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Simulation Study of the Method of Random Kinematic Road Excitation's Reconstruction Based on Suspension Dynamic Responses with Signal Disruptions

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Abstract

The paper presents the results of simulation studies of the method of random kinematic road excitation's reconstruction based on the dynamic responses of the suspension acquired in road tests. The method uses registered unsprung mass accelerations as well as model of suspension's vertical dynamics and tracking control with PID controller to monitor unsprung mass accelerations' signal in simulation. In the simulation the quality of reconstruction of random irregularities of the road profile was tested. The road profiles were generated based on their power spectral density of road profile heights that is in line with the description given in ISO 8608 standard. Four road classes had their profiles estimations tested – A, B, C and D (corresponding to highways through city roads to the very bad quality roads). The influence of the simulated noise in the suspension's dynamic response signal – i.e. unsprung mass acceleration – was also tested. The methods of processing of the initial acceleration's signal from the road tests were proposed and achieved accuracy was defined. Lastly, the necessary requirements to use the method effectively were defined and its limitations were listed.

Keywords: suspension, kinematic excitation, dynamic responses

1. Introduction

There are two types of excitations that are encountered in vehicle's exploitation – the dynamic and kinematic ones, the latter of which is the focus of this paper. They appear due to the changing road profile irregularities' heights and their value depends on the velocity of the vehicle. Road profile and kinematic excitations are not the same tough – rather, kinematic excitations are derived from road profile, but modified through environmental factors and filtering properties of the pneumatic tyres. Acquisition or prediction of the kinematic excitation signal is hard, as it depends on variety of the mentioned factors. On one hand, researchers could measure road profile and try to calculate kinematic excitations using transfer functions, however this has limited use as the linear model assumption is necessary, and that cannot be always fulfilled. On the other hand, vehicle's responses can be measured and the kinematic excitations could be calculated from the dynamic responses of the suspension, such as the accelerations. That precisely is the approach of researchers in this paper. The problem encountered with this approach is that even the most similar to road excitations, easily measurable dynamic response, i.e. unsprung mass acceleration, cannot be used to calculate kinematic excitation by just a simple double integration. That is why the researchers proposed a method of estimating this excitation via the use of feedback-loop with PID controller, which uses the registered unsprung mass acceleration's signal as a reference and applies a correction based on error which occurs, when the input to the simulation is the result of double integration of recorded unsprung mass acceleration. The specifics were described in author's other work [1]. The results from testing on the determined excitation signal that were meant to be replicated were promising, showing the maximum error of less than 8% of the amplitude for the 25 Hz sine wave and much less for lower frequencies (1% to 5.5% of the amplitude). Those results lead researchers to believe that the proposed method can be successfully implemented in the estimation of real road kinematic excitation of random character.

The authors' goal in the research described in this paper was to verify whether or not the proposed method is suited for replicating randomized signals that represent kinematic excitation on roads of various classes. Secondly, the authors want to analyse the influence of noise added to the signal on the accuracy of the kinematic excitation estimation.

2. Research method

The models used to test the estimation method were three-fold: the vehicle model, road model and noise model. The vehicle model was a simple linear quarter car model with 2 DOF and parameters typical for a C segment vehicle – Table 1. The input to the model are the kinematic excitations and the outputs are the dynamic responses used for later verification of the signals, i.e. suspension deflections and unsprung mass accelerations. The parameters used to describe the model were the sprung mass M, the unsprung mass m, tyre damping c_m and tyre stiffness k_m as well as suspension damping c_M and suspension stiffness k_M.

Table 1. Quarter car model parameters used in research

m [kg]	M [kg]	c_m [Ns/m]	k_m [N/m]	c_M [Ns/m]	k_M [N/m]
50	400	220	138200	2500	19300

The road model used in the research was generated so that it corresponds to the road classes described in the ISO 8608 standard [2]. The generation process was described for example in [3], [4]. The researchers chose the longest and the shortest irregularity wavelengths to be included in the profile to be 100 m and 0.1 m respectively. They generated road profiles for four different road classes, from A (new highways and airstrips), through B (standard quality asphalt roads) and C (damaged, aging pavements) to D class (unpaved and rural roads). The tire filtration was implemented by using a moving average that smoothed out the unrealistically sharp edges.

To simulate the noise present in real measurements, the researchers used the white noise generated with use of dedicated block from *Simulink* library. It generated noise signal of unsprung mass acceleration every 0.0003 s with the noise PSD equal of 10^{-5} [$(m/s^2)^2$/Hz]. That simulated noise was then added to the original acceleration signal (Figure 1) and the result was used for profile reconstruction after proper processing, which is described in chapter 4.

