



Extraction of Information from a PSD for the Control of Vehicle Suspension

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Abstract. Road irregularities are the main effect influencing driving quality, due to its unpredictability driver can not find the best driving parameters easily and fast. Identification of road profile lets us control the vehicle's damping characteristics and increase driving quality as fast as possible. Power Spectral Density (PSD) could be easily found from the road profile. Deduction of road waviness and amplitudes from PSD could be used to provide the mandatory information required for controllable damping system. Using our developed dynamic model of the car, we performed a simulation of the vehicle passing artificially generated road profiles with different waviness. Obtained results show that the straight-line approximation of PSD of the road profile as recommended by ISO standard doesn't provide suitable information required for the control of car suspension. We define that, two split approximations of PSD spectra is a better solution for this purpose. It provides reliable results and allows to choose optimal damping coefficient value with a small delay for long distances.

Keywords: Road profile · Power spectra density · Waviness · Damping

1 Introduction

A road surface is never perfectly flat, even rarely smooth. Potholes cause damages to vehicles [1]. Road irregularities have a direct impact on ride quality, fuel consumption, tire wear, maintenance costs, etc. Knowledge of road profiles is vital for transport authorities maintaining adequate ride quality for vehicles [2]. The suspension system is being developed from passive to semi-active and active control in automotive technology [3]. Thus, knowledge of road profiles provides information needed to adjust control parameters to improve ride comfort and vehicle handling [4].

Road profile estimation algorithms can be divided into three distinct types, namely contact measurement (as profilograph or longitudinal profile analyzer), non-contact measurement (as inertial profiler), and system response-based estimation [5]. Response-based methods give possibilities to change from dedicated vehicles with special sensors to general-purpose sensors mounted on each vehicle. So finally, it is necessary to identify road profile, then count off parameters and relate them with required control parameters.

Mostly two methods are used in semi-active suspension constructions: control from sensors readings [6–9] or self-control systems, that uses shock absorbers movement value [10–12]. Despite differences in control structures and control types, the main goal of such systems is to adjust suspension to achieve the best vehicle performance and efficiency. Road profile recognition can be performed by reading signals from sensors (for example linear variable differential transformer (LVDT)) mounted on the shock absorber [6] or measuring acceleration in the z-axis as shown in [7–9]. Some authors [9, 13] use PSD of road displacement to control suspension. Information about road irregularities, road waviness or road class is critical to determine right parameters for damping control.

Here we show that one road waviness value and road class are insufficient parameters to control suspension properly. Also, we propose a new principle to maintain ride comfort.

2 PSD Approximation and Road Profile Generation

The ISO 8608 standard [14] regulates that the PSD first should be smoothed (from the lowest calculated frequency up to the centre frequency of 0.0312 cycles/m in octave bands; then to a centre frequency of 0.25 cycles/m in third-octave bands; and up to the highest calculated frequency in twelfth-octave bands) and approximated with a straight line in log-log scale (1).

$$G_d(\Omega) = G_d(\Omega_0) \cdot (\Omega / \Omega_0)^{-w} \quad (1)$$

where $G_d(\Omega_0)$ is the degree of roughness, Ω ($\Omega_0 = 1$ rad/m) is the angular spatial frequency, and w is waviness. According to the review of approximation functions made by Andr  n [15], the two split approximation has the smallest error.

$$G_d(\Omega) = \begin{cases} G_d(\Omega_0)\Omega^{-w_1} & \text{for } \Omega \leq \Omega_1 \\ G_d(\Omega_0)\Omega^{-w_2} & \text{for } \Omega_1 \leq \Omega \leq \Omega_2 \\ G_d(\Omega_0)\Omega^{-w_3} & \text{for } \Omega_2 \leq \Omega \end{cases} \quad (2)$$

where $\Omega_0 = 1$ rad/m, $\Omega_1 = 0.21 \times 2\pi$ rad/m and $\Omega_2 = 1.22 \times 2\pi$ rad/m. We used this principle for PSD approximation in the range of spatial frequency n from 0.0442 cycles/m up to 1.2241 cycles/m.

