Classification of the road surface condition on the basis of vibrations of the sprung mass in a passenger car

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Abstract. In order to identify the state of the wheel balance in a passenger car on the basis of vibrations of the car body under actual conditions of its operation, it is necessary to determine the impact of random interferences resulting from a changing environment. For this purpose, the criterion for the evaluation of the road surface condition was developed on the basis of longitudinal vibrations of the car body of the tested car in the speed range from 50 km/h to 110 km/h. Selected functions such as: probability distribution and methods in the frequency domain: short-time Fourier transform (STFT) and power spectral density (PSD) were used to analyse recorded signals.

1. Introduction
Kinematic inputs caused by random road irregularities are the main source of vibrations of the while driving (h_w - figure 1). Other sources may include dynamic inputs connected with the rotation of wheels and suspension system (e.g. those connected with the heterogeneous nature of tires, improper shape or balance of wheels) and resulting inertial forces affecting the car body. As a result of the impact of the kinematic input (h_w) on the wheel (unsprung mass), the following variables change: (zm₁) and (zm₂) which determine the suspension and wheel deflection, acceleration of both of these masses, and contact force between the tire and the surface F_u(ω), presented in figure 1 as the so-called quarter car model.

![Figure 1. Dynamic system in the form of the quarter car model.](image)
In case of the occurrence of the wheel malfunction in the form of unbalance \( F_u(\omega) \) or heterogeneous nature of the tire, the described mass transfers \( m_1 \) will increase due to the rotation of the wheel. It is particularly disadvantageous in the range of the wheel natural frequency, i.e., in the wheel rotation frequency range of approx. 12 Hz. The resonance phenomenon leading to a significant increase in the amplitude of mass accelerations \( \ddot{m}_2 \) is the result of such a situation. The relationship between the input and variables is described by the transfer (amplification) function presented in figure 1. It is very important to understand this function from the point of view of the evaluation of comfort and safety. Comfort is evaluated by means of the function of amplification of sprung mass accelerations whereas safety is evaluated by means of the analysis of the function of amplification of the dynamic load [1]. During the operation of the passenger car, ratios \( (k_1, k_2, c_1, c_2) \) are subject to change (damage, ageing of the material, material loss), which, in turn, results in the change in the range of natural frequencies, acceleration values and amplification function. It results in an increased amplitude of mass vibrations \( (m_2 – \text{car body}) \) in relation to the amplitude of the road irregularities causing vibrations [1,2,3,4,5]. While maintaining constant linear velocity should not be instantaneous longitudinal acceleration of the vehicle body. Dominant amplitude resulting from irregular work power train (engine, transmission), have a frequency range different from the frequency of rotation of the wheel. The occurrence of instantaneous longitudinal acceleration may therefore indicate the presence of significant unevenness in the road.

2. Measurement condition (SNR)

In each real measuring signal there are interferences in the form of noise that is defined as a stochastic process independent of the transmitted information [5,6]. The SNR ratio (signal-to-noise ratio) described by the below given equation (1) is used for the evaluation of stochastic disturbances in the signal. The SNR ratio also determines the useful signal power value in the predetermined frequency band in relation to the noise (interference) power occurring in the same frequency band or as a ratio of the amplitude of these signals which are often presented in the logarithmic form for dB unit to emphasise the difference from the SNR ratio.

\[
\text{SNR} = 20 \log_{10} \left( \frac{A_{\text{signal}}}{A_{\text{noise}}} \right) = 10 \log_{10} \left( \frac{A_{\text{signal}}}{A_{\text{noise}}} \right)^2
\]

(1)

where:

- \( A_{\text{signal}} \) – signal amplitude,
- \( A_{\text{noise}} \) – noise amplitude.

