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Contribution of using Vibration Diagnostic Tools in Assessing the Condition of Gear Elements in Off-Road Vehicle Gearboxes

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Abstract: The aim of this paper is to contribute to the possibility of using vibration diagnostics as a modern, non-destructive tool for assessing the condition of gears in the gearbox of off-road vehicles when the vehicles are used in real operating conditions, despite the non-stationary change in load during work. The method of vibration analysis in a vehicle gearbox under real operating conditions was determined and the adaptability of vibration analysis tools in determining the conditions of gears in off-road vehicles was considered. The data collected in the research shows that the vibration diagnostic method as a non-destructive tool for determining the condition of gears in off-road vehicle gearboxes under real operating conditions provides data on the condition of gear elements at different stages of vehicle operation. In this way, research time is shortened, there is no need to develop special test-tables for gearbox tests, the research method is non-destructive and it can identify processes that are characteristic of both early and later operating stages of the vehicle. Finally, the decision as to whether certain forms of gearbox maintenance are required can be made based on the assessed condition of the gears in the gearbox.

Keywords: vibrations, vibration diagnostic, gears, signal, vehicle

1. Introduction

Noise and vibration [1], [8] are physical phenomena that occur in machines with rotating elements (gears, bearings, shafts, etc.) due to the dynamic forces of rotational movements and the rigidity of machine systems. They can be defined as:

$$V = F \cdot [k] \tag{1}$$

where: V – vibration, F – dynamic force, and $[k]$ – system rigidity. By changing either force or rigidity, the vibration state of the entire system also changes. Vibration is a clear picture of the state of the system and can be used to determine the state of machine systems or their subparts. The basic causes of vibration and noise can be divided into the following groups [2]: construction parameters (such as dimensions, mass, etc.), technological parameters (such as gap, tolerance, surface quality, etc.), work processes (such as stationary-dynamic, etc.), and maintenance technology.

Vibration analysis has evolved over the last 60 to 70 years to become one of the basic and fundamental tools for evaluating machine condition and has come a long way from fault detection (mostly) at the beginning of use to today’s requirements for more effective use of all resources [1], [4], [5], [8]. One aspect of vibration that is being studied in vehicles is the so-called „human vibration” [3], [11], [12].

Vibration diagnostics is the other aspect in the vehicle where vibrations and their signature are studied by many different researchers around the world. Vibration diagnostic tools are often used to detect and monitor problems in various gears. The latest methods and overviews of the state of the art can be found in [16], [17], [18], [19], [26]. In the last ten to fifteen years, many different researches and methods have been carried out to detect gearbox problems using vibration diagnostics. Some methods are based on acoustic studies [13], [14], [15], [25], but most researchers develop methods based on analyzing vibration signals [10]. When it comes to the research of vehicle gearboxes and gear faults on a vehicle gearbox, there are also several research works on this topic dealing with variable gearbox shaft speed and non-variable gearbox speed [20], [21], [22], [23], [24], [25], where the common approach is to use a test desk.

The vibrations of the gearbox can be considered in the time domain (function related to time) or in the frequency domain (function related to frequency). The modeling and signal analysis has been performed by a number of authors in the past [1], [4], [8], [9]. When measuring in the time domain, we obtain continuous analog signals that must be converted into a digital form, i.e. a series of discrete values, so that they can be stored or processed in the measuring instrument (Fig. 1).

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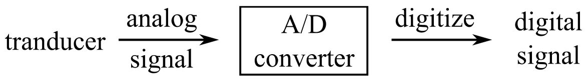

Fig. 1. Conversion of analog to digital signal.

The result of the signal transformation from the time to the frequency domain is the spectrum and the fact that the analysis based on electrical signals is used for the detection of mechanical faults [5] is used for the detection and determination of gears in general and in this case in a vehicle gearbox.

This research contributes to the use of vibration diagnostic tools for detecting potential problems with gears in a vehicle gearbox. As in [21], the main idea was to perform a new form of field test under real operating conditions with real loads for the tested off-road vehicle to determine the condition of the gears of a given gear ratio, using the vehicle as a test desk. With this approach, we made a good condition assessment of the gear in the gearbox of the vehicle by performing vibration diagnosis and conducting the proposed test of the off-road vehicle under real operating conditions using regular and classical analysis methods, frequency analysis and order analysis [8], [9], [18].

2. SUBJECT & METHODS

Vibration diagnosis in the power transmission system while the vehicle is moving is made more difficult by the fact that the loads in the power transmission system are not constant. This makes the qualitative analysis of the measured vibration signals in the context of a dynamic vehicle transmission considerably more difficult. The conditions for measuring vehicle vibrations under operating loads are such that the speed of the input shaft is not stationary (rotational speed of the gearbox shafts n≠const). The number of revolutions of the engine output shaft is variable and the number of revolutions varies depending on the driving mode, gear ratio in the gearbox, road conditions on which the driving takes place, etc.

There are three typical frequencies on gears that we use for vibration analysis: the input speed f_{in} or input shaft rotation frequency f_{shaft}, the gear mesh frequency $f_{toothing}$ (2), and the output speed or output shaft rotation frequency f_{out} (3).

$$f_{toothing} = f_{shaft} \times N_{tooth} \tag{2}$$

$$f_{out} = f_{in} \frac{N_{in\,teeth}}{N_{out\,teeth}} \tag{3}$$

where: $f_{toothing}$ - gear mesh frequency, f_{out} , f_{in} - frequency of the output/input shaft, N - number of teeth in input/output gear.

Most gear problems are studied using frequency domain analysis and order analysis [8], [9], [16], [17], [18], [19], where the gear mesh frequency and its 2- and 3-fold time harmonics are considered and analyzed along with the sidebands around these frequencies. There are a number of reasons for gear failure that have been explored in the past [6], [7], [18]: cracked or broken tooth (the most severe problem in gears that produce a high amplitude peak in shaft rotation speed), tooth wear (as a result of the physical contact of the sides of the two teeth with each other), tooth load (where the amplitude of the tooth mesh frequency depends on the orientation of the shafts carrying the gears and the load on the gear), gear run-in (a subtle phenomenon, characteristic of the initial state of the gears), eccentric gears (eccentric gears generate sidebands arranged around the gear mesh frequency at the shaft speed), gear backlash (generate shaft speed sidebands around the gear mesh frequency), misaligned gears (generate high gear mesh frequencies with sidebands).

