Fig. 8).

Comparison of the power spectrum of each acceleration $\ddot{\varphi}$, \ddot{x} and \ddot{y} for each gear defect (Fig. 9) clearly shows the change of the vibration signals – the change in the energy ratio of the spectrum components.

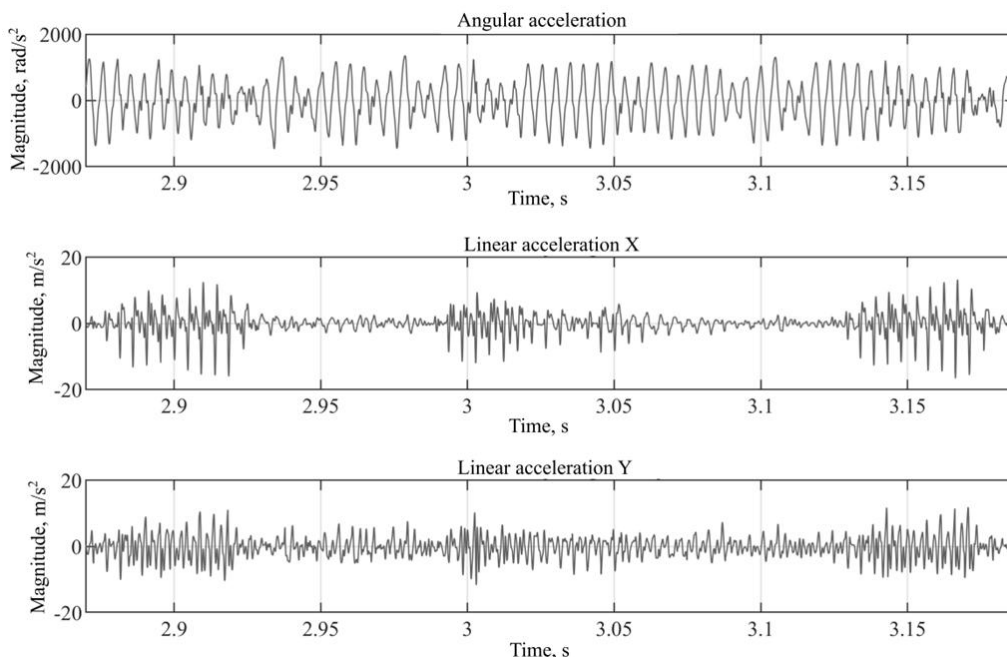


Fig. 7. The measured angular and linear accelerations by the WAS-Sensor. The pinion with the chipped tooth. Time domain