The relationship above can be used to present examples of changes in the values of the SNR ratio of the analysed signal of acceleration of the car body (mass \( m_2 \)), obtained in test-stand measurements and road tests in relation to the speed profile (figure 2). The SNR ratio for standard tests carried out under conditions free from road irregularity interferences reaches values in the range from 15 dB to 170 dB (figure 2a) whereas the maximum values are obtained at 85 dB and unsprung mass resonance frequency (12 Hz) and then they decrease. Such vibrations may result from the contact of the tire tread face with the roller of the chassis dynamometer. As a result of the predetermined unbalance of the (front right) wheel with the mass \( m_{nw} = 0.08 \text{ kg} \), the value of the SNR ratio increases (figure 2b), reaching a significant value of 350 dB (at 17.2 Hz), as the wheel rotation frequency increases. In this case, the SNR value reaches 200 dB at 12 Hz.
Figure 2. Changes in the SNR of the acceleration signal $a_z$: a) standard test-stand measurements, b) test-stand measurements, unbalanced wheel with the mass $m_{nw}=0.08$ kg, c) road tests, unbalanced wheel with the mass $m_{nw}=0.08$ kg.

Road irregularity interferences (figure 2c) led to the decrease in the SNR values the maximum value of which did not exceed 175 dB at 14 Hz. The mass acceleration signal($m_2$) is useful in the diagnostics of selected elements of wheels and suspension system for frequencies exceeding 10 Hz.
3. Inputs caused by road irregularities
The road profile is described in literature[1,2,7,8] as the sum of waves of different lengths which form road macro profiles (waves of length exceeding 100 m) and micro profiles (waves of length from 0.1 to 100 m). Road parameters are determined on the basis of the autocorrelation and power spectral density (PSD) function under the assumption of the stationary function of random road surface irregularities. According to ISO 8606 of year 1995, roads were divided into 8 classes (marked with letters: A, B, C, D, E, F, G, H) to the description of which the PSD function was used. Graphs of functions $S_g(Ω)$ are determined for the frequency $Ω$ determined in the coordinate domain of horizontal movement of the vehicle on section sand bound by the relationship $Ω=1/λ$, ($λ$- length of the wave of the harmonic component of the road irregularity signal). Indicated functions are described by the following relationship (2):

$$S_g(Ω)=A_gΩ^{-m}$$

where: $A_g$ - road roughness index, m- function slope (with a value close to 2).

The quality of the road surface is then evaluated on the basis of the value $S_0=S_g(Ω_0)$ determined for the harmonics with specified wave length $λ$ (for asphalt surfaces $Ω_0=1/2π=0.16$ c/m [cycle/metre]). The identification of the specific road surface class requires specialised equipment; it is not used in the conditions of normal operation of the vehicle. However, damage to the road surface, such as: wheel tracks, transverse technological welds, cracks and spalling cracks, affects the acceleration of the unsprung and sprung mass of the vehicle.

It was assumed in the analysed matter that the detection of the unbalanced wheel during the road test is possible provided that the value of the amplitude caused by the unbalanced wheel is higher than the noise (interference) amplitude in the analysed range of frequency band from 7 Hz to15 Hz. The SNR ratio(signal-to-noise ratio) determining the useful signal amplitude value in the predetermined frequency band to the noise power in the same band is used for the evaluation of stochastic disturbances of the signal [5].

4. Measuring equipment
The measuring system used (figure 3) consists of the acceleration sensor 3DM-GX3-25 with the measurement range of ±50 m/s$^2$, and initial bias error of ± 0.002 m/s$^2$, head for the non-contact car body speed measurementL-350 AQUA (measurement range: 0.3- 250 km/h) connected to the card NI USB 6212. The acceleration measurement sensor was installed on the windshield inside the cabin of the vehicle.

A mid-size passenger car with a petrol engine of capacity 1.2 16V was used for the road tests. Experiments were carried out on roads with bituminous surface. Tire pressure was 0.2 MPa for each of the wheels. Vehicle weight during tests was 1160 kg (kerb weight 990 kg plus two persons 170kg).