If there are no characteristic peaks as a result of broken teeth, further analysis is carried out to detect other possible faults in the gears. The gear condition analysis is usually performed in the medium vibration range, between 500-2000 Hz. Conditions beyond 2000 Hz are areas of high vibration that contain frequencies characteristic of bearing failures, which is not the subject of this paper. The shafts on which the gears are located rotate with a certain number of revolutions, i.e. with a certain frequency, so that we practically have a constant engagement and disengagement of two teeth, i.e. we have several engagements and disengagements per second. Due to the complexity of the analytical model as well as the large number of influences that must be taken into account, we moved to vibration diagnostics by analyzing digitized analog vibration signals. This paved the way for a more comprehensive and simpler use of vibration analysis in all areas of mechanical engineering where rotating elements are present, such as in the transmission of a vehicle.

Measurement, vibration analysis and evaluation of gearbox gears with subsequent analysis require a regulated methodological approach using different but interrelated methods and techniques. An appropriate approach to the problem is required, which is taken into account through the use of non-destructive vibrodiagnostic analysis. In a final step, a decision was made on the need and level of maintenance of the elements or gearbox.

The method of vibration diagnosis has phases, which are shown in the block diagram (Fig. 2):

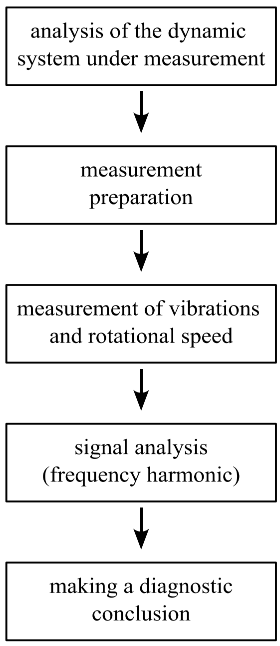

Fig. 2. Block diagram of the vibration diagnostic method.

A. Analysis of the dynamic system under measurement

The subject of the investigation was mechanical, stepped, synchronized gearbox of the type MS 80.P28 (Fig. 3) with six gear ratios for the forward and one for the reverse vehicle driving. It is usually installed in off-road vehicles from the manufacturer FAP (FAP 1118 in this study, Fig. 4). It has three shafts with fixed axles (input, output, and intermediate shaft). The input shaft is connected to the intermediate shaft by two permanently coupled gears with tooth numbers 19/41.

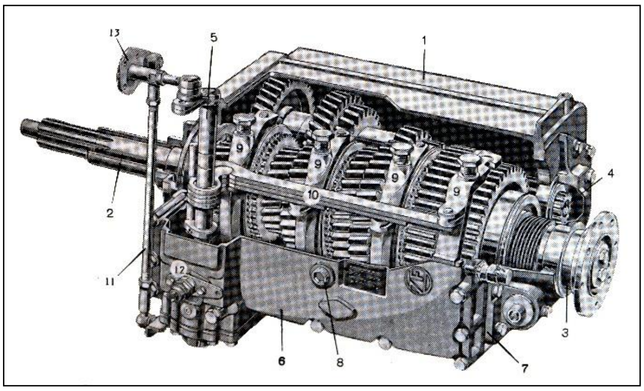

Fig. 3. Gearbox type 6MS 80:
1 – gearbox housing, 2 – input shaft, 3 – exit shaft, 4 – intermediate shaft, 5 – shaft for gear engagement, 6 – side cover, 7 – back cover, 8 – oil filler cap, 9 – forks, 10 – longitudinal fork support, 11 – pusher, 12 – carrier, 13 – flange.

The basic prerequisite for measuring vibrations on a gearbox is the initial identification of the gearbox and its elements. This is an important step for the upcoming evaluation of the measurement method, the selection and installation of measuring instruments and the determination of the measurement mode, etc. For the use of vibration diagnostics, it is necessary to calculate the kinematic operating conditions of the elements of the gearbox. The basic data required are the calculation of the gear ratios for the gears, the number of rotations and the rotational frequencies as well as the gear mesh frequency for the individual gears. The connection between the intermediate shaft and the output shaft is established by connecting the gear with the desired gear ratio to the synchronous coupling of the output shaft. The rotational speed of the intermediate shaft ω_{mv} is:

$$\omega_{mv} = \omega_{in} \cdot \frac{z_{in}}{z_{out}} = 2000 \cdot \frac{19}{41} = 926.8 \approx 927 \text{ rpm} \quad (4)$$

The rotational speed of the output shaft ω_{out} can be calculated using (5):

$$\omega_{out} = \frac{\omega_{in}}{\frac{z_{s2}}{z_{s1}} \cdot \frac{z_{outn}}{z_{inn}}} \quad (5)$$

where: n – gear ratio, ω_{in} – input shaft rotation speed in rpm, ω_{out} – output shaft rotation speed in rpm, z_{s1} and z_{s2} – tooth numbers of permanently coupled gears 19/41, z_{inn}/z_{outn} – number of teeth of the gears in n^{th} gear ratio.

The gearbox has the following characteristics, Table 1 [27].

Table 1. 6MS 80.P28 gearbox main characteristics.

Gear	I	II	III	IV	V	VI
Couple	50/12	36/15	32/22	26/27	24/36	19/41
Gear ratio	9	5.18	3.14	2.08	1.44	1
ω_{out} [rpm]	222	386	637	962	1389	2000
f_{out} [Hz]	3.7	6.4	10.6	16	23.15	33.3
G_m [rpm/Hz]	11100 /185	13896 /230	20381 /340	25000/ 417	33336 /556	38000 /634

During the measurements, the input shaft had a constant rotational speed of around 2000 rpm, (approx. 33.3 Hz). The decision on the rotational speed of the input shaft was made after calculating the towing of a vehicle. The shaft speed of 2000 rpm of the engine crankshaft (which corresponds to the speed of the input shaft of the gearbox) is the speed that ensures stable work of the engine/vehicle in all gear ratios and can be used for the measurements and analysis of all gear ratios of the gearbox. The intermediate shaft rotation speed is calculated using (4) and is around 927 rpm. Since the gears are in constant coupling with a gear ratio of 19/41 teeth and the measurements were performed at an output engine speed of about 2000 rpm, the speed of the intermediate shaft can be considered constant. This approach of establishing an appropriate constant rotation speed for gear ratio testing, which remains constant during measurement, represents a specific cross-over, from variable speed and load measurement to constant shaft speed measurement, which is more reliable and suitable for collecting data for gear analysis and drawing appropriate conclusions about gear condition.

