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METHODS FOR ASSESSING THE TECHNICAL CONDITION OF BEARING HUBS IN MEANS OF TRANSPORT

Summary. This article presents two methods of testing bearing hubs, which may supplement the existing subjective and unreliable methods of diagnostics of rolling bearings used in wheel bearing hubs of motor vehicles and other means of road transport. One of the most important elements responsible for the safety of a vehicle is the bearing hub. Regular monitoring of the technical condition of bearings should become an obligation at vehicle inspection stations when carrying out a technical inspection of a vehicle, authorising it to travel on public roads. This article presents the results of vehicle tests with signs of damage to rolling bearings, using two test stands: one on which the dynamic balancer acted as a device for accelerating the wheel, and the other, which was designed as a test dedicated to automotive rolling bearings, where a dynamic weighbridge was used as the wheel drive, made it impossible to test the wheel at lower rotational speeds. The newly designed and manufactured bearing testing device eliminates the disadvantages of the previous

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stand, and additionally, enables the measurement of a fully loaded bearing hub, which enables the simulation of real operating conditions on the bearing hub.
Keywords: vibration diagnostics, bearing, wear, means of transport

1. INTRODUCTION

Increasing technological progress, growing expectations of users and standards related to environmental protection are one of the reasons for the growing use of rolling bearings in means of transport. However, the degree of complexity of the construction of means of transport is increasing, which in turn causes the extension of repair and maintenance procedures, making access to bearing hubs more difficult compared to the previous structures [1-3]. Often, rolling bearings, for example, in automotive vehicles, despite a relatively low price, can cause damage to other components and entire components due to failure, generating significant repair costs. The significant function of transport means, including motor vehicles, should also be considered in the entire logistics process aimed at moving people and goods among other things. Thus, the reliability of the means of transport has a great influence on the proper functioning of the transport. Subsequently, breakdowns of motor vehicles caused by damage to rolling bearings are often surprising, unexpected, disrupting the transport cycle. Therefore, it is necessary to use reliable methods for assessing the technical condition of rolling bearings used in road transport [4, 5].

The widespread use of rolling bearings in the construction of machines and means of transport has many advantages. The main advantages of rolling bearings are:

- low movement resistance, which is especially important during start-up,
- standardising the basic dimensions of the bearings, which facilitates their practical application,
- compactness of bearing hubs structure,
- motion stability at low speeds,
- giving off a small amount of heat,
- structural materials of the shaft do not have a significant impact on the durability of bearings and their functioning,
- the amount of lubricant required is small, which usually makes bearing maintenance-free.

Rolling bearings also have disadvantages, including:

- the need for high-quality steel susceptible to cracking and chipping,
- using specialised procedures related to bearing assembly,
- the need to use specialised devices to prevent dirt,
- sensitivity to lubricant contaminants, which results in repeated shortening of durability [4-7].

One of the drawbacks that deserves special attention is the generation of mechanical vibrations through bearing hubs equipped with rolling bearings. This phenomenon is closely related to the bearing geometry and the structural materials from which they are made. However, the parameters of generated vibrations, after registration and appropriate analysis, may become the basis for diagnosing the technical condition of rolling bearings [8-12]. This method is used to diagnose other elements in machines, including cars [13-18].

Automotive manufacturers do not specify procedures or time periods for reviewing or replacing most rolling bearings, including bearings fitted in car wheel bearing hubs. Vehicle control stations and car services do not have a highly specialised diagnostic procedure for diagnosing automotive rolling bearings. They refer only to unreliable organoleptic methods consisting of auscultation of the diagnosed placenta with or without a stethoscope. It is worth mentioning that periodic rolling bearing diagnostics is regularly used in the industry, especially concerning stationary rotor machines. However, it cannot be used directly in motor vehicles, due to their completely different nature of functioning associated with mobility, which often forces operation in transient states.

This article presents original methods for assessing the technical condition of rolling bearings using two test stands.

2. DIAGNOSTICS OF ROLLING BEARINGS

The basic symptom related to the functioning of rolling bearings is:

- generating noise (both in the acoustic band and outside it),
- generating vibrations in a wide frequency band,
- generating heat
- generating electromagnetic field interference,
- the appearance of wear products (for example, in a lubricant),
- degradation of the internal structure of the material in the form of, for example, corrosion, microcracks,
- the state of cooperating surfaces of elements of tribological pairs [19-21].

Rolling bearing diagnostics can be carried out based on their observation and analysis. Considering the symptoms described, they determine the diagnostic methods for disassembly and without disassembly.

