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A contribution to investigation of oscillatory loads of driving axles in order to create conditions for laboratory tests of trucks

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Abstract: Motor vehicles are complex dynamic systems due to spatial vibratory displacements during movement, changes in the characteristics of components during life cycle, a large number of influences and disturbances, the occurrence of clearance, friction, hysteresis, etc. The mentioned dynamic phenomena, especially vibrations, cause fatigue of the driver and passengers, reduce the life cycle of the vehicle and its systems, etc. In the general case, the movement of motor vehicles is done on uneven roads (terrain) and curvilinear paths in flat roads (terrains). Oscillatory movements cause loading of vehicle parts, but they also negatively affect human health. Therefore, even in the design phase of the vehicle, special attention must be paid to the harmonization of the mutual movement of the vehicle subsystem, and in particular, the suspension system. Theoretical, experimental or combined methods can be used for this purpose, and it is very useful to have experimental results of vibration of the vehicle subsystems in real operational conditions. Therefore, it is very useful to have experimental results of vibration of vehicle subsystems in operational conditions. Bearing that in mind, the aim of this wpaper was to use the movement of FAP 1118, 4x4 wheel formula, in operational conditions (due to higher speeds - in road conditions) to define laboratory conditions for testing. This is made possible by registering and identifying statistical parameters of registered quantities.

Keywords: *Motor vehicle, axles, oscillatory loads, laboratory tests*.

1. Introduction

Motor vehicles are complex dynamic systems due to spatial vibratory displacements during movement, changes in the characteristics of components during life cycle, a large number of influences and disturbances, the occurrence of clearance, friction, hysteresis, etc. [1-12]. The mentioned dynamic phenomena, especially vibrations, cause fatigue of the driver and passengers, reduce the life cycle of the vehicle and its systems, etc.

In the general case, the movement of motor vehicles is done on uneven roads (terrain) and curvilinear paths in flat roads (terrains). Oscillatory movements cause loading of vehicle parts, but they also negatively affect human health [1-3, 11]. Therefore, even in the design phase of the vehicle, special attention must be paid to the harmonization of the mutual movement of the vehicle subsystem, and in particular, the suspension system [12]. Theoretical, experimental or combined methods can be used for

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this purpose, and it is very useful to have experimental results of vibration of the vehicle subsystems in real operational conditions.
The road (terrain) can be identified on the basis of its spatial geometry (macro relief) and micro-roughness (micro relief) [13-16]. The movements of the vehicle subsystem are conditioned, in first, by the shape and size of the unevenness, as an external factor and oscillatory-inertial characteristics, engine torque and vehicle velocity, as phenomena related to the vehicle itself. Based on that, it can be stated that careful research and definition of micro-roughness characteristics of roads on which vehicles move, both in terms of periodicity characteristics and in terms of energy levels, development and automation of roughness measurement and mathematical apparatus for processing data, contribute to reliability, optimality and safety of the construction of the vehicle itself. As the description of the road parameters and their identification are described in detail in [1-16], they will not be elaborated here…
As it is known [17], in laboratory conditions, reproductions of signals registered in operation can be performed on shakers. Therefore, the aim of this work was to establish the oscillatory movements of axles in operating conditions (when driving in road conditions), FAP 1118 vehicle, in order to create conditions for laboratory testing.

2. Experiment

Desing of experiment is a complex problem [17]. In this particular case, the subject of research is a vehicle FAP 1118, with 4x4 drive formula and load capacity of 4t. The maximum mass of the test vehicle is 11000 kg, and during the test the vehicle was partially loaded (total mass 7800 kg - static load of the front axle was 4200, and the rear 2850, daN). The test truck vehicle is equipped with hydraulic servo steer and classic suspension systems with leaf springs. The roll axe is located, approximately, between vehicle axles and the pins of leaf springs (high 435, mm from ground).
The measuring chain for measuring the dynamic parameters of the vehicle consisted of the following elements:

- Kistler Correvit S-350 sensors for direct, slip-free measurement of longitudinal and transverse vehicle dynamic,
- HBM Quantum MX 840B universal measuring acquisition system connected to a QuantumX CX22B-W computer,
- B-12 acceleration sensor, located in the center of gravity of the rear truck bridge,
- SST 810 dynamic inclinometer, placed in the center of gravity of vehicle axles. With it, angle, velocity and acceleration was measured around the X, Y and Z axes.

All measured quantities are being processed by using HMB Catman easy software.
The scheme of measuring points is given in Figure 1.