In the case of power transmission in the gearbox, we have constant rotation of the input shaft, intermediate shaft and output shaft, which means that the gear pair 19/41 is permanently coupled. As a result, the signal shows the frequencies of the input, output and intermediate shafts as well as the frequency of the gear coupling in constant engagement and the frequency of the gear coupling at a certain gear ratio. All this complicates the analysis of vibration signals, because it is necessary to identify and find each of these frequencies in the signal together with their harmonics. After that, we can proceed with the comparative analysis of the signal and draw some conclusions.

B. Measurement preparation

After analyzing the test object, it is necessary to prepare the measurement. This includes selecting the measuring devices, placing them on the test object and connecting the measuring devices to the measuring chain (Fig. 4). The measuring chain for measuring vibrations on the gearbox consisted of the following elements (Fig. 4 and Fig. 5):

- Universal data acquisition system for measuring noise and vibration parameters, type NetdB 12, French manufacturer 01dB-Metravib, which has the following characteristics: universal acquisition with twelve measurement channels, with BNC input connectors for sensors; frequency rate during measurement from 51.2 KHz, with 24-bit digitization; the measuring device works with specially developed software for measuring and analyzing noise and vibration parameters, type dBFA Suite 4.8.1.

- Acceleration sensors of type CTC AC 131-1A, US manufacturer, with a wide measuring range, from -500 g to +500 g at peak, with a sensor sensitivity of 10 mV/g; the frequency response of the accelerometer is 60-900000 CPM (cycles per minute); the temperature working range from -50 °C to +121 °C.
- RPM sensor ROLS-W from Monarch Instrument ROLS-W: measuring range 1-250000 rpm (revolutions per minute); temperature working range -40 °C to +80 °C; the angle for sensor adjustment is up to 45°; the sensor has a laser indicator directed to the rotating part of the measured object on which the stamp is located.

Fig. 4. Measurement device and vehicle FAP 1118, 4×4.

The sensors are attached to the vehicle gearbox as follows according to the measurement chain diagram in Fig. 5:

- Accelerometers 1 and 3 on the gearbox input shaft, on the bearing housing. The sensors are mounted in a horizontal plane, with the measuring direction normal to the longitudinal axis of the vehicle.
- Accelerometers 2 and 4 on the gearbox output shaft, on the bearing housing. The sensors are mounted in a horizontal plane, with the measuring direction normal to the longitudinal axis of the vehicle.
- RPM sensor on the cardan shaft, which is connected to the gearbox output shaft.

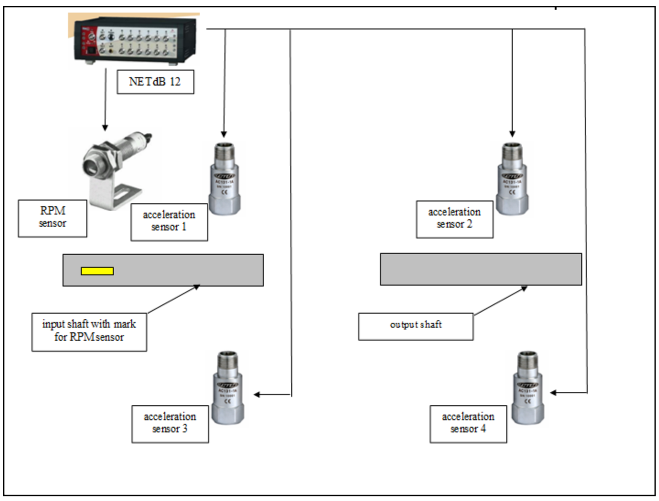

Fig. 5. Measurement chain diagram for vibration measurement on a vehicle gearbox.

Vibrations were measured using 4 accelerometers, but for the purpose of this paper, the data from accelerometer 1 and/or accelerometer 4 will be used. Other data can be used to determine the condition of shafts and bearings, which is not the subject of this paper.

After establishing the measurement chain, the next step is to record the vibration signal in the corresponding gear ratio, under the corresponding vehicle operating conditions and on the corresponding test tracks under real vehicle operating conditions. Considering that the working loads of the gearbox are variable under the actual dynamic operating conditions, it is necessary to bring the measurement and analysis of the condition closer to these operating conditions. However, the variability of the load during the operation of the gearbox and the measurement of vibrations under such operating conditions makes it difficult to apply vibration diagnostics as a means of analyzing the condition of the elements of the gearbox. Therefore, it is necessary to perform measurements under the dynamic operating conditions of the gearbox in the vehicle, but the initial conditions for the measurement itself must be defined.

The original idea is that the vehicle is tested under real operating conditions, based on different starting conditions:

- The test conditions correspond to the actual operating conditions of the vehicle, so that a more realistic picture of the gearbox element condition in research is obtained.
- The vehicle is used as a test rig, thus avoiding the development of special test rigs, which are sometimes expensive, require additional time for development and often have to be built specially for individual transmission types and models.
- The time required for research is reduced as the tests of the gearbox are carried out during the field testing of the vehicles.
- Universal measuring devices were used to measure noise and vibration parameters, which can also be used for other measurement purposes with other means.

All measurements were performed under dynamic conditions (in real driving conditions) to bring the tests closer to the actual vehicle operating conditions, trying to keep the driving mode constant at 2000 rpm of the engine crankshaft, in each gear ratio. A control recording of the gearbox output shaft speed was made, from which the speed of the gear elements in the gearbox was also calculated. Each measurement was carried out for one gear ratio, on the same track, under the same load conditions on the test track and at a constant vehicle speed (so you get a constant vehicle speed when testing with the same track and load conditions of the engine and gearbox). In this way, the measurement of vibrations on the gearbox under non-stationary, variable conditions is avoided, giving the measurement comparable values. This created a specific cross-over from measurement under variable load conditions to measurement under stationary conditions, while the test was carried out under field test conditions with real vehicle loads.