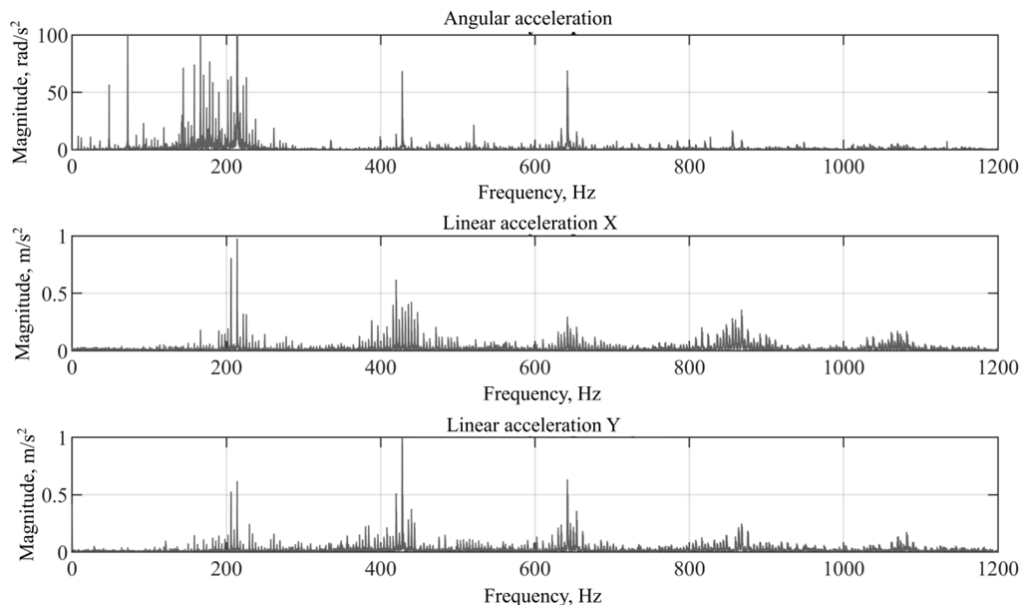


Fig. 8. Separated angular and linear accelerations. Pinion with the chipped tooth. Frequency domain

Moreover, the power spectrum grows around multiple of the tooth ripples f_z (214 Hz, 428 Hz, 642 Hz, 856 Hz), for the case 'the chipped tooth pinion'. Furthermore, the levels of discrete components of linear acceleration x are significantly lower in the region of multiple f_z frequencies for broken tooth case than for the chipped tooth case. On the other hand, the depth of modulation around the multiple of the tooth ripples substantially increased (Fig. 9). Thus, the paradoxical behaviour of the spectral characteristics for the different size of the tooth defect is clearly shown.

As previously mentioned, the presence of local defects affects a change of the stiffness gear-meshing function. A change of stiffness effects on a change of the force in the tooth contact pattern and a change of the angular acceleration of the gears. Moreover, a local defect affects a change of the magnitude of the frequency components which are related to the frequency meshing defected tooth.

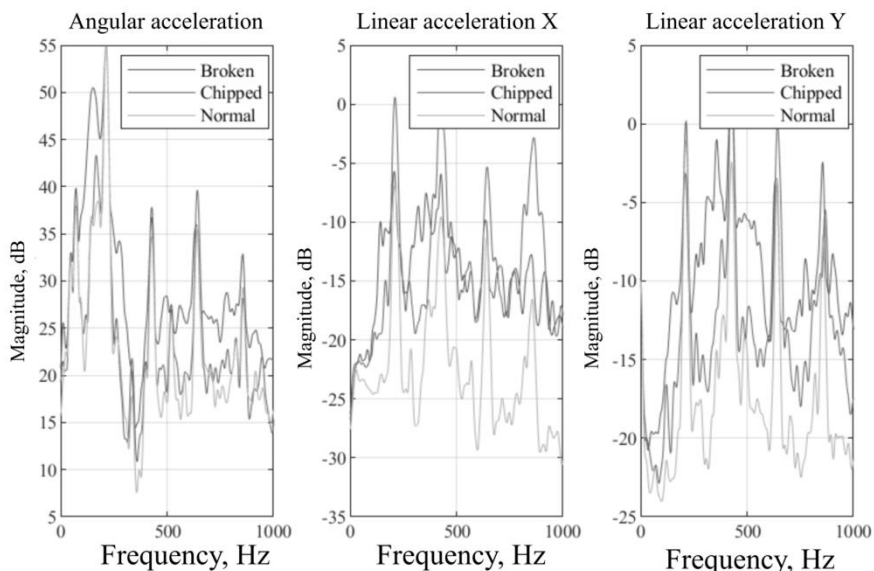


Fig. 9. The power spectrum for defects of the pinion. 'Broken' – broken tooth, 'Chipped' – chipped tooth, 'Normal' – without defect

The growth of a local defect (from chipped to breaking) leads to an increase in the amplitude of the first harmonic of angular acceleration $A^{\dot{\varphi}}$ due to a reduction of the stiffness gear-meshing. Thus,

$$A_{Normal}^{\dot{\varphi}} = 7,6 \text{ rad/s}^2; A_{Chipped}^{\dot{\varphi}} = 10,7 \text{ rad/s}^2; A_{Broken}^{\dot{\varphi}} = 22,9 \text{ rad/s}^2,$$

where $A_{Normal}^{\ddot{\phi}}$ – the pinion without defect, $A_{Chipped}^{\ddot{\phi}}$ – the pinion with chipped tooth, $A_{Broken}^{\ddot{\phi}}$ – the pinion with broken tooth.