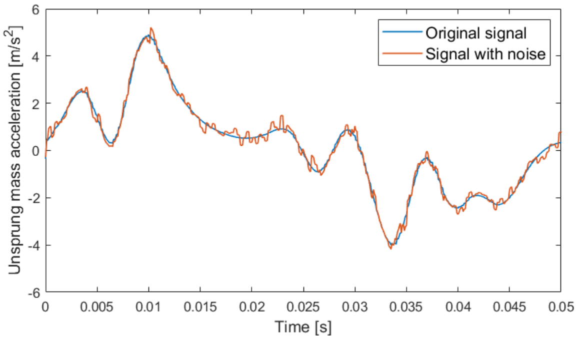

Figure 1. The effects of adding noise to the acceleration signal

Having created aforementioned models, the kinematic excitation reconstruction method was tested. The method uses (obtained in tests) unsprung mass acceleration $\ddot{z}_{m\_T}$ signal as an input for estimating kinematic excitations. That acceleration signal is integrated twice, resulting in obtaining wheel displacement signal z_m. This signal is different from kinematic excitation z_r, however it is fed to the quarter car model as an input and the output is unsprung mass acceleration from simulation $\ddot{z}_{m\_S}$. The error is calculated as the difference between accelerations from test $\ddot{z}_{m\_T}$ and from simulation $\ddot{z}_{m\_S}$. This error is then also double integrated and its value is added to the wheel displacement signal, creating an estimation of kinematic excitation. It must be noted, that this correction happens an iteration after the original error was calculated, this however can be dealt with by having small time steps – in the case of this research, the time step was set to 0.0001 s. This allows the correction to occur after only a miniscule change in acceleration, allowing for the reconstruction method to work [1].

The reconstruction process went as follows: firstly, road profiles of classes A to D were generated. After that, they were used as inputs to quarter car models and unsprung mass acceleration registered in these test was saved, to be used later as a reference, “test” acceleration $\ddot{z}_{m\_T}$. Then, this acceleration signal is ran through the reconstruction algorithm described above. Finally, the original excitation signal is compared with the reconstructed one and conclusions are drawn. The modification that needed to be done when compared to reconstructing simpler, determined signals like sine waves of differing frequencies, was that in the case of randomized signals postprocessing in the form of detrending data was necessary.

3. Results

The kinematic excitation reconstruction method was first tested without added noise, on roads of classes from A to D. Acceleration signal on every road was acquired, while the simulated quarter car model was travelling at different speeds (Table 2).

Table 2. Velocities on different roads for “test” unsprung mass acceleration generation

	A class	**B class**	**C class**	**D class**
Speed [m/s]	40	30	20	5

All of the reconstructed signals displayed strong linear trends, that were eliminated in postprocessing by calculating that trend's equation and subtracting the resulting values from the signal. The results are presented in Figure 2 and Figure 3. The full, 30 s long series is not shown for the clarity of the image. The original and reconstructed signals can be observed to be virtually the same for all presented road classes. It should be noted tough, that with worsening road class, the absolute differences between those two profiles are getting bigger and bigger. This however is mitigated by the fact, that the profile itself has much greater changes in value, so the relative error is in similar range of values for all road classes.

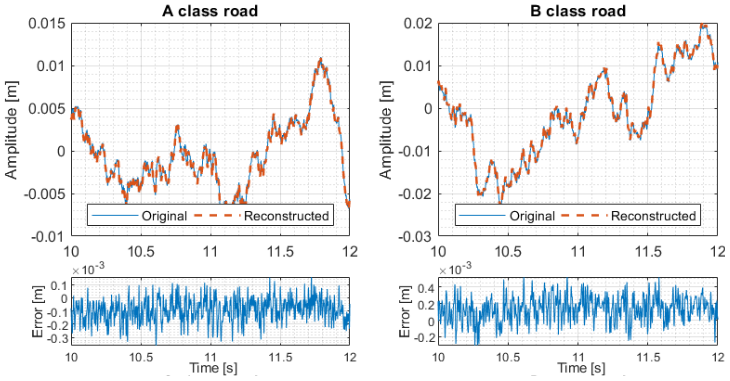

Figure 2. Comparison of reconstructed
and original kinematic excitation signals – classes A and B

The other observation to be made, although it is not so clearly visible for such short plotted periods, is the occurring linear trend for all errors, causing the absolute value of error to grow with time. This growth however also does not decrease the accuracy of the reconstructed profile, as the difference caused by this linear trend is less than 1 cm at 150 m, which translates to 0.007% slope – a value which will not affect the simulation results in regard to vehicle's dynamic responses in any significant way.