The measurement on the vehicle was carried out on characteristic gravel roads where the road conditions (surface, road gradient, load condition of the vehicle, etc.) were identical. After the initial measurement, the first measurement (test 1) was carried out after 10000 km of intensive driving tests. The second measurement (test 2) was then carried out on the test track after a total of 20000 km. All measurements were performed under the same road conditions: the outside temperature was around 23 °C, the gradient on the parts of both test roads used for the measurement was around 5 degrees, the vehicle was heated up to the operating temperature of the service fluids and lubricated according to the manufacturer's recommendations. In this paper, the signals recorded by accelerometers 1 and/or accelerometer 4 are used to analyze the data on gear conditions.

By measuring the values (vibrations and rpm) in off-road driving conditions, random time signals were obtained, which are mathematically averaged and analyzed to obtain a picture of the measured system and the individual elements in it, as well as to assess possible damage and failures.

3. RESULTS

The measurements carried out on the test roads were performed for all gears, but in this paper the results are presented for third gear, which is used most frequently during intensive driving tests under off-road conditions within 20000 km.

First, the initial measurement was taken, at the beginning of the test to determine the initial value of the signal for future comparisons and trends. The signal analysis (frequency and order analysis [18]) provides the results of the research, which is the fourth phase of the vibration diagnostic method.

Some characteristic frequencies for the third gear ratio of the gearbox are:

- 340 Hz, the I-order gear mesh frequency of the third gear ratio, i.e. the gear frequency of the third gear (G_m);
- 15.45 Hz, the I-order frequency of the intermediate gearbox shaft around 927 rpm
  (927 rpm / 60 = 15.45 Hz);
- 10.6 Hz, the I-order frequency of the output gearbox shaft around 637 rpm (637 rpm / 60 = 10.6 Hz) and its second harmonic at 21 Hz;
- around 633.4 Hz, the I-order frequency of the coupling of the gears in a constant engagement.

Fig. 6 shows the acceleration signal over time, recorded by sensor number 1 (accelerometer 1). Fig. 6 shows the dependence of the acceleration value in m/s^2 (0Y axis) and the time in seconds (0X axis). This shows that the amplitude of the acceleration is around the value of 70 m/s^2.

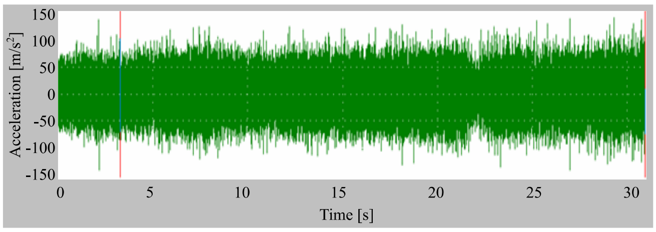

Fig. 6. The acceleration signal over time, for third gear ratio, accelerometer 1.

The frequency spectra of the signals from sensors 1 and 4 are shown in Fig. 7 and Fig. 8, with the signal from sensor 1 shown in red and the signal from sensor 4 in blue. The frequency spectrum of the signal in Fig. 7 and Fig. 8 can be matched when analyzing the gear elements of the gearbox (frequencies up to 2000 Hz), so that either the signals recorded by sensor 1 or sensor 4 can be used to analyze the condition of the gearbox. Both the signals from sensor 1 and sensor 4 are used to analyze the condition of the third gear ratio of the vehicle transmission.

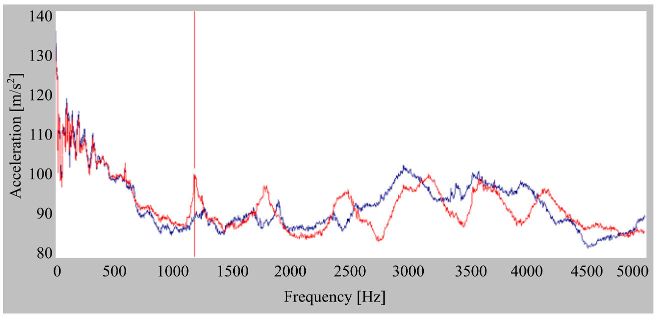

Fig. 7. Frequency spectrum, sensors 1 and 4.

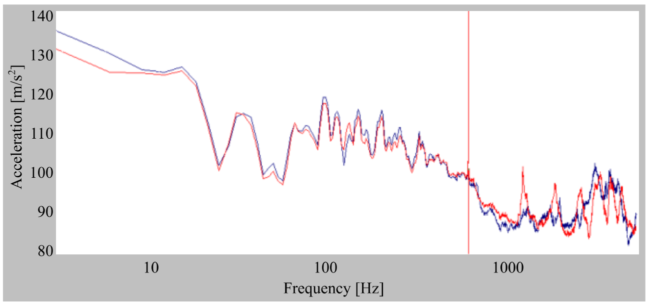

Fig. 8. Logarithm of frequency spectrum, sensors 1 and 4.

Fig. 9 shows the dependence of the RMS value of the signal in m/s^2 (on the 0Y axis) on the frequency in Hz (on the 0X axis) of sensor 4. The harmonics of the gear mesh frequency of the gear in the third gear ratio in Fig. 9 show that the first harmonic of the gear mesh of the gear in the third gear ratio is dominant in its amplitude in relation to others.

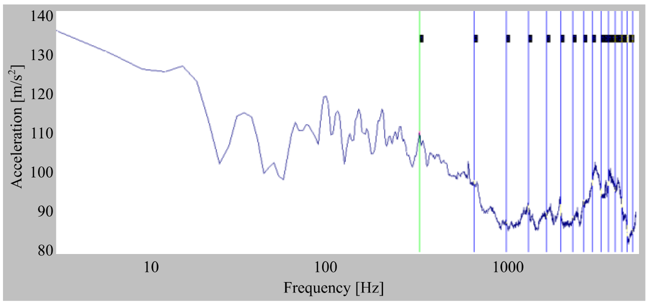

Fig. 9. Logarithm of the harmonics from gear mesh frequencies.