As a result, the grown of the local defect leads to a monotonic increase magnitude of the $A^{\ddot{\phi}}$. Moreover, that trend continues at other rotation frequencies of the pinion (Fig. 10).

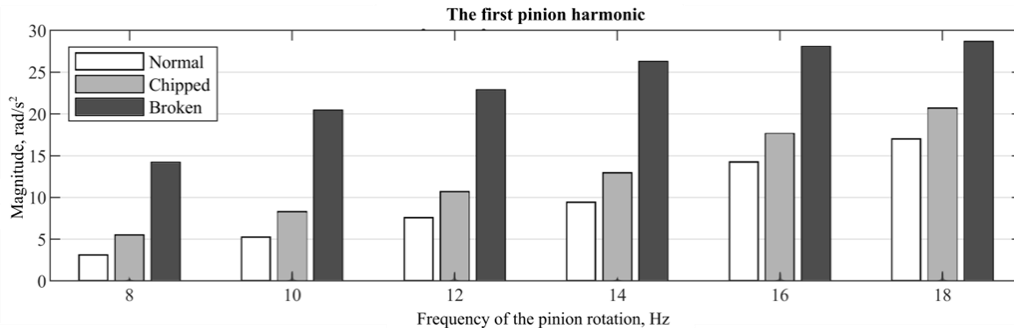


Fig. 10. The magnitude of the first harmonic of the pinion in angular acceleration for various local defects. ‘Broken’ – the pinion with broken tooth, ‘Chipped’ – the pinion with chipped tooth, ‘Normal’ – the pinion without defects

The amplitude of the first rotation frequency component in angular acceleration is increased with the increasing rotation frequency of the pinion. Moreover, the amplitude of the first rotation frequency component for the faultless case has an almost linear dependence on the rotation frequency from 8 to 18 Hz (Fig. 11).

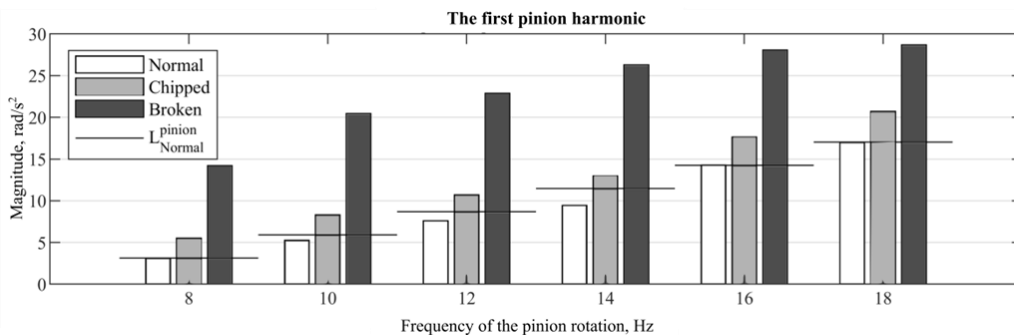


Fig. 11. The magnitude of the first harmonic of the pinion in angular acceleration for various local defects. ‘Broken’ – the pinion with broken tooth, ‘Chipped’ – the pinion with chipped tooth, ‘Normal’ – the pinion without defects, L_{Normal}^{pinion} – the linear function between the lower and the upper rotation frequency

Moreover, the amplitude of the first rotation frequency component is below the corresponding value of the bounding function $L_{Normal}^{pinion}(f_{pinion})$, where f_{pinion} is frequency of the pinion rotation (Fig. 12).

The function

$$L_{Normal}^{pinion}(f_{pinion}) = k_{normal} \cdot f_{pinion} + b_{normal},$$

where k_{normal} – slope coefficient of the bounding function, b_{normal} – constant displacement of the bounding function.