Treating the rolling bearing as a mechanical vibration generator, the most common diagnostic method is vibration diagnostics, based on the recording of time courses of parameters describing the generated vibration. Obtained and properly processed time courses are used to build measures of the technical condition of rolling bearings. The advantage of this method is its assembly-free nature and a large amount of information in a relatively short unit of time.

The course of rolling bearing damage over time can be divided into three stages [21, 22]:

- noise stage - the broadband nature of the acceleration of vibrations associated with the normal operation of the bearing is narrowed to frequencies associated with the operation of individual bearing components. However, the maximum acceleration of housing vibrations takes on large values, which indicates the need to replace the bearing with new ones.
- vibration stage - the progressive degradation of the surface layer of rolling elements results in a significant increase in the actual values of housing vibration acceleration.
- thermal stage - there is avalanche wear of the surface of the elements, which results in their deformation and increasing friction is generated, causing a very high temperature of the bearing hub, followed by failures.

Vibration diagnostics of rolling bearings makes it possible to determine the suitability of a rolling bearing for further operation at the noise stage.

This method clearly surpasses the subjective and unreliable organoleptic methods currently used in the field of vehicle service, which consists of detecting possible play or auscultation of the bearing hub.

However, using this method entails the need to consider many individual design features, including not only the hub itself but also the entire vehicle, with particular emphasis on the propulsion and running gear [23, 24]. Specialised equipment is also required, for example, a device for accelerating non-driven road wheels and an apparatus that records the signal from vibration acceleration sensors.

The use of vibroacoustic methods allows for objective results, and the effectiveness of this method depends on the correct selection of measuring points and ensuring the right measurement conditions. The design of rolling bearings causes the detection of damage to individual components of the bearings to cause another disturbance in the vibroacoustic signal. In the frequency spectrum, the local damage to each component corresponds to a different component, so that spectral analysis can answer not only whether damage has occurred but also which bearing element has been damaged [5, 21].

From an operational point of view, however, it is more important to detect damage in the early stages of its development or excessive wear than determining which bearing component has been damaged. Observing the frequency spectrum for changes in the frequency amplitudes of the characteristic bearings may enable this task. The repeat frequencies of the damage-induced impressions are determined by formula 1 to 3 [5, 21].

Failure of the current element causes a pattern to occur in the frequency component spectrum [5, 21]:

$$f_{et} = \frac{D}{d} f_r (1 - \frac{d^2}{D^2} \cos^2 \beta) \tag{1}$$

where: D – bearing split diameter, d – rolling element diameter, f_r – relative frequency of rotation between inner and outer raceways, β – bearing operating angle.

The frequency caused by damage to the inner raceway can be recorded with the formula [5, 21]:

$$f_{bw} = \frac{e}{2} f_r (1 + \frac{d}{D} cos\ \beta) \tag{2}$$

where: e – number of elements.

The frequency caused by damage to the outer raceway can be determined by the formula [5, 21]:

$$f_{bz} = \frac{e}{2} f_r \left(1 - \frac{d}{D} cos\beta\right) \tag{3}$$

Determining the amplitudes of characteristic frequencies and comparing them with the symptom database or with the results of measurements previously performed on the test subject allows one to determine whether there have been adverse changes in the technical condition.

3. METHODS OF DIAGNOSTIC OF ROLLING

The results of the conducted tests indicate that it is possible to diagnose rolling bearings used in various means of transport. The methods for diagnosing rolling bearings using two test stands are presented in this section. The tests were carried out on an Opel car model Corsa D, in which various symptoms indicating damage to the wheel hub bearing could be observed while driving. The research used vibroacoustic measurements, which were then subjected to appropriate transformations and analysis. For signal recording, a manual LMS SCADAS XS data acquisition module was used. This enables the recording of 6 channels with a sampling frequency of 51.2 kHz and 3 vibration acceleration sensors. Signal transformations and analysis were performed using the Matlab 2019b computing environment using the Signal Processing Toolbox. For measuring the rotational speed of the wheel, a SELS PCID-8ZP induction sensor with an operating range of 8 mm was used. Figure 1 shows the view of the mounted vibration acceleration sensors in the test vehicle, together with the marking of the axis measurement directions by the vibration acceleration sensors. Regardless of the test method used, the vibration acceleration sensors remained mounted in the same places.