The 15 harmonics of the gear mesh frequency of the gear in the third gear ratio in Fig. 9 are shown in tabular form in Table 2.

Table 2. Third gear harmonics of conjunction frequency values.

Harmonic	Frequency [Hz]	Level [m/s^2]
1	318.8	110.1
2	637.5	96.9
3	956.3	87.0
4	1275.0	90.5
5	1593.8	88.6
6	1912.5	90.2
7	2231.3	88.0
8	2550.0	93.0
9	2868.8	97.9
10	3187.5	95.1
11	3506.3	97.0
12	3825.0	95.5
13	4143.8	93.1
14	4462.5	85.3
15	4781.3	85.2

Fig. 10 shows the dependence of the RMS value of the signal in m/s^2 (on the OY axis) on the frequency in Hz (on the OX axis) for the intermediate shaft and the harmonics of the intermediate shaft speed are presented. Fig. 11 shows the dependence of the RMS value of the signal in m/s^2 (on the OY axis) on the frequency in Hz (on the OX axis) for the output shaft and the harmonics of the frequencies of the input shaft speed of the gearbox.

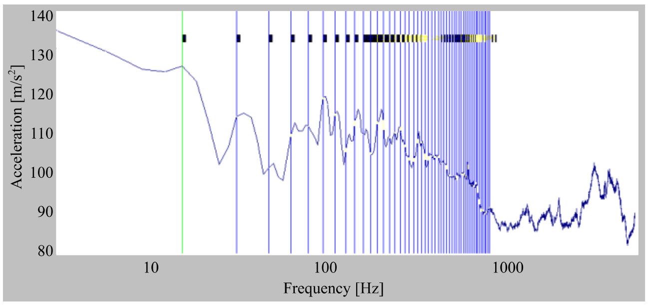

Fig. 10. Intermediate shaft speed harmonics.

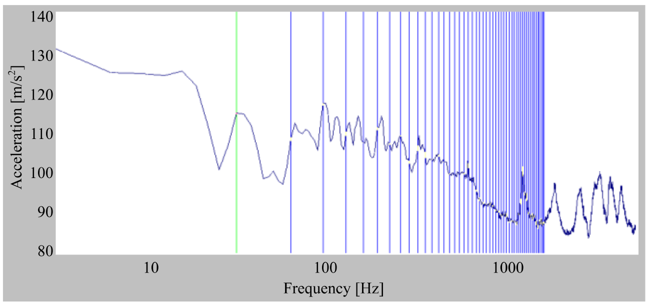

Fig. 11. Input shaft speed harmonics.

Fig. 12 shows the dependence of the RMS value of the signal in m/s^2 (on the OY axis) on the frequency in Hz (on the OX axis), with the harmonics on the gear mesh frequency of the permanent gears.

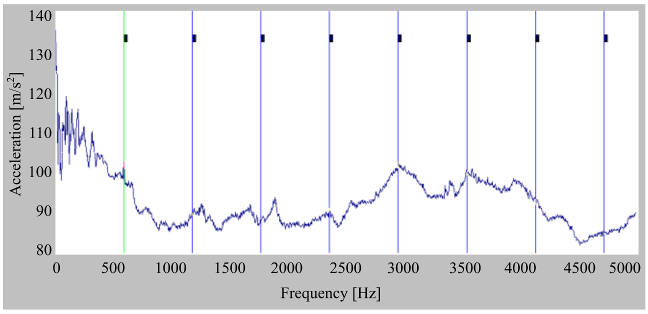

Fig. 12. Harmonics of the gear mesh frequency of permanent gears.

From the previous frequency spectrum diagrams (Fig. 9, Fig. 10, Fig. 11 and Fig. 12), it can be concluded that all peaks in the spectrum are characterized and identified as harmonics of the gear mesh frequency of the gearbox in third gear, as well as the intermediate shaft speed harmonics, the input shaft harmonics and the gear mesh frequency of the permanent gears. The peaks in the signal are identified as harmonics of a characteristic frequency for the third gear ratio of the gearbox. The fundamental frequency of the third gear ratio is dominant in relation to the other harmonics. The equidistant sidebands are found and identified around the gear mesh frequency of the third gear ratio at the distance of the gearbox input shaft frequency from the gear mesh frequency of the third gear ratio (Fig. 13). The sidebands were not observed at the second harmonic of the third gear mesh frequency. Considering that the first coupling harmonic has a dominant amplitude in relation to the others and that there are sidebands around it, tooth wear can be suspected.

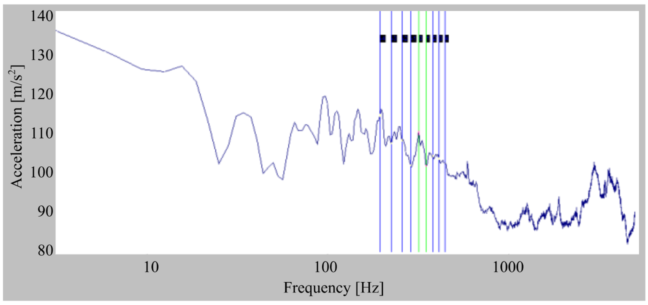

Fig. 13. Sidebands around the third gear mesh frequency.

Table 3 contains numerical data on the sidebands identified around the third gear mesh frequency.

Table 3. Sideband level around the gear mesh frequency of the third gear ratio.

Harmonic	Frequency [Hz]	Level [m/s^2]
-4	318.8	110.1
-3	637.5	96.9
-2	956.3	87.0
-1	1275.0	90.5
0	1593.8	88.6
1	1912.5	90.2
2	2231.3	88.0
3	2550.0	93.0
4	2868.8	97.9

The waterfall diagram in Fig. 14 shows the RMS value of the signal in m/s^2 (on the OZ axis) from the frequency in Hz (on the OX axis) and the time in seconds (on the OY axis), showing the dependence on the third gear mesh frequency and its harmonic. In the same figure, a drop in signal energy can be seen after the gear mesh frequency of the third gear ratio.