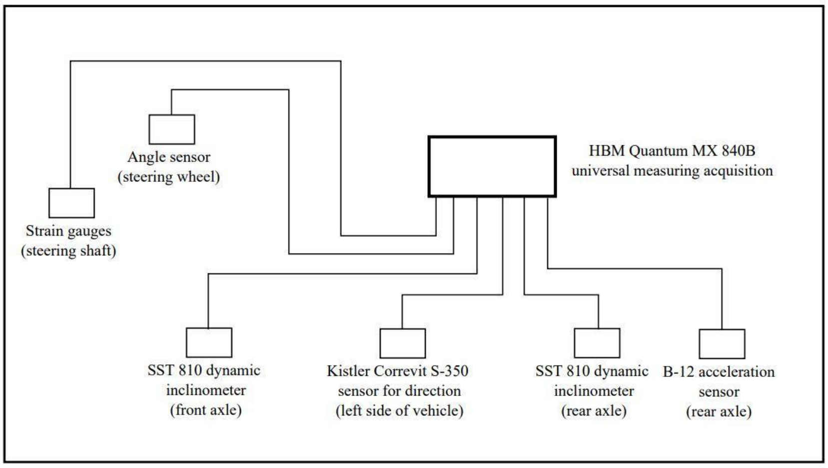

Figure 1. The scheme of measuring points during the FAP 1118 road test

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Based on previous experiences at the Military Academy, it was considered expedient to test the vehicle while driving in real operational conditions, on an asphalt regional road near Belgrade (maximum speed, 67 km/h – design vehicle limited speed 80 km/h). During the experiment, the weather was sunny and the surface was dry. The length of the time records was 260 s (13000 points, and the sampling step was 0.02 s).
For illustration, Figures 2 - 4 show the time histories of vehicle velocity and the oscillatory movements of the front drive axle.

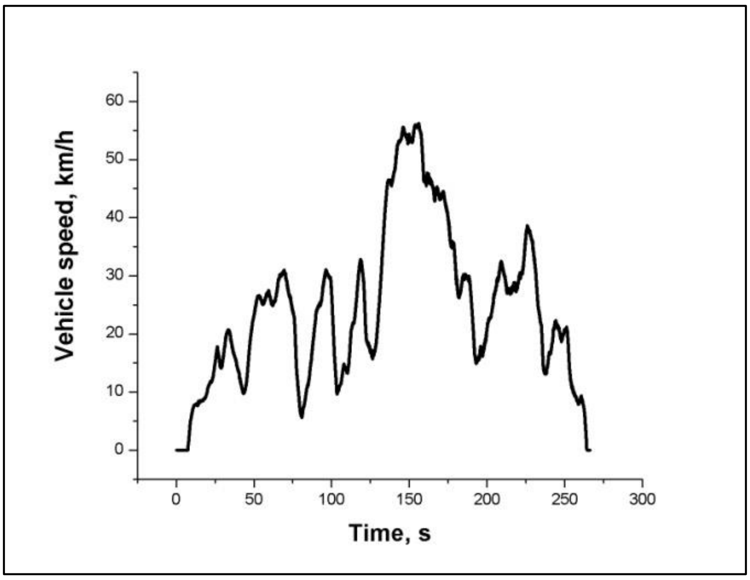

Figure 2. Vehicle velocity change during drive

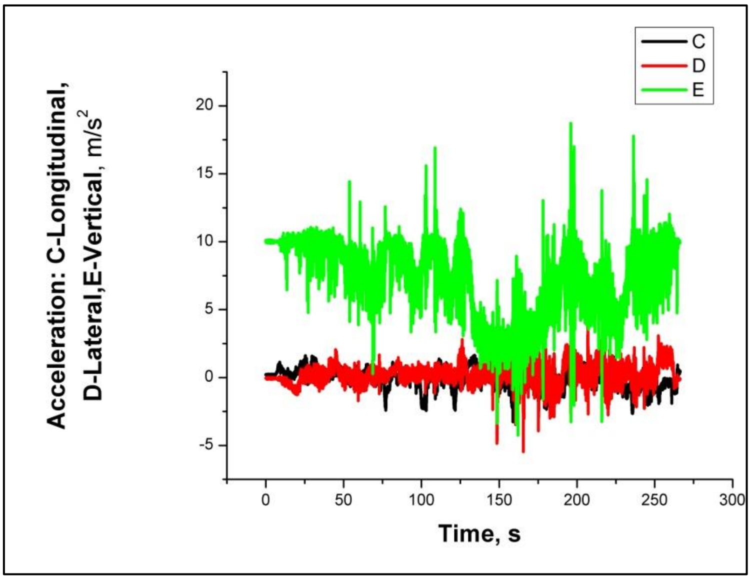

Figure 3. Longitudinal, lateral and vertical acceleration of the vehicle's front drive axle