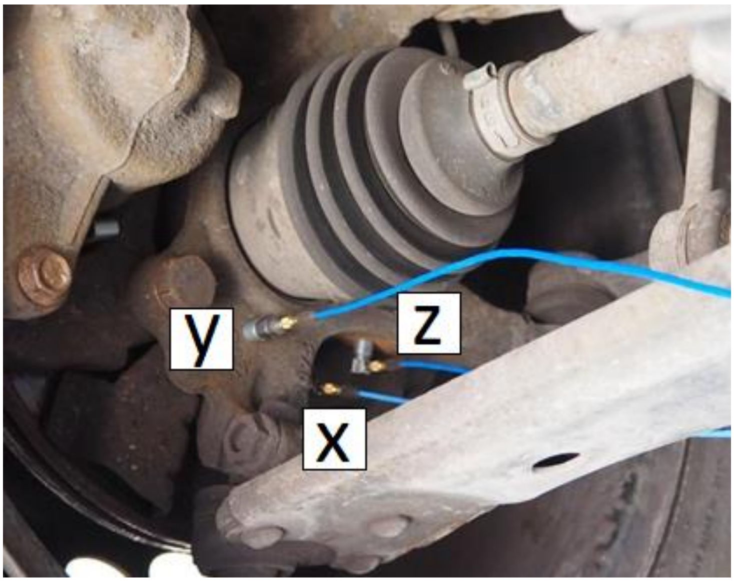

Fig. 1. View of placing vibration acceleration sensors on the wheel hub of the tested vehicle

The methods for diagnosing rolling bearings using two test stands are presented thus; The first test post was the position described in Section 3.1. – dynamic balancer of the vehicle wheel. While the second test bench was the position described in Section 3.2. – prototype stand – stand designed for testing vehicle wheel bearing hubs.

3.1. Diagnostics of rolling bearings implemented with the use of the vehicle wheel dynamic balancer

During the bench tests, the car was raised on a two-column lift. A dynamic balancer was used to accelerate the wheel, which enables acceleration of one wheel for two different values of wheel speed. Figure 2 shows the performance of tests while accelerating the wheel with a dynamic wheel balancer.

Fig. 2. Measurement stand during tests

During the tests, vibration accelerations in three directions around the bearing hub were recorded. The vibration signals and the rotational speed signal were recorded with a sampling frequency of 51.2 kHz and stored in a digital form on the memory card of the data acquisition device. Based on the mileage of the wheel speed signal, the actual wheel speed was calculated. The wheel speed time course is shown in Figure 3. The time of execution of 4 full turns of the wheel was = 0.1027 s.

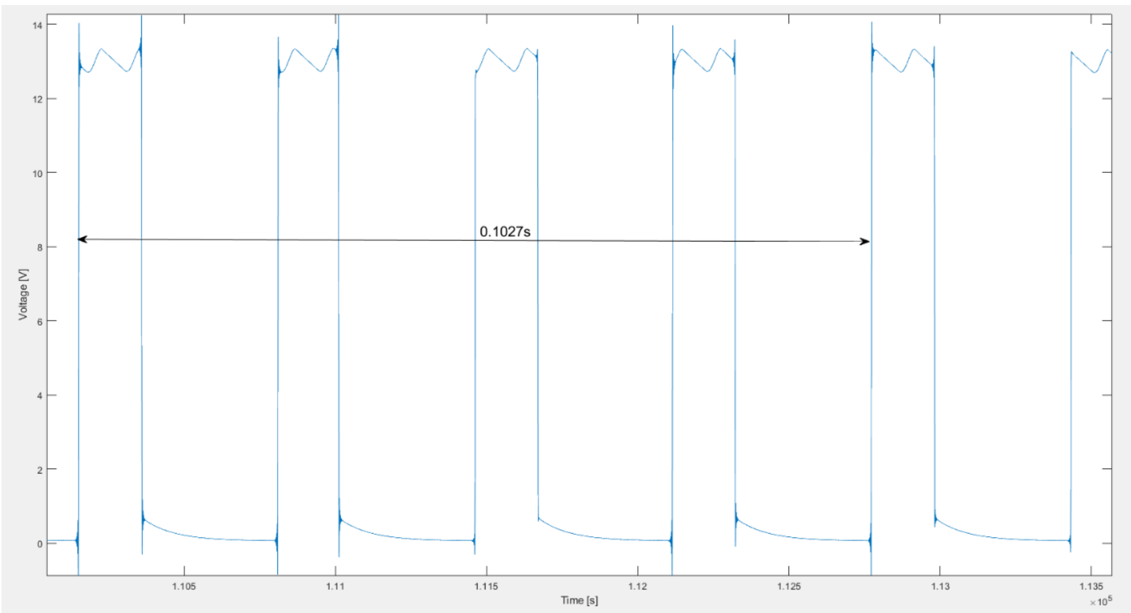

Fig. 3. Time course of the wheel speed signal - dynamic balancer

A dynamic balancer accelerated the wheel of the vehicle to a constant speed of 129.6 km/h, which corresponds to f_wheel = 37.5 Hz. Then, a spectral analysis of the recorded signals was performed to search for frequencies characteristic of damage to the individual elements of the bearing hub. Figure 4 presents an analysis of the time-frequency waveforms of recorded signals.