After the initial measurements, the vehicle was further tested on the test road after an intensive drive of 10000 km (test 1), whereupon the second measurement of the vibrations on the gearbox was performed.

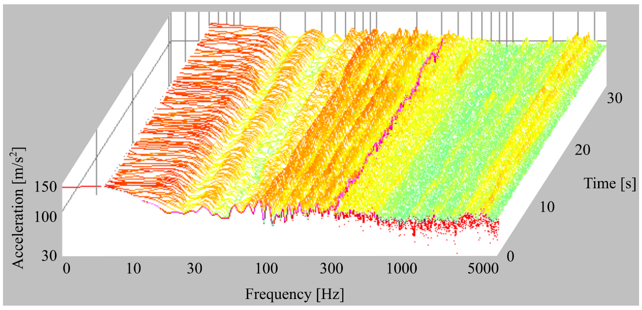

Fig. 14. Waterfall diagram of the signal from sensor 4.

Fig. 15 shows the dependence of the accelerations in m/s^2 (on the 0Y axis) and the time in seconds (on the 0X axis) of sensor 1 in the third gear ratio. This shows that the acceleration is around 70 m/s^2.

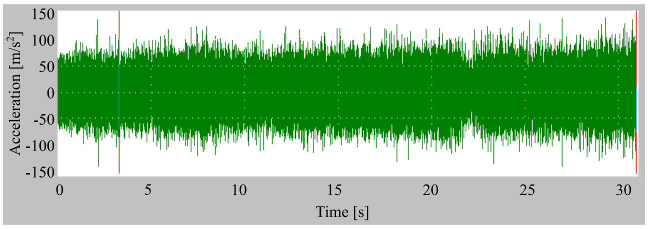

Fig. 15. The acceleration signal over time, third gear ratio, sensor 1, test 1.

Fig. 16 shows the logarithmic representation of the RMS value of the signal in m/s^2 (on the OY axis) from the frequency in Hz (on the OX axis) of sensors 1 and 4. A logarithmic representation of the frequency spectra of the signals recorded by sensors 1 and 4 in Fig. 16 shows that the recorded signals almost overlap, up to a frequency value above 2000 Hz, which is in the range of the bearing diagnostic. The purple color is a signal from sensor 1 and the blue color is signal from sensor 4.

Fig. 17 shows the logarithmic representation of the RMS value of the signal in m/s^2 (on the OY axis) from the frequency in Hz (on the OX axis) of sensor 1. It can be seen that the first harmonic of the gear mesh frequency in third gear is again dominant in relation to the other peaks in the signal, with a small increase in signal level at the second harmonic of the gear mesh frequency in the constant coupling on the intermediate shaft. In addition, there are sidebands around the third gear clutch frequency that are removed by the value of the input shaft frequency (Fig. 18).

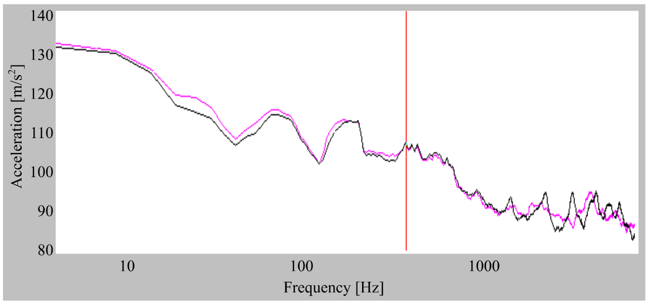

Fig. 16. Comparative logarithmic representation of the frequency spectrum, sensors 1 and 4.

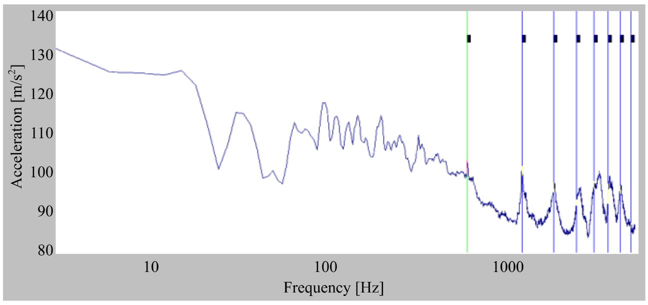

Fig. 17. Gear coupling frequency harmonics in constant coupling on the intermediate shaft.

Fig. 18, like Fig. 17, shows the logarithmic representation of the RMS value of the signal in m/s^2 (on the OY axis) from the frequency in Hz (on the OX axis) of sensor 1, where we can observe sidebands around third gear ratio mesh frequency. In addition to the data from Fig. 17, there are sidebands around the first harmonic of the third gear mesh frequency, which is removed by the value of the input shaft frequency.

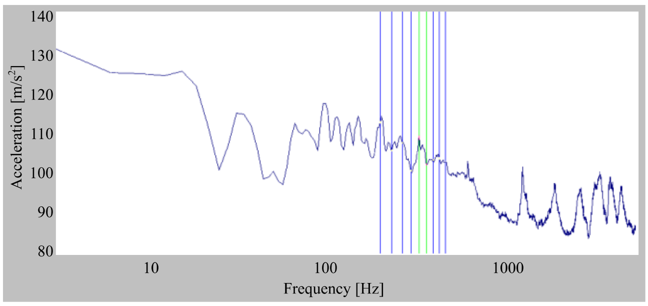

Fig. 18. Sidebands around the gear mesh frequency.

The waterfall diagram (Fig. 19) shows the RMS value of the signal in m/s^2 (on the OZ axis) from the frequency in Hz (on the OX axis) and the time in seconds (on the OY axis) of sensor 1. The harmonics of the gear mesh frequency are clearly visible on the waterfall diagram in Fig. 19. It can also be seen that the energy of the signal is slightly lower compared to the initial measurements (Fig. 14). The conclusion after the measurement in test 1 is that there are no critical faults and damage to the gears in third gear, so that only monitoring of the vibrations in the subsequent measurements is necessary.