For the experimental case

$$k_{normal} = 1,3898, b_{normal} = -7,9864.$$

In turn, all values of the amplitudes of the first harmonic for each rotation frequency of each defective case are more than the values of the bounding function $L_{Normal}^{pinion}(f_{pinion})$. In addition, the values for both defects cases are close to direct dependence on the rotation frequency as well as for the defect-free case. Thus, a diagnostic criterion for detecting a local defect of the gearbox pinion is function $L_{chipped}^{pinion}$. The function

$$L_{chipped}^{pinion} = k_{border} \cdot f_{pinion} + b_{border}; \quad k_{border} = k_{normal}, b_{border} = b_{normal} + b_{shift}^{chipped}.$$

where k_{border} – slope coefficient of the criteria function, b_{border} – constant displacement of the criteria function $b_{shift}^{chipped}$ – constant displacement of the criteria function relatively the bounding function

$$L_{Normal}^{pinion} (f_{pinion}).$$

For the experimental case (Fig. 12) $b_{shift}^{chipped} = 0,5$.

The difference between the values of the amplitude of the 'chipped pinion' and the value of the criteria function $L_{chipped}^{pinion}$ vacillates between 1 and 3.2 rad/s² for different rotation frequencies. The difference between the values of the amplitude of the 'broken pinion' and the value of the criteria function $L_{chipped}^{pinion}$ are between 10.6 and 14.3 rad/s² for different rotation frequencies.

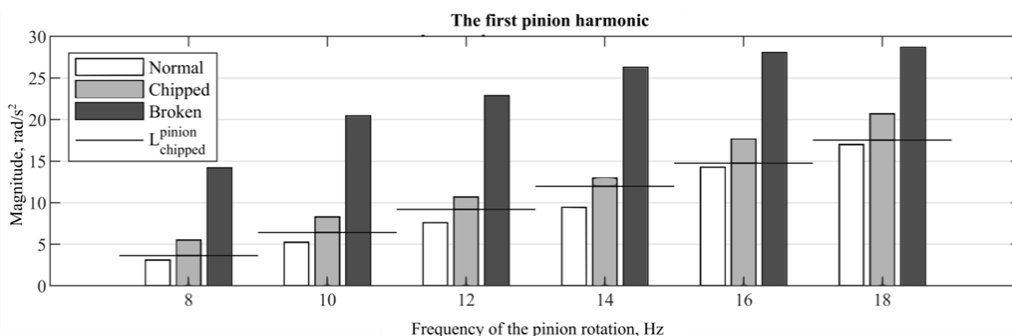


Fig. 12. The magnitude of the first harmonic of the pinion in angular acceleration for various local defects at various rotation frequencies. 'Broken' – the pinion with broken tooth, 'Chipped' – the pinion with chipped tooth, 'Normal' – the pinion without defect, $L_{chipped}^{pinion}$ – the criteria function detecting of a 'chipped tooth' defect at various rotation frequencies

The ICP-accelerometer (by PCB Piezotronics) was mounted on the gearbox body for comparing the proposed approach with the traditional approach receiving diagnosis information (from a gearbox body). The ICP-accelerometer has a 3-axis with a sensitivity of 100 mV/g. The linear accelerations were measured at the same rotation frequencies and with the same defects such as the proposed approach. However, the results show the magnitude of the first harmonic of the pinion in linear accelerations does not depend on the rotation frequency and the defect (Fig. 13).