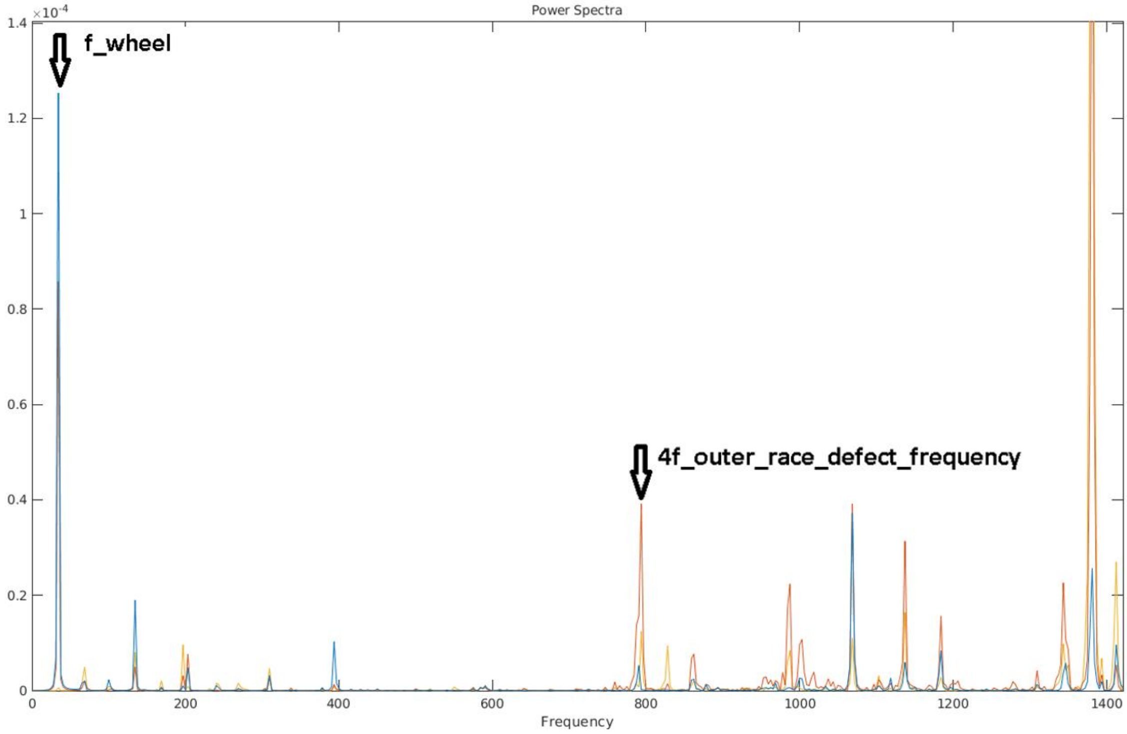

Fig. 4. Analysis of vibration signal waveforms of a wheel with a damaged rolling bearing - dynamic balancer – where: blue line - X-axis, red line - Y-axis, yellow - Z-axis

Based on the geometrical parameters of the bearing, the bearing failure frequency was determined for a bearing failure frequency of f_wheel = 37.5 Hz. Based on formulas 1 to 3, the following frequencies were calculated:

- wheel speed frequency 37,50 Hz,
- inner race defect frequency 307,54 Hz,
- outer race defect frequency 217,46 Hz,
- cage defect frequency 21,97 Hz.

As seen, the 4th harmonic of the outer track damage frequency changes depending on the measurement axis. The highest amplitude values are assumed for the Y-axis, which corresponds to the vertical displacement of the bearing hub. Then the same measuring procedure was used for the bearing hub with the new bearing. The same analysis of the recorded vibration signal was also made. The obtained results are a reference for earlier measurements and analysis of vibration signals of a bearing hub equipped with a worn bearing. Comparison of the obtained results enables the construction of measures of the technical condition of the tested bearing hub. Figure 5 shows the time-frequency course of vibration accelerations for a new bearing.