Longitudinal road profiles were generated using a sinusoidal approximation in the time domain:

$$z(t) = \sum_{i=1}^N Z_i \cos(\Omega_i vt + \varphi_i) \text{ with} \quad (3)$$

$$Z_i = \sqrt{2G_d(\Omega_i)\Delta\Omega}. \quad (4)$$

Where Z_i is the amplitude of i^{th} harmonic, $N = (\Omega_U - \Omega_L) / \Delta\Omega$ is number of frequency bands into which the total PSD spectrum is divided, Ω_U , Ω_L are upper and lower spatial frequencies in the PSD spectrum [rad/m], $\Delta\Omega$ is the width of each frequency band,

$\Omega_i = \Omega_L + (i - 1)\Delta\Omega$ is the spatial frequency of i^{th} harmonic or i^{th} frequency band. The phase angle of i^{th} harmonic φ_i uniformly distributed in the interval $[0, 2\pi]$.

There is a suggestion that the lower spatial frequency limit has no reason to measured lower than $n_L = 0.01$ cycles/m for on-road vehicles and 0.05 cycles/m for off-road vehicles [14]. For vibration analysis of suspension on-road vehicles an upper spatial frequency limit of $n_U = 10$ cycles/m has been suggested by considering the low pass filtering effect due to tire enveloping. For spatial angular frequency, this means the range $2\pi \times 0.01 \leq \Omega \leq 2\pi \times 10$ rad/m. The frequency band was divided into $N = 1000$ intervals. Time step is $dt = 0.0015$ s. The degree of roughness corresponds to the ISO road class B ($G_d(\Omega_0) = 4 \times 10^{-6} \text{ m}^3$ [14]). To more coincide measured PSD spectra of real road, we modified Eq. (2) by reducing the amplitude of frequencies lower than $0.04 \times 2\pi$ rad/m and higher than Ω_2 :

$$G_d(\Omega) = \begin{cases} G_d(\Omega_0)\Omega^{-1} & \text{for } \Omega \leq 0.04 \times 2\pi \text{ rad/m} \\ G_d(\Omega_0)\Omega^{-w_1} & \text{for } 0.04 \times 2\pi \text{ rad/m} \leq \Omega \leq \Omega_1 \\ G_d(\Omega_0)\Omega^{-w_2} & \text{for } \Omega_1 \leq \Omega \leq \Omega_2 \\ G_d(\Omega_0)\Omega^{-5} & \text{for } \Omega_2 \leq \Omega \end{cases} \quad (5)$$

The road profile repeats at each $1/n_L$ distance. To avoid repeatability of profile segments, we divided profile length to blocks and for each block, generate a new random set of initial phases. Such a technique can develop the appearance of abrupt shift at the connections between blocks. To minimize this effect, we added Welch type windowing function with the value of exponent equal 10 to get flatter surface:

$$\varpi(i) = 1 - \left(\frac{i - \frac{1}{2}(n-1)}{\frac{1}{2}(n+1)} \right)^{10}, \quad (6)$$

where n is the number of blocks, and i is the number of samples in the block.

3 Results and Discussion

Generated road profiles using Eqs. (3)–(6) with different w_1 and w_2 values are shown in Fig. 1. Each profile is generated with the same sequences of random numbers for comparison. The profiles are named as “pr w_1w_2 ”. Root mean square (RMS) values of displacement of each profile, expressed in mm are presented in brackets.

Our developed dynamic model of the full car [16] was used to simulate vehicle passing these profiles with speed $v = 90$ km/h. Damping coefficients that define suspension behaviour were optimized to reach minimal RMS value of driver acceleration; in other words, the suspension has been adjusted for maximum comfort level. Optimized suspension's damping coefficient values for generated profiles are shown in Table 1. For example, profiles pr22C and pr22D, which match ISO class C and D (4 and 16 times higher degree of roughness than pr22 and the same waviness $w = 2$), have higher RMS values of displacement than pr22 profile, their values are equal to 8.63 mm and 17.26 mm, respectively. Nevertheless, their optimized damping coefficient remains the same as for profile pr22. We can conclude that the required information for control parameters one can obtain from waviness w , but not from the degree of roughness $G_d(\Omega_0)$.