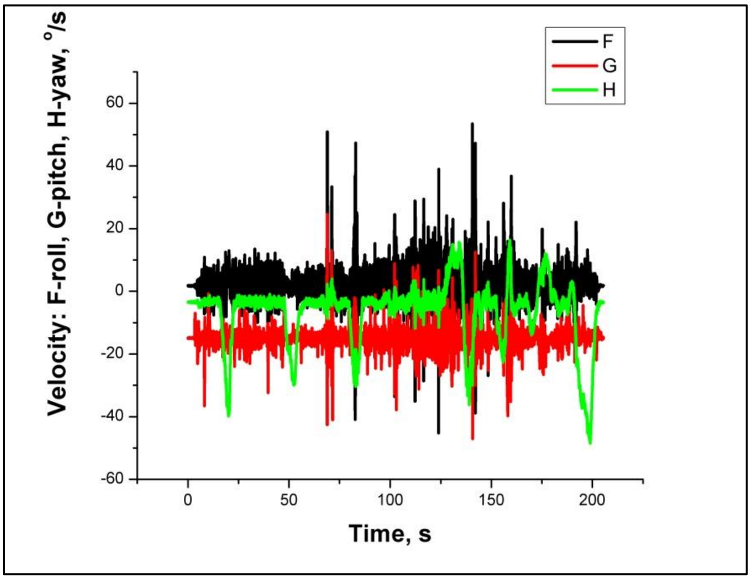

Figure 4. Roll, pitch and yaw velocity of vehicle's rear drive axle

Figures 2 – 4 shows that the registered parameters of oscillatory motions of drive axles depend on time. The registered accelerations and angular velocities of the front and rear drive axles belong to the group of random processes [18]. There are a number of methods for processing such signals [18] and we will use some of them in this paper.

3. Signal processing and data analysis

Having in mind the random character of the registered values, it was considered expedient to calculate: mean, RMS, minimum and maximum value of all registered oscillatory values. For this purpose, the software Analsigdem [19] was used, and the values given in Tables 1 and 2.

Table 1. The statistical parameters of front axle vibration

Measured parameters	Min.value	Max.value	Mean value	RMS
Vehicle velocity, km/h	0.0	61.7	31.2	34.9
Longitudinal acceleration, m/s^2	-3.2	1.64	-0.0039	0.67
Lateral accelerations, m/s^2	-5.45	5.61	0.15	0.70
Vertical acceleration, m/s^2	-4.24	18.7	7.34	7.86
Roll velocity, o/s	-48.1	54.1	2.2	4.1
Pitch velocity, o/s	-16.6	18.6	1.0	2.3
Yaw velocity, o/s	-32.6	20.2	-2.3	7.4

Table 2. The statistical parameters of rear axle vibration

Measured parameters	Min.value	Max.value	Mean value	RMS
Vehicle velocity, km/h	0.0	61.7	31.2	34.9
Longitudinal acceleration, m/s^2	-8.8	5.0	0.3	1.1
Lateral acceleration, m/s^2	-4.7	7.5	0.2	0.9
Vertical acceleration, m/s^2	-10.1	31.9	9.65	9.8
Roll velocity, °/s	-45.1	53.4	1.9	5.8
Pitch velocity, °/s	-47.0	24.5	-14.8	15.2
Yaw velocity, °/s	-48.4	16.3	-6.4	11.9

By analyzing the data from Tables 1 and 2, it can be concluded that there are differences in the oscillatory movements of the front and rear axles in operating conditions. As the differences are not unambiguous, additional analyzes are needed.
In order to determine the character of the registered signals, using the same software [19], autocorrelation functions were calculated and shown in Figures 5-8.