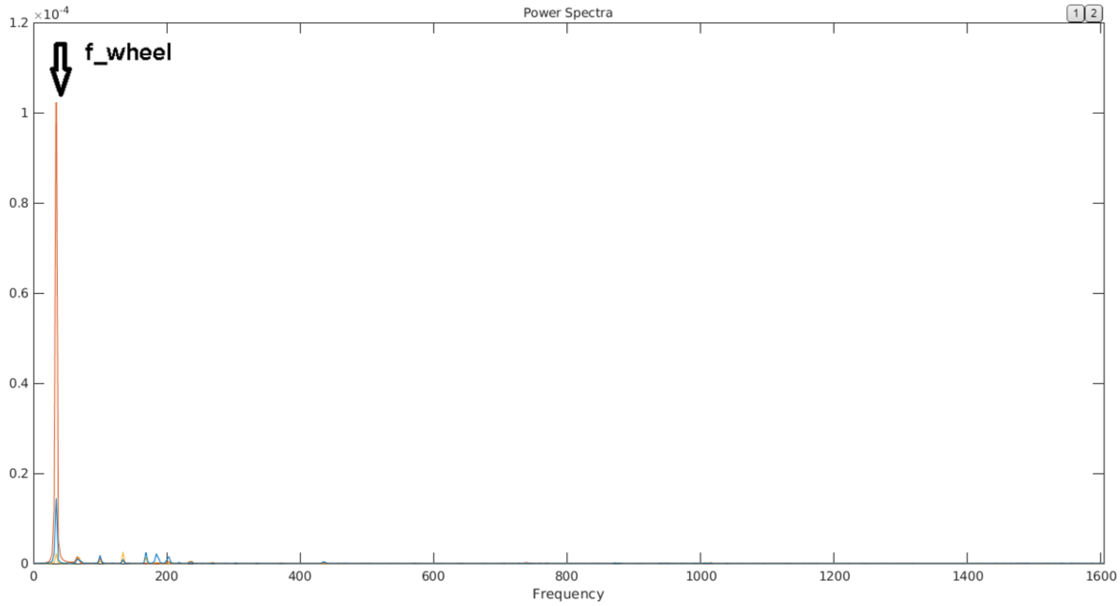

Fig. 5. Analysis of time-frequency waveforms of vibration signals of a wheel with a new rolling bearing – where: blue line - X-axis, red line - Y-axis, yellow - Z-axis

Figure 6 shows a comparison of time-frequency courses of damaged vibration accelerations and a new rolling bearing, whose measurements were made for the Y-axis. As seen in Figure 6, the analysis of the time-frequency waveform of vibration signals shows the differences between a signal with a damaged bearing (red line) and a signal recorded with a new bearing (green). For a bearing junction with a new rolling bearing, the time-frequency spectrum has no higher component frequencies, and none of the frequencies characteristic of damage to individual bearing components occurs.

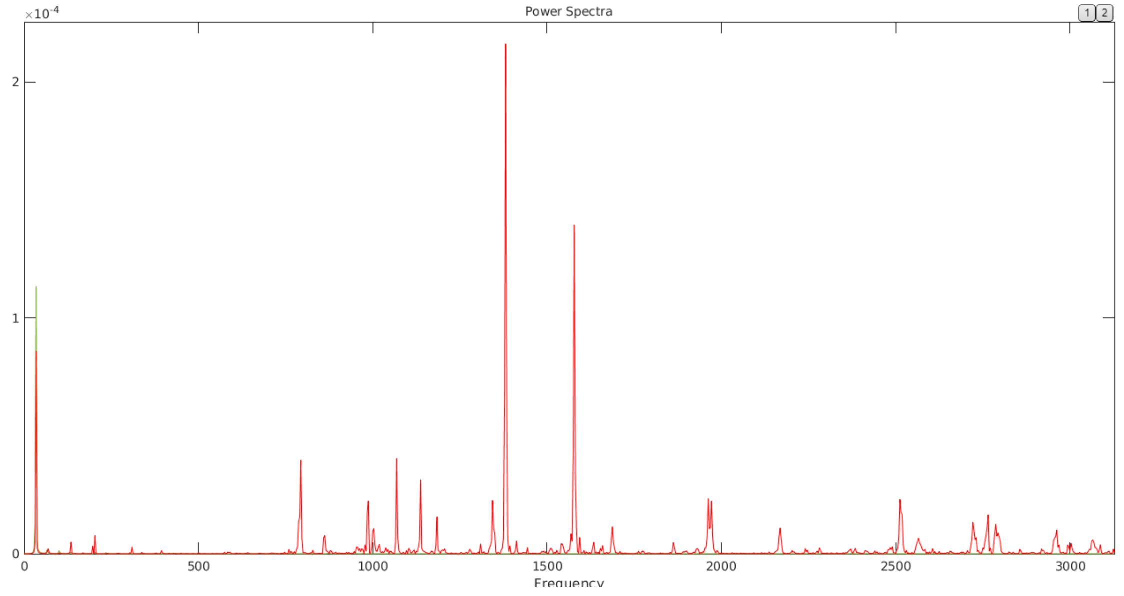

Fig. 6. Analysis of the time-frequency waveforms of the road wheel - comparison of a new and a damaged bearing - where green line indicates a new bearing, red line indicates a damaged bearing