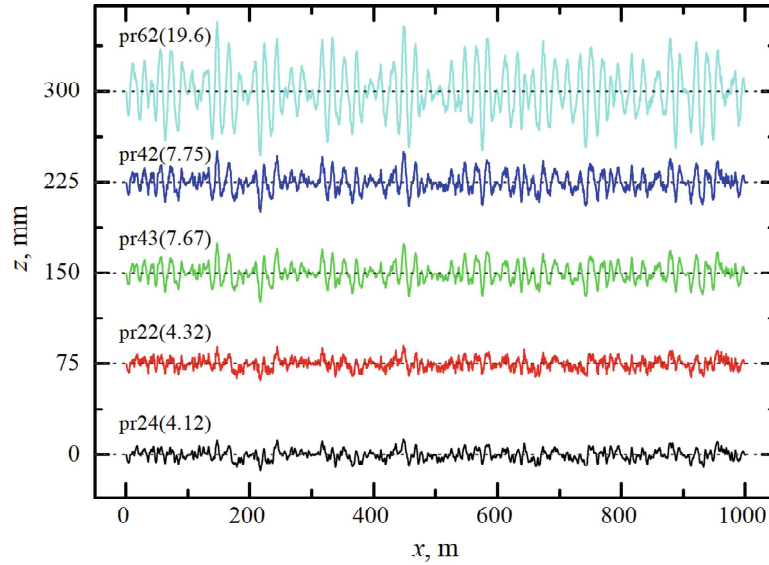


Fig. 1. Generated road profiles with different w_1 and w_2 values. Profiles are shifted vertically for clarity

Table 1. Optimized suspension's damping coefficient h_s values

Profile	pr22	pr22C	pr22D	pr42	pr43	pr62
h_s , Ns/m	4210	4210	4210	7820	8060	11920

Displacement PSD spectra of four profiles were calculated using Fast Fourier Transformation (FFT) with averaging and are presented in Fig. 2(a). FFT was calculated for 100 m distance (from $N = 100$ [m]/v[m/s]/ Δt [s] points and recalculated after $N/20$ points, where time step $\Delta t = 0.005$ s). Each subsequent FFT result was added to previous and averaged. Finally, the result was smoothed using a method provided by ISO [14], however not in twelfth octave bands above spatial frequency 0.25 cycles/m. We can clearly distinguish PSD spectra related to different waviness w_1 and w_2 values in Fig. 2(a). Points indicate the centres of bands.

Waviness w values of straight-line approximation of averaged PSD spectra are shown in Fig. 2(b). As can be seen, profiles pr43 and pr62 have nearly same waviness w . However, the optimized damping coefficient of profile pr43 is much closer to pr42 case than pr62 profile. Such distribution indicates that linear approximation is insufficient for proper selection of the required damping coefficient and confirms our choice to use two split approximation. Results of two split approximation of averaged PSD spectra are shown in Fig. 3. Here in Fig. 3 (a), w_1 is the slope in the range (0.044; 0.223) cycles/m and w_2 is the slope in the range (0.223; 1.224) cycles/m (Fig. 3(b)). Estimated values of w_1 and w_2 closely match waviness values used for generating a profile.

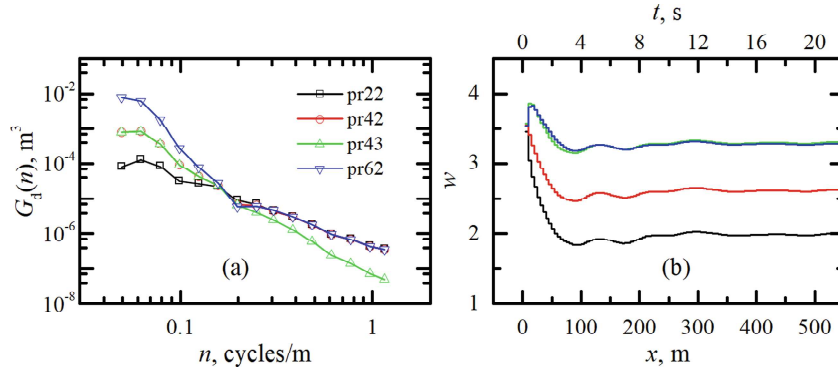


Fig. 2. (a) Smoothed and averaged displacement PSD spectra of profiles for 1000 m; (b) waviness of straight-line approximation of averaged displacement PSD spectra of profiles. The colours of the curves in (a) and (b) corresponds to profile name, as shown in (a)