The car used in road tests has front suspension type McPherson with a single-control arm and a telescopic shock absorber as a steering column with a coil spring which is a spring element. In order to reduce the impact of vibrations generated by rolling wheels on the car body and the impact of the irregularity of roads with small wavelengths, apart from the vertical flexibility of suspension, its flexibility in the longitudinal direction is also required. It is ensured by the damping element in the form of the rubber and steel bushing. Suspension systems with steering columns show greater sensitivity to unbalanced wheels, improper shape of tires or other structures, e.g. multi-arm suspension [2,3].
5. Determination of the criterion for the evaluation of road surface condition
The influence of the type of road surface on the value of the amplitude of the acceleration of the tested car body was determined by means of tests carried out with the use of the chassis dynamometer and on selected sections of road with bituminous surface which are presented in figure 4. Due to the surface defects, the selected sections of the road were defined as: road A without visible surface defects, road B with visible surface defects, road C with considerable bituminous surface defects, transverse cracks and transversely deformed surface (folds).

During the tests, the authors tried to maintain a constant linear velocity with accuracy (+/- 5 km/h) for selected speed ranges (from 50 km/h to 90 km/h). The car body acceleration recording time was established in such a way that it included at least 20 wheel rotations. The autocorrelation function, power spectral density, short-time Fourier transform (STFT) and probability distribution were used for the analysis of data obtained under stationary conditions (using the chassis dynamometer) and in road tests for bituminous surfaces defined as road A, B and C. The influence of the road surface condition on the value of the power spectral density was presented in figure 5. As a result of test-stand measurements carried out by means of the chassis dynamometer MAHA MSR 500, the values of the vertical acceleration of the sprung mass $m_2$ and unsprung mass $m_1$ free from interferences caused by road irregularities were obtained. It was stated that in case of a good road surface (road A and chassis dynamometer), in the wheel rotation frequency range (11.3 Hz) the values were similar and amounted to $0.042 \text{m}^2/(\text{s}^4\text{Hz})$ whereas in case of road C, the PSD value was $0.2 \text{m}^2/(\text{s}^4\text{Hz})$. 
Figure 5. PSD of the component of the acceleration of vibrations of the car body in the vertical direction, caused by the technical condition of the road surface on which a wheel rolls.

The use of the STFT function, the information on the change in the spectrum of the analysed signal was obtained by monitoring its characteristics in the time and frequency domain. Irregularities of roads B and C result in an increase in the amplitude of vibrations of the car body in the vertical direction ($a_z$) in the frequency band range from 1 Hz to 30 Hz. Contrary to the spectrum obtained for road A, there are no evident amplitudes corresponding to the rotational speed of wheels of the vehicle. It is connected with the occurrence of significant road surface irregularities. It results in an apparent increase in background amplitudes in the frequency range up to 60 Hz from 0.02 m/s$^2$ for road A, up to 0.12 m/s$^2$ for road B and 0.18 m/s$^2$ for road C. Local increases in amplitudes can also be seen in obtained spectrograms which prove that there are significant irregularities and defects in the road surface.

In amplitude spectra obtained for tests carried out with balanced wheels there is a multiple increase in the amplitude of vibrations of the car body in the longitudinal direction ($x$ axis) and in the vertical direction ($z$ axis) for tests carried out on roads B and C in relation to road A and test-stand measurements.