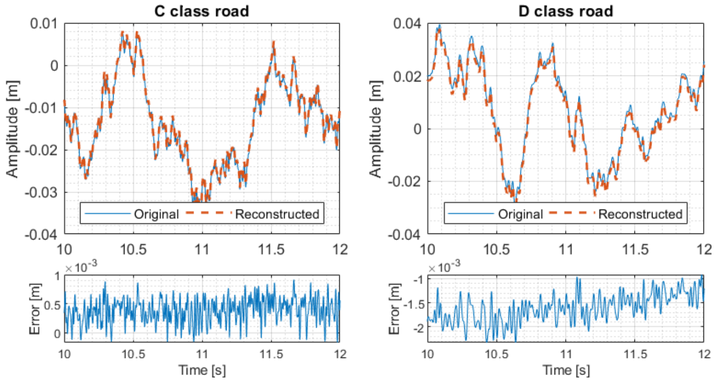

Figure 3. Comparison of reconstructed
and original kinematic excitation signals – classes C and D

In order to compare the quality of results, besides comparing signals in the time domain, two indicators were calculated. First of these indicators was the goodness of fit in reference to standard deviation (fit for short from now on) and the second was International Roughness Index or IRI. Fit was chosen as it is a relative indicator, so it allows for direct comparisons between signals. Fit is calculated using the following formula

$$fit = 100 \cdot \frac{\left\| z_{r\_R} - z_{r\_O} \right\|}{N \cdot \sigma\left(z_{r\_O}\right)} \tag{1}$$

where z_{r_O} is original kinematic excitation vector, z_{r_R} is reconstructed kinematic excitation vector, $\sigma\left(z_{r\_O}\right)$ is standard deviation of the original kinematic excitation and N is the length of z_{r_O} vector.

IRI was calculated, as it is an indicator often used to measure the smoothness of pavement, so the original and reconstructed signal should have its value as similar as possible. IRI is calculated by summing the total suspension deflection of a quarter car model with the parameters of a "Golden Car" [5]. The formula for calculating IRI ([6]) is

$$IRI = \frac{1}{L}\int_0^{\frac{L}{v}} |\dot{z}_M - \dot{z}_m| dt \tag{2}$$

where L is the distance that vehicle travels, v is its speed, which is always 80 km/h, $\dot{z}_M - \dot{z}_m$ is the velocity of suspension deflection. The results for both fit and IRI calculations are gathered in Table 3.

Table 3 IRI and fit values for original (org.) and reconstructed (rec.) kinematic excitation signals. Values for fit are calculated with original signal as the reference

	A org.	**A rec.**	**B org.**	**B rec.**	**C org.**	**C rec.**	**D org.**	**D rec.**
IRI [m/km]	2.07	2.10	3.70	3.81	5.96	6.06	7.94	8.05
fit [%]	0.0059		0.0042		0.0079		0.0164	

The IRI values are very similar for all four road classes and they all belong to the same categories of roads, as described in [7]. All reconstructed profiles have slightly higher IRI values, which means that the ride on them can be expected to cause slightly bigger dynamic responses, this difference however is almost negligible when compared to the reference value. The biggest relative difference in IRI value is registered for the B class road and its value is 2.97%.

The fit is very good for all road classes, as the small value of that parameter means the reconstructed profile is closer to the original one. This time the lowest fit value, so the closest to original, is for the reconstructed profile from B class. The fact that it had the highest relative and absolute difference in IRI might be caused by greater amount of sharp changes of value, which make the reconstructed profile closer to the original, while at the same time causing greater suspension deflections, which is reflected in higher IRI value.

4. Method verification for noisy signals

Once the method has been established to be suited for reconstructing excitations from random road profiles, the researchers tested the method on signal with artificially added noise, what simulates real acceleration signal typically registered during road tests.

The goal was to simulate signals that are measured in real life and always exhibit some form of imperfections, often in the form of noise of high frequency. The way that noise was simulated is described in chapter 0. As was to be expected, reconstruction of kinematic excitation from such a signal caused large errors to occur.

That is why the researchers came to the conclusion that preliminary filtration of the noisy signal is necessary. The chosen method of filtration was using a low-pass filter with the stop frequency of 650 Hz. Such a high frequency ensured that only noise was filtered out, leaving all the important (from the dynamic responses' point of view) frequency components intact. The effects of this filtration are showcased in Figure 4.