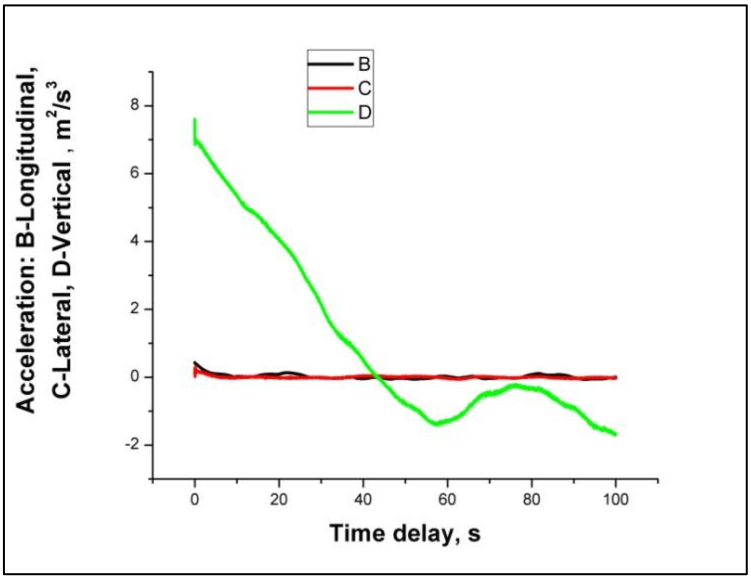

Figure 5. Autocorrelation function of longitudinal, lateral and vertical acceleration of the front axle

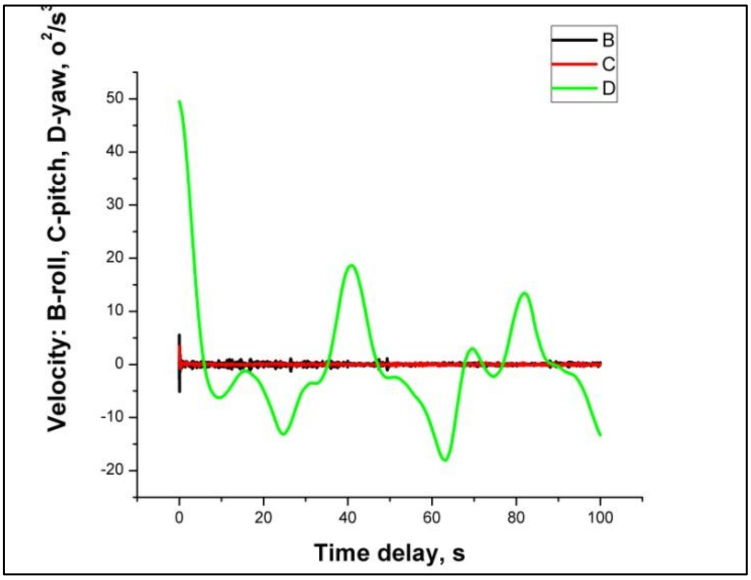

Figure 6. Autocorrelation function of roll, pitch and yaw velocity of vehicle's front drive axle

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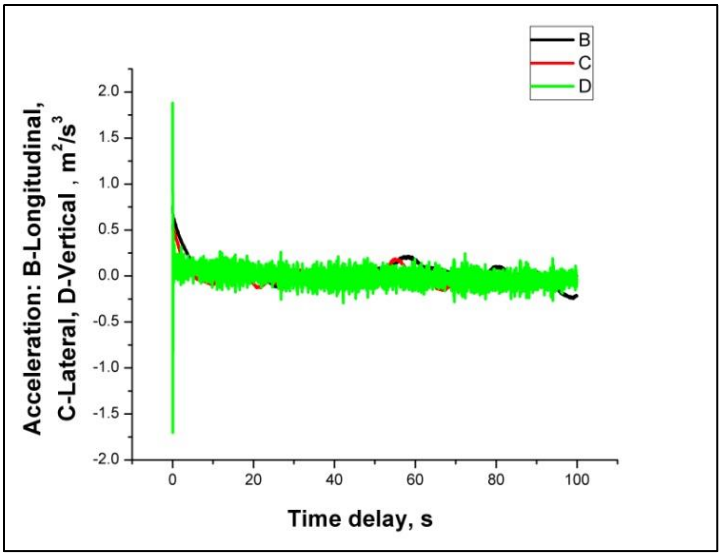

Figure 7. Autocorrelation function of longitudinal, lateral and vertical acceleration of the rear axle