3.2. Bearing diagnostics using a prototype stand dedicated to testing bearing hubs

Bench tests of the technical condition of rolling bearings were carried out with the use of a typical device, which is a dynamic wheel balancer. The dynamic wheel balancer has its advantages, for example, ease of access and quick measurement. Due to the limitations of the method presented in Section 3.1., a station for testing rolling bearings of road wheels was designed and manufactured, which enables, among others:

- acceleration and maintenance of constant speed of the road wheel in a wide range of rotational speed,
- measurement of slip occurring between the wheel and the ground,
- constant measurement of wheel pressure on the road.

During the tests, acceleration of vibrations in the three axis directions and rotational speeds of the road wheel and the drum driving the wheel near the bearing hub were recorded. The wheel pressure on the device was mapped according to real conditions. The road wheel was accelerated to a frequency of 5 Hz, which corresponds to a speed of 17.28 km/h. Reducing the wheel speed results in the elimination of higher frequency components and simultaneously reduces the signal amplitude. Figure 7 shows a partial view of the station and the tested vehicle.

Fig. 7. Prototype stand during tests of the technical condition of the road wheel bearing hub

Based on the pulse time course determining the speed of the driven road wheel, the vehicle speed is determined. The results of the analysis in the form of time frequencies of wheel vibration signals with a damaged rolling bearing are shown in Figure 8.

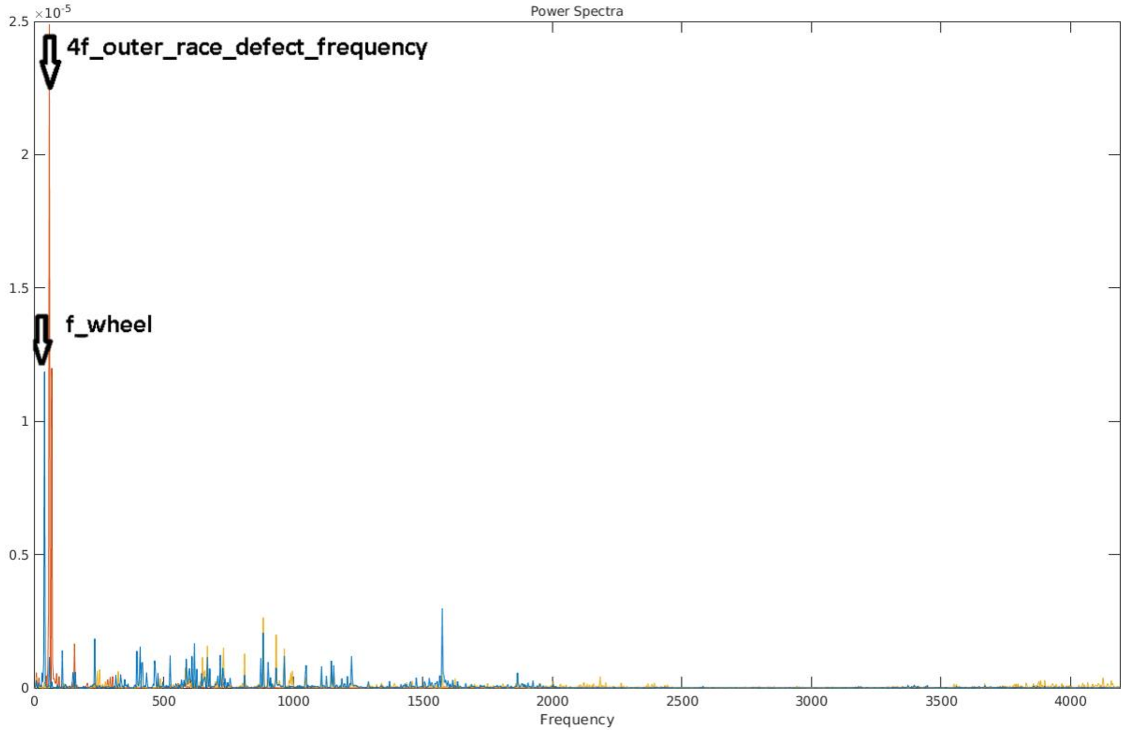

Fig. 8. Analysis of time-frequency waveforms of vibration signals of a wheel with a damaged rolling bearing - prototype stand – where: blue line - X-axis, red line - Y-axis, yellow - Z-axis

A peak can be observed at a frequency of 29 Hz. For the tested bearing hub, based on formulas 1 to 3, the frequency of damage to individual rolling bearing components is:

- shaft speed frequency 5,00 Hz,
- inner race defect frequency 41,01 Hz,
- outer race defect frequency 29,00 Hz,
- cage defect frequency 2,93 Hz.