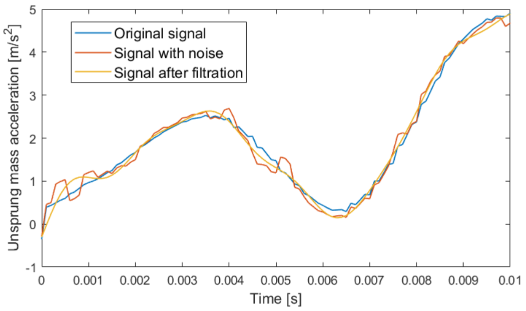

Figure 4. The effects of filtering noisy acceleration signal

After the preliminary filtration, the acceleration signal was ready to be used as an input to the reconstruction algorithm. The results needed to be further filtered, this time using the high-pass filter. The researchers found out that the most effective method of filtering those long wavelengths is by using long moving average (from 20000 closest samples) across the whole timeseries, and subtracting the moving average value from the reconstructed signal. The results of that process are shown in Figure 5.

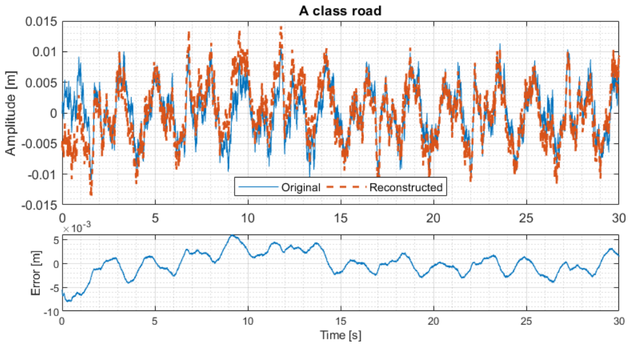

Figure 5. Reconstruction of kinematic excitation of class A
from the noisy acceleration signal

The reconstructed signal differs significantly from the original one for the first second or so, this however is caused by the way the low-pass filter works and things quickly stabilize after that and the error value drop to much lower values, oscillating around 0 mm. There are points in which the estimated profiles exhibits quite a large difference in momentary value from the original one, those however mostly stem from the inability to completely filter out the long wavelengths, that still influence the reconstruction, but do not affect significantly the model's responses.

Table 4. IRI and fit values for original and reconstructed kinematic excitation signals from noisy data. Values for fit are calculated with original signal as the reference

	A org.	**A rec.**	**B org.**	**B rec.**	**C org.**	**C rec.**	**D org.**	**D rec.**
IRI [m/km]	2.07	2.17	3.70	3.86	5.96	6.02	7.94	8.04
fit [%]	0.1108		0.0875		0.1062		0.1368	

In terms of the indicators of similarity between signals, fit and IRI values were calculated once again. The IRI value for the original A class road's kinematic excitation was 2.07 m/km, while the value for reconstruction was 2.17 m/km. It is a much bigger difference than in the case of signal without any noise added (0.1 compared to 0.03 difference), it still however is a satisfactory result, which puts the reconstructed profile in the same category of roads as the original one. As the quality of the road decreases, the difference in IRI becomes smaller and smaller, with classes C and D having even slightly more similar IRI values than before. The fit value for the two profiles is also worse than for the reconstructed signal without noise – it is 0.111%, which is much bigger compared to 0.0059% for A class road and similar decrease in similarity is noticeable for all road classes. Considering how much worse the reconstruction from noisy signal was, it is still a satisfactory result for the researchers.

5. Conclusions

The proposed method of kinematic excitation reconstruction was tested on the random kinematic excitation signals generated according to the contents of ISO 8608 standard. The authors implemented models for the roads of different classes (A to D), as well as linear quarter car model and noise model. In the first part of the research, the authors focused on testing how well the method is able to reconstruct excitations close to those encountered in real life. The results, after postprocessing involving detrending the reconstructed signal, are very good and they closely resemble original kinematic excitations.

To check their similarity the researchers used two indicators – the fit and IRI. The IRI values for all four road classes differed by no more than 0.11 m/km and reconstructed profiles fit in the same road categories established by Sayers and Karamihas [7]. The fit values were also very small, which means the signals were similar, with bigger fit values for worse quality roads that had their kinematic excitations reconstructed.

Having established that the method was well suited for the reconstruction of random profiles, the researchers added noise to acceleration signals, that constituted an input to the reconstruction algorithm to test its influence on the results. They came to the conclusion that in order to get satisfactory results, signal preparation and postprocessing of results was needed. Preparation involves using low-pass filter on the noisy signal, while postprocessing is done by using high-pass filter in the form on subtracting moving average of the profile. Those practices allow for satisfactory reconstruction of kinematic excitation, that for the A class road kinematic excitation resulted in IRI difference of 0.11 m/km and fit of 0.111% of standard deviation.

In the future research the authors plan to examine, how accurate the proposed method is when using real-life measurements. Non-linear or more complicated vehicle models will also be tested to determine if the proposed method yields similarly good results for those cases.

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