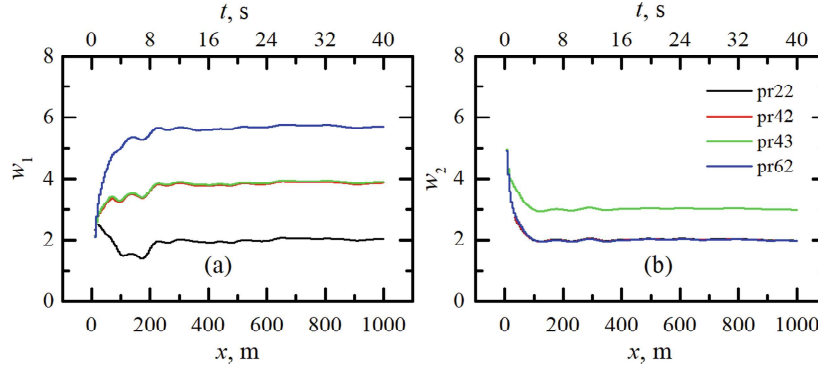


Fig. 3. Waviness (a) w_1 and (b) w_2 of two split approximation of averaged displacement PSD spectra of profiles. The colours of the curves in (a) and (b) corresponds to profile name, as shown in (b)

Waviness values vary mostly for first 100 m (see Fig. 2(b), Fig. 3(a, b)) because in the beginning FFT does not have all needed points for calculation, and instead of missing points FFT algorithm adds zeros. Also, this distance is related to the lowest frequency used for generating profiles. To accommodate the lowest frequency harmonic n_L , the required length will be $x \geq \frac{1}{n_L} = 100$ m. Taking into account that and results of Fig. 2(b) and Fig. 3(a, b)) we increased block length for FFT up to 200 m.

Results obtained by applying a straight line and two split approximations to PSD spectrum of the merged profile are shown in Fig. 4. It should be noted that here FFT calculation was done without averaging. Vertical dotted lines show the boundary between different profiles. Using two split approximation, the changed profile is defined well enough with the delay of FFT block length. The decrease of this length minimizes the delay but increases deviations and vice versa.

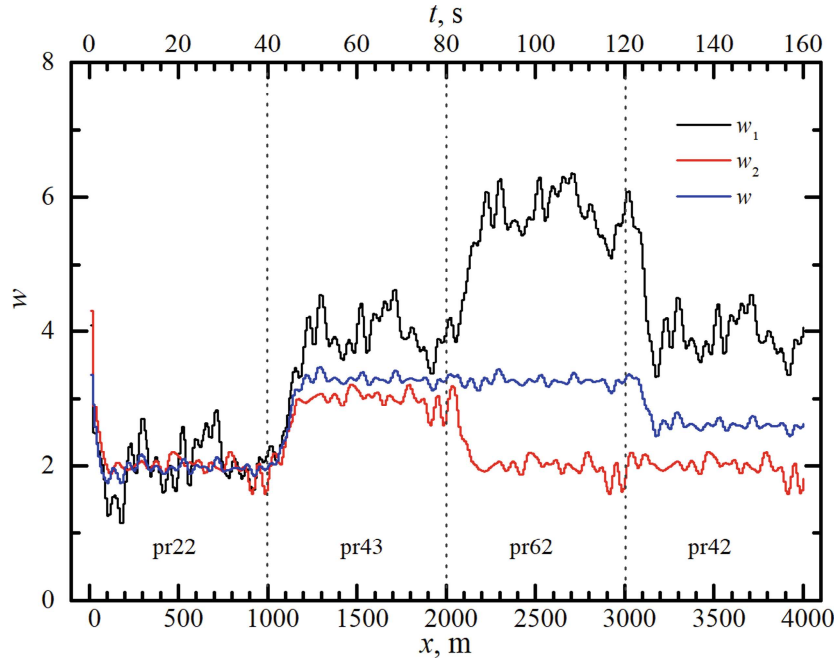


Fig. 4. Results of straight line and two split approximations of PSD spectra of merged profile

This principle we can use to control ride comfort depending on road profile. Knowledge of transfer function between measured acceleration and road displacement and relations between waviness parameters and optimized damping coefficients gives a possibility to control vehicle suspension using the accelerometers. The drawback of the proposed method is that it has some delay and can control averaged parameters for some distances.

4 Conclusions

Our simulation of full car dynamics, and definition of optimized damping coefficients for each artificially generated road profile with different waviness, showed that ISO standard recommended straight-line approximation with two parameters (degree of roughness $G_d(\Omega_0)$ and waviness w) is not the best way to relate road profile with parameters used for suspension control. From obtained results, it is seen that the damping coefficient is independent of the roughness degree $G_d(\Omega_0)$. Moreover, road profiles with identical waviness value could require to apply different damping coefficient to ensure maximum driver's comfort level.

Our obtained results allow us to state that two split approximation of PSD is a promising solution for road profile definition and adjustment of optimal suspension parameters. Delay after changed profile directly depends on FFT block length. However, the decrease of this length increases the deviation of waviness.

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