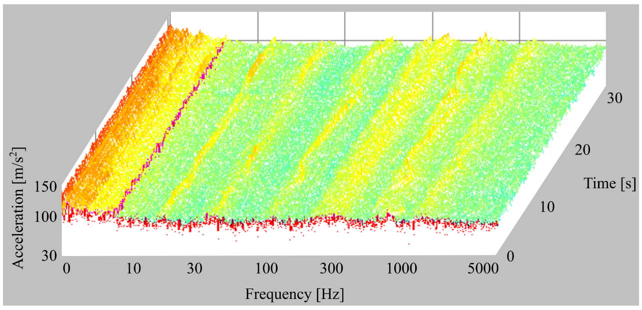

Fig. 19. Waterfall diagram, sensor 1, test 1.

After the above measurements, the tests of the vehicle under driving conditions were continued and after another 10000 km (test 2), the next measurement of the vibrations on the vehicle gearbox was carried out. Fig. 20 shows the dependence of the accelerations in m/s^2 (on the 0Y axis) and the time in seconds (on the 0X axis) of sensor 1 in third gear.

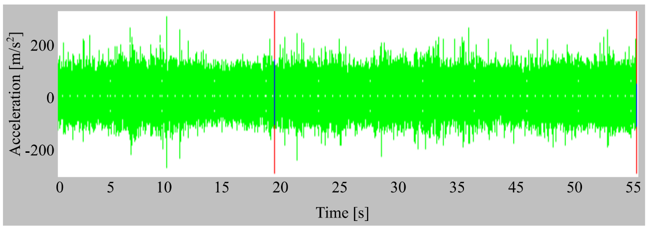

Fig. 20. Acceleration signal in time, sensors 1.

The signal of acceleration in time (Fig. 20) shows that the level of amplitude of the signal recorded by sensor 1 is at the level of the previous measurements, shown in Fig. 6 and Fig. 15.

Fig. 21 shows the logarithmic representation of the RMS value of the signal in m/s^2 (on the OY axis) from the frequency in Hz (on the OX axis) of sensor 1 and sensor 4, where the signal from test 1 is colored blue and the signal from test 2 is colored purple.

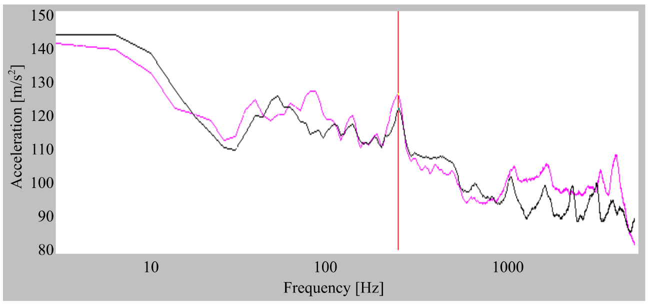

Fig. 21. The logarithm of the frequency spectrum, sensors 1 and 4, test 2.

The logarithm of the frequency spectrum (Fig. 21) of sensors 1 and 4 shows that the first harmonic of the gear mesh frequency of the third gear ratio is still dominant compared to the other harmonics, with although this time there are no sidebands around the harmonics of the gear mesh frequency of the third gear ratio in the signal.

The conclusion after all measurements (initial, test 1 and test 2) is that there are still no critical faults and damage to the gears in third gear, so that only monitoring of the vibrations in the subsequent measurements is necessary until clear levels and peaks in the signals are defined that indicate problems with the gears in third gear.

4. DISCUSSION

After all measurements (initial, test 1 and test 2), the signals recorded after 10000 km and 20000 km were compared and discussed. Fig. 22 shows the logarithmic representation of the comparative RMS value of the signals from sensor 1 after test 1 and test 2 in m/s^2 (on the OY axis) from the frequency in Hz (on the OX axis), with the signal from test 1 in blue color and the signal from test 2 in red color.

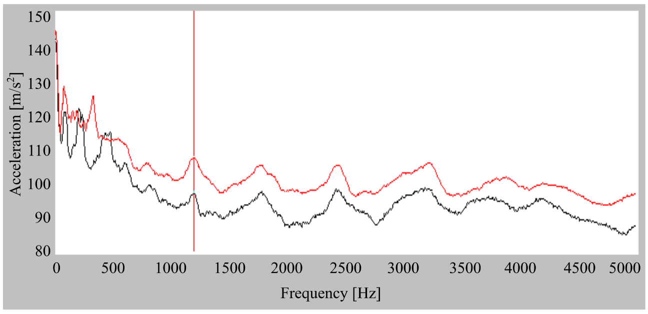

Fig. 22. Comparative frequency spectrum, test 1 and test 2, sensor 4.

The comparative frequency spectrum of the signals recorded in tests 1 and 2 (Fig. 22), measured with sensor 4, shows that the signal levels in test 2 are slightly higher than the signal levels after test 1, which is to be expected after heavier use. The signals themselves are quite similar in appearance and values. The signal coincidence in the range around 300 Hz is noticeable and there is an increase in signal level in the range of the first harmonic of the third gear mesh frequency, by about 10 % in the peak value. There is no higher signal level in test 1 compared to the signal in test 2. Sidebands identified after initial measurements (Fig. 13) and test 1 (Fig. 18) are not present in the signal recorded in test 2, at sensors 1 and 4. All this leads to the conclusion that the gears in third gear were gearing-in during the first 20000 test kilometers and that we recorded a signal characteristic for gearing-in of the gears in test 1. This can be found in a new gearbox such as this one. The frequency spectrum signal levels (Fig. 16, Fig. 18 and Fig. 21) show that the first harmonic of the third gear mesh frequency is dominant in all measurements, with sidebands around the harmonics of the gear frequency of the third gear ratio in the signal after the initial measurement and test 1 (Fig. 13 for the initial measurement and Fig. 18 for test 1) and without sidebands around the gear frequency. This supports our assertion that the gearbox was in the state of gearing-in and that we will not need to carry out any further maintenance work on the gearbox gears in the future, only regular monitoring.

The final inspection of the vehicle gearbox was carried out after 20000 km of intensive driving (Fig. 23 and Fig. 24). During the final inspection, the gearbox was removed from the vehicle. A more detailed analysis of the gearbox and the disassembly of the gearbox down to the level of the gears was tackled. There were surface marks on the gears themselves, i.e. on the teeth of the gears, which had been formed by the gearing-in of the gears and the gear meshing. After gearing-in, there was a clear demarcation, i.e. the contact line between two teeth during coupling (Fig. 22 and Fig. 23). No broken or damaged gear tooth or gear surface was found.