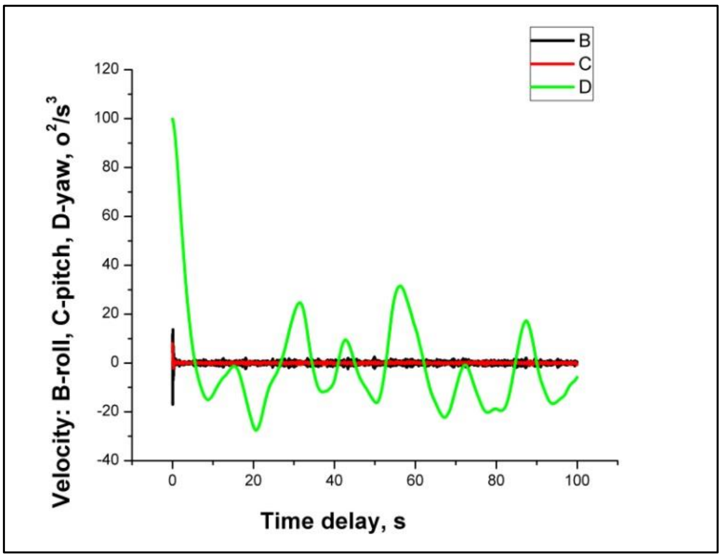

Figure 8. Autocorrelation function of roll, pitch and yaw velocity of vehicle's rear drive axle

Analysis of all data, partially given at Figures 5-8. shows that autocorrelation functions decrease with increasing time delay and that they oscillate slightly around zero. This points to the fact that registered oscillatory values can be treated as stationary [18].