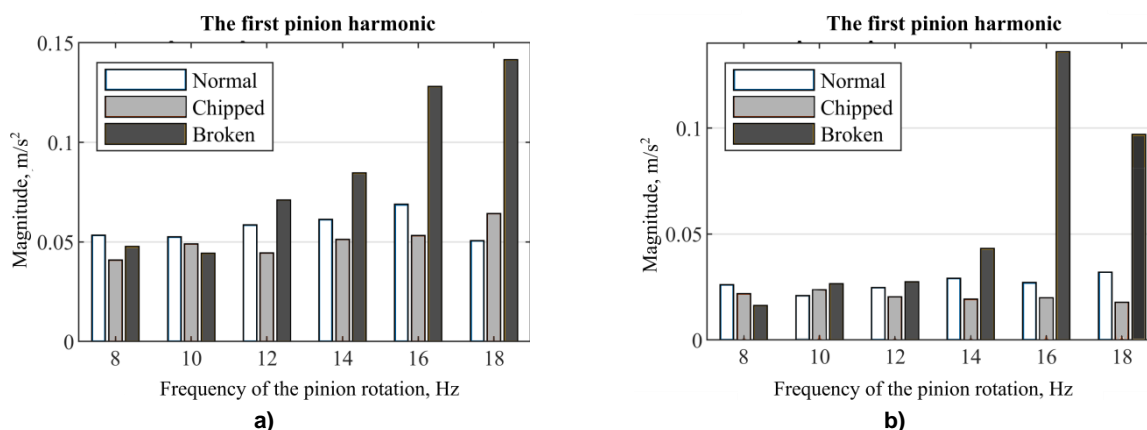


Fig. 13. The magnitude of the first harmonic of the pinion in linear accelerations measured by the ICP-accelerometer (a – horizontal axis, b – vertical axis) for various local defects at various rotation frequencies. 'Broken' – the pinion with broken tooth, 'Chipped' – the pinion with chipped tooth, 'Normal' – the pinion without defect

Moreover, the value of the magnitude for a 'normal' case is more than the values of a 'chipped' and a 'broken' cases at some rotation frequencies.

Discussion

The proposed approach allows clearly detecting the pinion local defect on the first pinion rotation frequency. On the other hand, the local pinion defect information is hidden in data from the traditional approach (from a gearbox body). Hence, the measurement angular acceleration from a shaft allows receiving extended information about the behaviour of the mechanical system. The application of the proposed approach diagnosis allows detecting a local defect of the pinion, for example, 'chipped tooth' type easily. The approach dispenses without special signal processing methods unlike with the traditional approach. Nevertheless, the proposed approach requires an additional extended experimental investigation for various types of gearbox with various mechanical loads. It will be the topic of the future research.

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ПОДХОД К ДИАГНОСТИКЕ ЗУБЧАТЫХ ПЕРЕДАЧ НА ОСНОВЕ МГНОВЕННОГО УГЛОВОГО УСКОРЕНИЯ. ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ

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Введение. Зубчатые передачи являются важными частями практически каждого исполнительного механизма во многих отраслях промышленности. В связи с этим мониторинг состояния редуктора является важной частью общего мониторинга состояния механизма в целом. В свою очередь вибрация – наиболее применяемый источник диагностической информации о техническом состоянии исполнительного механизма. Традиционно вибрация измеряется при помощи акселерометров, которые закреплены на корпусе механизма. Однако анализ измеренных сигналов требует применения разнообразных развитых методов обработки информации. С другой стороны, применение новых подходов к месту закрепления акселерометров позволяет получить дополнительную информацию о техническом состоянии, а также упростить процесс обнаружения дефектов в механизмах. **Цель.** Показать возможности применения новых подходов к месту закрепления акселерометров и измеряемой расширенной информации для диагностики коробки передач. **Материалы и методы.** Новое место крепления акселерометров – вращающийся вал механизма. В свою очередь, дополнительный источник информации – угловое ускорение вращающегося вала. В исследовании приведено теоретическое обоснование углового ускорения в качестве источника диагностической информации. **Результаты.** Исследование содержит экспериментальные результаты обнаружения неисправностей, таких как «сколотый зуб» и «сломанный зуб» шестерни. Более того, исследование содержит предложенные критерии для выявления локальной неисправности шестерни. **Заключе-**

чение. Результаты эксперимента и примененные критерии показывают, что предлагаемый подход позволяет четко обнаружить локальный дефект ведущего зубчатого колеса на частоте вращения первого зубчатого колеса на различных частотах вращения.

Ключевые слова: диагностика, акселерометр, беспроводной датчик ускорения, вращающийся вал, роторное оборудование, угловое ускорение.

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