This phenomenon confirms the previous assertion that the measurement was carried out in the initial phase of the vehicle life cycle. Various phenomena were recorded in third gear, such as a dominant first and second harmonic and sidebands in third gear, etc., indicating initial wear of the gear teeth due to mutual gearing-in and slight deviations from the required tool geometry in the manufacture of the gears. In the measurements after 10000 km of driving, the energy of the vibration signal decreases and the vibration levels calm down as the teeth run into each other and dissipate and after 20000 km the energy of the signal begins to increase, as expected, as a result of regular operation of the vehicle.

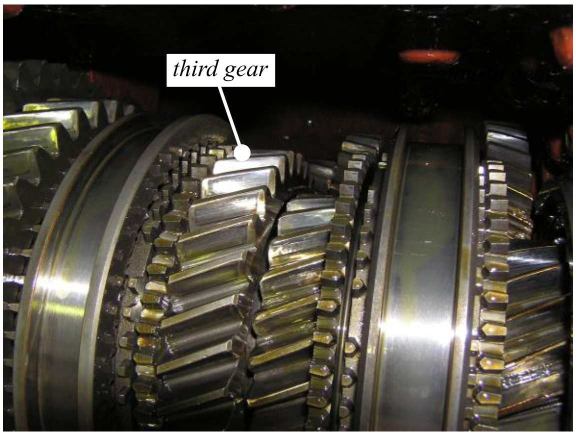

Fig. 23. The gear in third gear ratio of the gearbox on the output shaft.

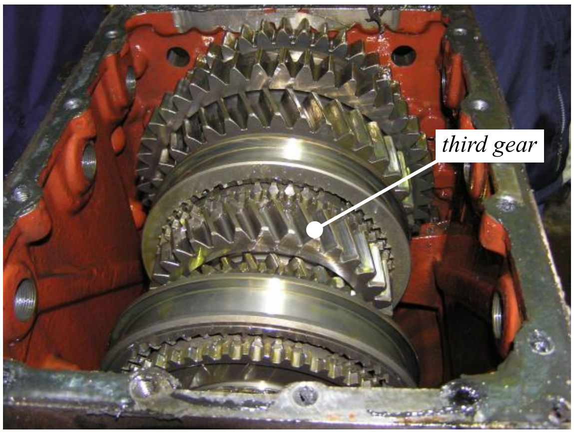

Fig. 24. The gear in third gear ratio of the gearbox after tests.

The general conclusion after all analyses is that no additional maintenance of the gearbox in third gear is required at this stage of use, only monitoring of the vibration levels in the vehicle gearbox in the future. This confirms the initial theory that vibration diagnostics can be used to determine the condition of the transmission in the vehicle gearbox, if the measurements are carried out under real operating conditions and real loads, under these specific test conditions.

5. Conclusions

Vibrations are unavoidable in vehicles. The vibrations that we usually cannot see are non-linear vibrations in vehicle assemblies such as the gearbox, which are a result of shaft rotation. The original idea of this paper was to investigate whether vibration diagnostics, as a non-destructive method, can be used to monitor and determine the condition of the gears in a vehicle gearbox under real operating conditions of a vehicle without having to remove the gears from the gearbox.

This paper presents that with some initial conditions for the measurement, we can measure the vibrations in the vehicle gearbox with a universal measurement equipment under real operating conditions, using the vehicle as a special test rig. This form of field test is used in this case as a tool for determining the condition of the gears in the vehicle gearbox, but is also used in other forms in other areas of vehicle field testing, particularly in the testing of off-road vehicle. All measurements are performed under real operating conditions, as this was one of the objectives of the paper, namely to determine the appropriate speed of the vehicle engine based on the calculation of the towing process of a vehicle and same test road conditions for the measurement. With these initial conditions, we have the repeatability of the test, and the comparability of the measurements, which is important to draw conclusions from the vibration diagnosis. The problem of variable load conditions in the gear meshing is solved with the proposed method, making the data usable for the investigation. This approach also does not increase the vehicle testing time, as only some time is needed to set up the measurements in the vehicle's gearbox, which is much less than the time needed to remove the gearbox and test it on a dedicated test desk. The problem of little extra time can be solved in the future if the sensors are installed during the production of the vehicle and the data is then monitored and analyzed in real time with the vehicle PC unit.

By analyzing the measured data in the vehicle gearbox, we came to the conclusions about the condition of the gears in the gearbox in third gear without removing the gears from the gearbox, which is the main benefit of using the vibration diagnostics as a non-destructive tool for the monitoring of the condition of gears in the vehicle transmission. All conclusions we drew about the condition of the gears were confirmed after all the measurements when we removed the gearbox and removed the gears. We can confirm our conclusions based on the vibration diagnostics that gears were gearing up at the given time of the investigation, as the marks on the gears are typical of this phenomenon.

The work confirms the use of vibration diagnostic tools in determining the condition of the gears in vehicle transmissions of off-road vehicles, applying the proposed method in the field test with the vehicle as a test rig and under the proposed measurement conditions.

Future work in this area will go in several directions. One of these is to attempt to use the same tools to determine the condition of other mechanical components of the gearbox, such as the condition of gearbox shafts and gearbox bearings. This data, together with the conclusions about the condition of gears will lead to a complete diagnostic method for gearbox components that uses vibration diagnostics to determine conditions of the gearbox elements and perform tests under real operating conditions and on the vehicle used as a test desk. The second direction is the use of vibration diagnostics together with artificial intelligence, which can monitor the data and perform real-time analysis to draw timely conclusions about the condition of the gearbox gears and prevent failures. The third direction is the use of vibration diagnostics as a tool in today's electronic vehicle control units (ECU) to determine the condition of the vehicle's transmission gears. Even though vibration diagnostics is used in various tests of assemblies with rotating parts, the measurement approach presented in this paper provides another solution for testing, not only in vehicle gearbox testing and vehicle gearbox research, but also in conducting various tests of mechanical gear reducers or multipliers used in various industries, as well as in some forms of field tests in which gears operate with variable loads.

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