Dominating amplitudes for speed from 90 km/h to 92 km/h occur in the frequency range from 5 Hz to 25 Hz (figure 6). In the longitudinal direction there is a significant increase in the average amplitude value for road B (0.02731 m/s$^2$) and road C (0.04573 m/s$^2$) as compared to road A (0.007627 m/s$^2$). Therefore, an attempt was made to determine the limit value of acceleration in the direction of the horizontal axis $a_x$, above which the measurement aiming at the identification of the unbalanced wheel under road test conditions cannot be carried out. For this purpose, the average value of the filtered acceleration signal of the longitudinal axis ($a_x$) in the frequency range from 0 to 100 Hz was used for each flexible time window of the STFT function. In order to evaluate the distribution of amplitudes of acceleration of the sprung mass $m_2$ in the longitudinal direction, the statistical inference was carried out for the assumed measurement range (3s) on the basis of the probability distribution function (figure 7).
It can be seen from the graph of the probability distribution function for road A (figure 7a) that the distribution of amplitudes in the longitudinal direction for frequencies from 9 Hz to 16 Hz is included in the range from 0.08 m/s² to 0.017 m/s². For frequencies: 10 Hz, 11 Hz and 13 Hz, the amplitude ranges from 0.069 m/s² to 0.0125 m/s² and takes a more uniform shape with two apparent modes. In case of 16 Hz, there is a shift of the maximum towards greater values of acceleration amplitudes amounting to 0.0165 m/s². The impact of speed on the average value of acceleration in the longitudinal direction can be observed at 16 Hz.

Dominating amplitudes for road B for wheel rotation frequency range from 9 Hz to 15 Hz (figure 7b) occur in the range from 0.069 m/s² to 0.0754 m/s². The graph shows a more even distribution of amplitudes at a frequency of 15 Hz. Despite the increase in the wheel rotation frequency, all dominating modes of vibrations of mass m₂ fall within the above-mentioned range, which proves that there is no significant impact of speed of the vehicle on the amplitude value. However, the difference in the amplitude value can be observed at 17 Hz; it amounts to 0.0983 m/s².

In case of road C (figure 7c), there is no apparent impact of speed on the value of the dominating mode as its value for the wheel rotation frequency 16 Hz is lower than for 9 Hz. However, there is an apparent increase in the value of amplitudes for 14 Hz and 16 Hz as compared to the results obtained for road B. There is also a significant increase in the value of amplitudes (higher by an order of magnitude) as compared to road A.
Thus, the information about the value of amplitudes dominating in the probability distribution function was obtained for selected ranges of frequency of rotation of the wheel rolling on roads A, B and C. The parameters of longitudinal accelerations of the car body for constant speed were calculated on the basis of such information in the wheel rotation frequency function (figure 8). On this basis the limit value of acceleration in the longitudinal direction was assumed at the level of 0.02 m/s², above which the measurements of wheel unbalance under road test conditions cannot be carried out.

Figure 7. Probability distribution function of the variable $a_x$ for: a) road A, b) road B, c) road C.
Figure 8. Classification of road surface on the basis of the probability distribution function of the variable $a_x$.

The results obtained by means of the spectral method using the average value of the tested signal window were the basis for the development of the algorithm of the influence of the road surface condition in terms of diagnostics of wheel unbalance under road test conditions (KSND – road surface condition classifier).

6. Conclusion

As a result of the analysis, test-stand measurements and road tests, it was stated that interferences caused by road surface irregularities have a significant influence on vibrations of the sprung mass of the car body. Therefore, an early detection of unbalanced wheel by means of the measurement of the sprung mass of the car body may be subject to interferences caused by road surface irregularities. Moreover, it was found that road surface irregularities lead to accelerations both in the vertical direction as well as in the longitudinal direction. Bituminous surface irregularities for arbitrarily selected road A with a good surface result in the decrease in the SNR ratio as compared to standard results obtained during test-stand measurements. The most preferred values of the SNR ratio for road tests were obtained at 13.8 Hz.

The criterion for the evaluation of the road surface condition under road test conditions was determined on the basis of the analysis based on the probability distribution; this criterion clearly indicates the limit value of the amplitude of longitudinal vibrations of the car body for a balanced wheel in the range of the tested wheel rotation frequency $f_k$ (from 8.5 Hz to 18 Hz), which did not exceed 0.018 m/s². The range for which it is possible to carry out measurements to identify wheel balance was thus determined. It was determined as a result of the experiment of the tested vehicle up to the value of 0.02 m/s² for longitudinal acceleration at constant linear velocity of the vehicle.

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