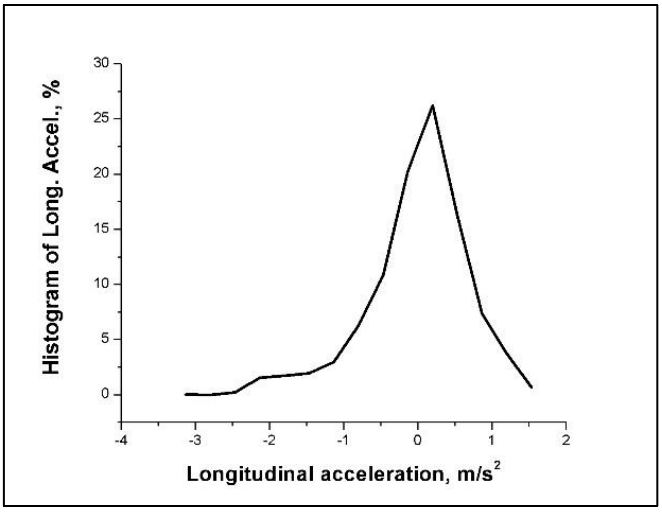

Figure 9. Front axle longitudinal acceleration distribution histogram

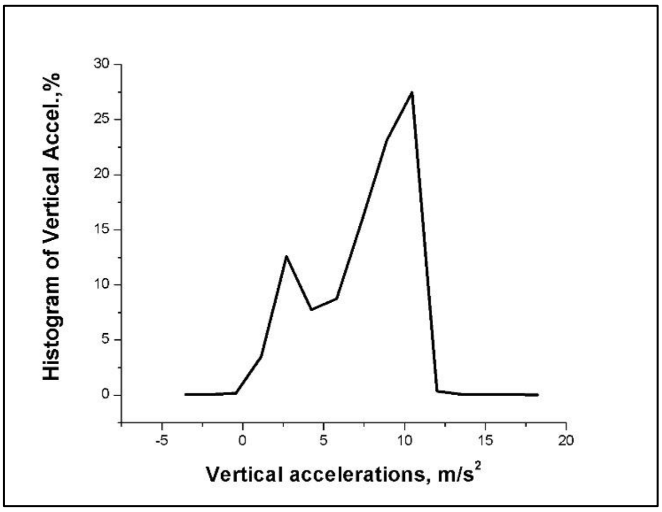

Figure 10. Front axle vertical acceleration distribution histogram

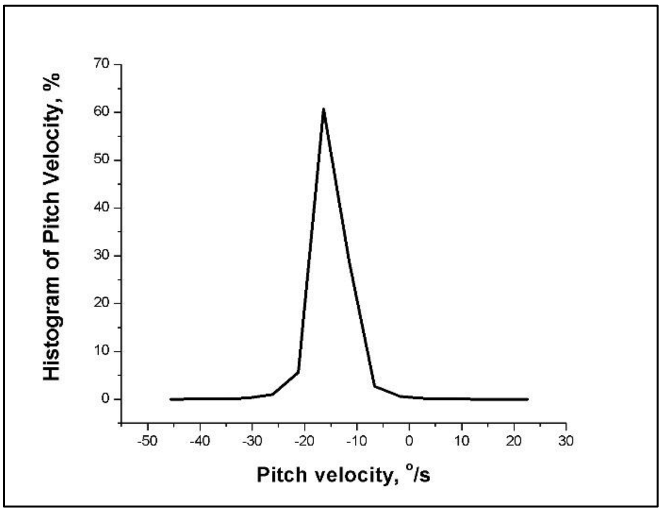

Figure 11. Rear axle distribution of the pitch velocity histogram

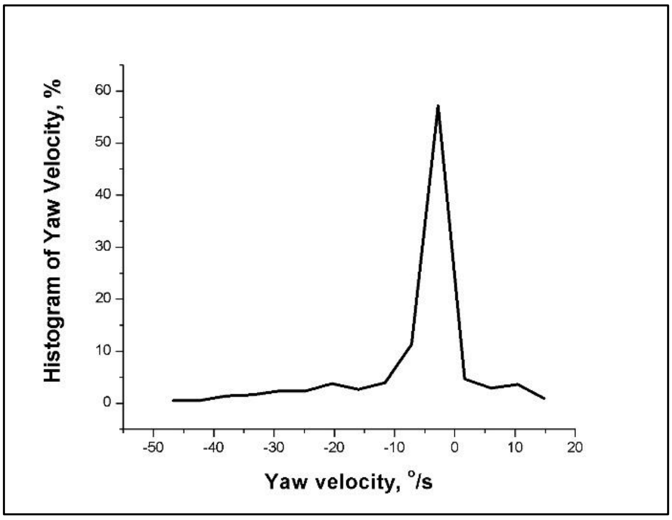

Figure 12. Rear axle yaw velocity distribution histogram

It was considered interesting to perform amplitude analysis of all registered parameters [18-20]. More precisely, the probability of occurrence of the observed values by levels (histogram, %) was calculated, using the software [19]. First, the minimum and maximum value of each variable, in 13000 points, was calculated using the aforementioned software. Then the interval between those values was divided into 500 fields and the number of occurrences of the variable within the limits for each field was automatically determined (histogram, %). The calculated values are, for the sake of illustration, partially shown in figures 9-12.

By analyzing the histogram of all registered values, it was observed that the maximum values are close to the domain of mean values. Bearing that in mind, it was assessed as relevant to test all data for normality, using the so-called „Null hypotheses" (from statistics known as „Normality test") [20].

The „Normality test" consists of comparing the mean value of the distribution of the registered data with a data that has a normal distribution and an infinite number of members. In this case, the mentioned test was implemented with a risk of 5%, using the Origin 8.5 software [21].

More precisely, using that software, the analysis of the correctness of the adopted null hypothesis (in this case for the mean value of 0) was performed for all measured values. It was found that there is a significant difference in the mean values, so the hypothesis cannot be accepted unconditionally.

Having that in mind, it was estimate useful to use the so-called $\chi 2$ test [20], which is defined as:

$$\chi^2 = \sum_{1}^{N} \frac{(f_i - f_{ti})^2}{f_{ti}} \tag{1}$$

where are:

f_i - frequencies of i-th class;

f_{ti} – theoretical frequency of i-th class;

N-number of classes.

In [20], a simple and reliable test, known as the „Romanovsky test", was especially recommended.

The criterion is defined by expression:

$$R = \frac{|\chi^2 - k|}{\sqrt{2k}} \tag{2}$$

where:

$$k = N - L - 1 \tag{3}$$

In expression (3), N is the number of additions in (1), and l is the number of unknown parameters in the assumed probability distribution. If R<3 the hypothesis is accepted, and for R>3 the hypothesis is rejected.

Bearing in mind that the mean values are not always positive, it was considered useful to perform hypothesis tests with Gaussian, Laplace and Cauchy distributions [20]. Previously, on the basis of experimental and theoretical distribution functions, using the method of minimizing the square of the difference, the parameters of the territorial distributions were identified (this procedure is known from [12], so it will not be discussed further). Analyzes have shown that the assumed probability density functions do not meet the Romanovsky criterion, so they do not belong to any of the observed distributions.

With this in mind, it was considered useful to show in Tables 3 and 4 the mean values of the observed values and the maximum density of probability of occurrence by levels.