This frequency corresponds to the frequency of damage to the outer race of the road wheel bearing.

Thereafter, the damaged bearing hub was replaced with a new one. The whole wheel bearing was tested again. The result of the time-frequency analysis of the new bearing hub is shown in Figure 9.

Then, the results of the time-frequency analysis of damaged and new bearings were compared, and the results are shown in Figure 10.

As observed, the value for a damaged bearing frequency = 29 Hz is 2.7x10^-5 m/s^2 and is almost three times higher than for a new bearing. In addition, there are higher frequency components for the damaged bearing that are not present for the new bearing.

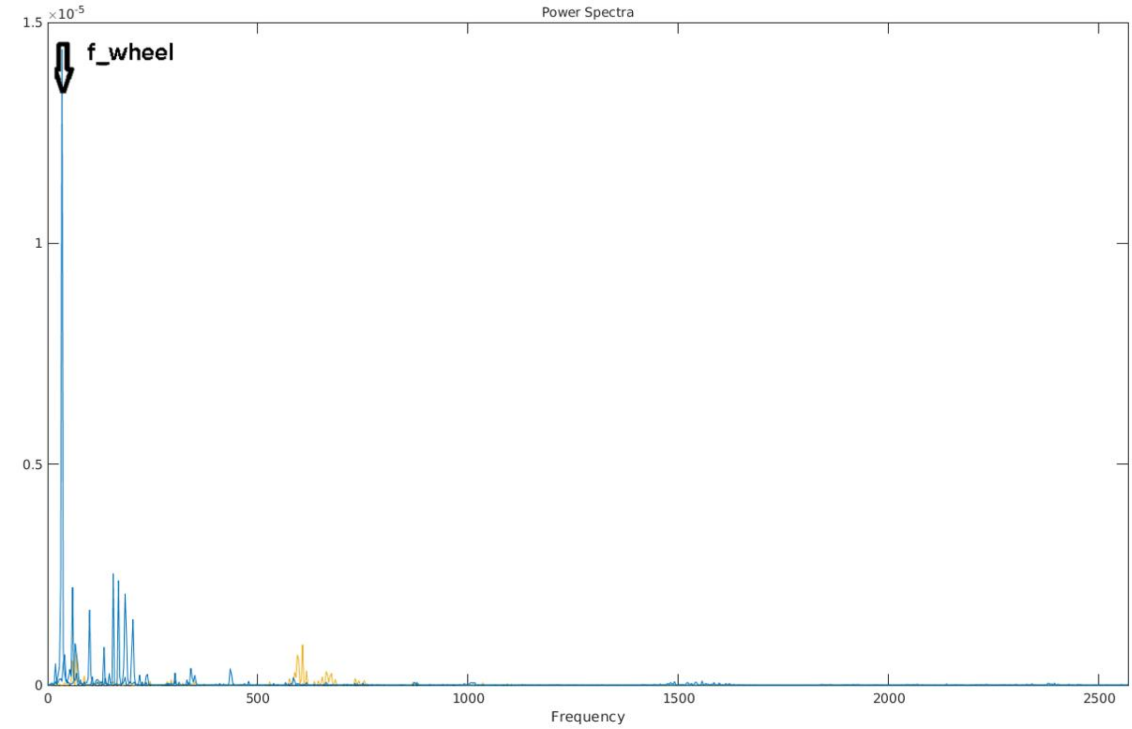

Fig. 9. Analysis of time-frequency waveforms of vibration signals of a wheel with a new rolling bearing-where: blue line - X-axis, red line - Y-axis, yellow - Z-axis

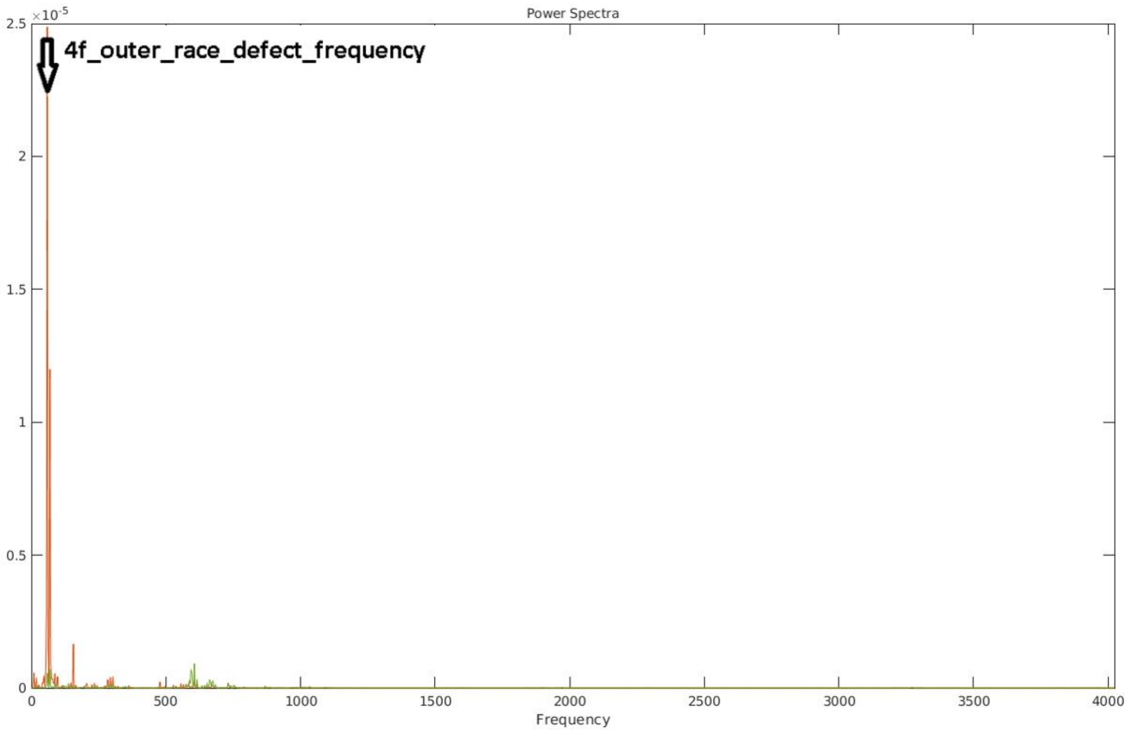

Fig. 10. Analysis of the vibration time-frequency waveforms - comparison of signals with new and damaged bearing - where green line indicates a new bearing, red line indicates a damaged bearing

4. SUMMARY

The testing methods of bearing hubs presented in this paper may complement existing, subjective and unreliable methods of rolling bearing diagnostics used in the bearing hubs of road wheels of motor vehicles and other means of road transport. Bearing hubs are one of the most important elements responsible for the safety of a motor vehicle. Regular monitoring of the technical condition of bearings should become an obligation at vehicle inspection stations when performing the technical inspection of a vehicle entitling the vehicle to drive on public roads.

The methods for diagnosing rolling bearings were presented using two test stands. The first test post was the position described in Section 3.1. – dynamic balancer of the vehicle wheel. The second test bench was the position described in Section 3.2. – prototype stand – stand designed for testing vehicle wheel bearing hubs.

The vehicle with symptoms of rolling bearing damage was tested using two test stands. One, in which a dynamic balancer was used as a wheel acceleration device, and the other, which was designed as a dedicated test for automotive rolling bearings. The previous stand, where a dynamic weighbridge was used as the wheel drive, made it impossible to test the wheel at lower rotational speeds. It was impossible to map real conditions, for example, those prevailing in urban conditions. In addition, an error resulting from the acceleration of the road wheel itself was introduced, because the accelerated wheel was a side part of the tyre. This type of acceleration introduces an additional normal force in the direction of the rolling bearing. Thus, this type of error may cause the generation of additional vibrations or damping of damage, which will be the subject of further research.

The designed and constructed device for testing bearings eliminates the previous disadvantages of the previous stand. In addition, it enables measurement of a fully loaded bearing hub. This allows simulation of the real conditions operating on the bearing hub.

Test results presented in this paper, regardless of the method used, showed that the outer race of the rolling bearing was damaged. Picture 11 shows the damage to the outer race of the rolling bearing, which was detected with the help of the aforementioned testing devices.

Fig. 11. View of damage to the outer race of the rolling bearing of the tested vehicle

Comparing the results of both methods, it can be concluded that the time-frequency waveforms of vibration signals differ from the method used. Using the balancing method, additional components are generated in the higher frequency range. These vibration signals are levelled during tests in which a stand dedicated to tests of rolling bearings of road wheels of means of transport was used.

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