Table 3. Front axle

Measured parameters	Mean value	Maximum prob. density, %
Longitudinal acceleration, m/s^2	0.20	26.24
Lateral acceleration, m/s^2	0.10	52.71
Vertical acceleration, m/s^2	8.90	23.13
Roll velocity, °/s	3,01	87.32
Pitch velocity, °/s	1.01	63.30
Yaw velocity, °/s	-2.41	59.90

Table 4. Rear axle

Measured parameters	Mean value	Maximum prob. density, %
Longitudinal acceleration, m/s^2	0.90	35.11
Lateral acceleration, m/s^2	-0.25	37.92
Vertical acceleration, m/s^2	10.75	55.75
Roll velocity, °/s	4.01	53.87
Pitch velocity, °/s	-16.36	60.74
Yaw velocity, °/s	-2.80	57.23

The data from Tables 3 and 4 can be used when generating schaker excitations, during vehicle testing in laboratory conditions.

For practical reasons, it can be argued that, in the vehicle design phase, it is acceptable that the registered quantities belong to the Gaussian distribution.

Frequency analysis was performed using the Analsigdem software [19] with 8192 points and a sampling step of 0.02 s, which enabled reliable analysis in the range 0.061 to 25 Hz [18] (the DC components are turned of for frequency analysis).

Analysis of random and bias errors, for the number of data used, showed that a sufficient number of averaging of 100 for one signal and 138 for two signals, which achieves a minimum reliable frequency of 0.049 Hz (this is acceptable in this case, because it is lower than those obtained on the basis of signal length [18]). Having in mind that the phases of the calculated spectra do not enable the analysis of the energy carried by the signal, it was considered expedient to observe only the magnitudes of the calculated spectra, which are shown in Figures 13-16.

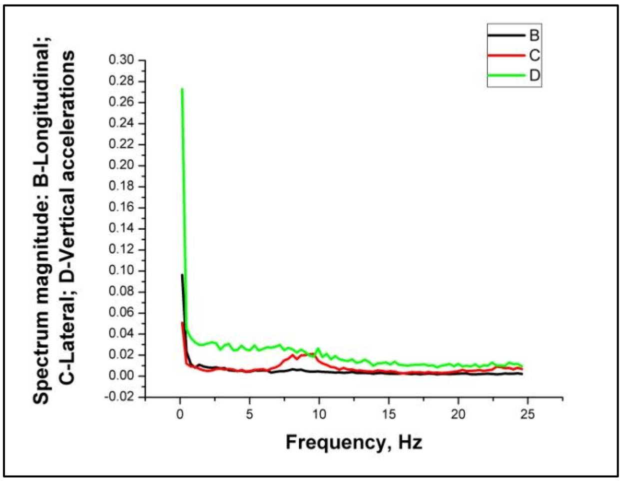

Figure 13. The magnitudes of the spectrum of the longitudinal, lateral and vertical acceleration of the front axle

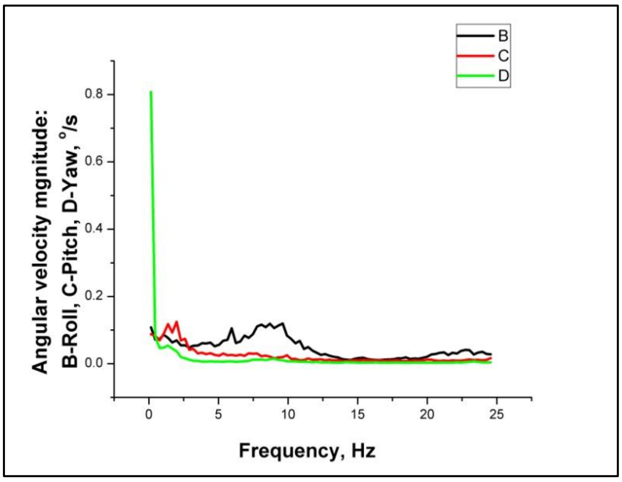

Figure 14. The magnitudes of the spectrum of the roll, pitch and yaw velocity of front axle

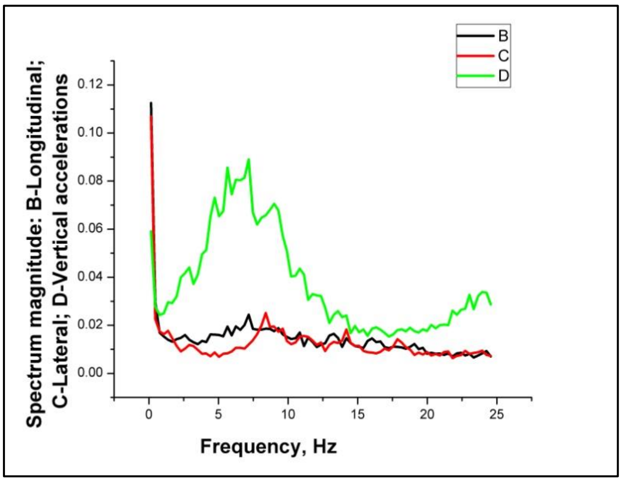

Figure 15 The magnitudes of the spectrum of the longitudinal, lateral and vertical of the rear axle

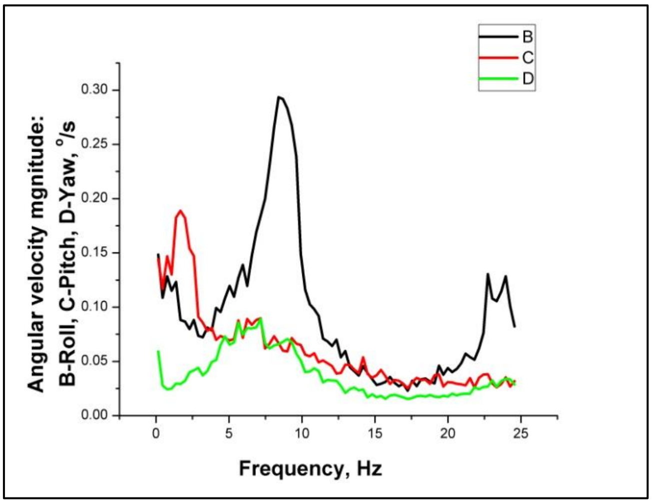

Figure 16. The magnitudes of the spectrum of the roll, pitch and yaw velocity of rear axle

Analyzes of the calculated spectrum magnitudes have shown that the largest amplitudes are not unambiguous: they depend on the axle (front, rear), as well as on the registered value. Namely, with the front axle (all observed values) and with the rear axle (linear accelerations), the maximum values occur at very low frequencies. However, when it comes to the angular velocities of the rear axle, this is not the case. Therefore, it was found useful to determine the magnitudes of the spectra at resonant frequencies. It is noted that the analysis does not include resonances originating from the sprunged mass, drive group, etc. Resonance parameters are shown in Table 5, and can be used when programming laboratory tests of trucks.

Table 5. Resonant parameters

Measured size	Amplitude/frequency front axle	Amplitude/frequency rear axle
Longitudinal acceleration, m/s^2	0.0577/3.59	0.016/4.42
Lateral acceleration, m/s^2	0.015/7.47	0.080/4.73
Vertical acceleration, m/s^2	0.029/5.34	0.083/5.64
Roll velocity, °/s	0.119/9.61	0.119/5.03
Pitch velocity, °/s	0.015/9.00	0.089/7.17
Yaw velocity, °/s	0.068/5.95	0.091/7.18

It can be seen from Table 5 that the corresponding resonance parameters of the front and rear axle are not equal to each other [11], so this should be taken into account when designing the suspension system for cargo vehicles. It is noted that, in practice, the vehicle suspension system is usually designed according to the resonance of vertical vibrations of the sprunged and unsprunged vehicle masses.

Based on the results of the performed analyzes (parameters of time identification-mean values and autocorrelation function, parameters of amplitude identification-probability density and parameters of frequency identification-spectra) it is possible to design research in laboratory conditions-on schakers. Depending on the available type of schaker, we need to select the values that will be reproduced. Most often, these are vertical vibration, but it can also be some other vibration movements (it is noted that there are rare schakers that can generate six excitations at the same time).

As the values have been registered in the middle of the axles during the measurements, in some potential laboratory test this should be taken into the account.

4. Conclusion

Tests performed on the FAP 1118 truck with 4x4 wheel formula showed that the observed measured values belong to the group of random processes, so the following methods were used for their identification: time, amplitude and frequency identification of parameters. Namely, mean values, autocorrelation functions and amplitude spectra were calculated.

Based on them, research can be programmed in laboratory conditions, on schakers. Depending on the available type of schaker, the size of the value that is to be reproduced should be selected. Most often, these are vertical vibrations, but they can be some other vibration movements.

As the values have been registered in the middle of the axles during the measurements, in some potential laboratory test this should be taken into account.

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