The method of kinematic excitation reconstruction based on measured suspension dynamic responses – experimental verification

Zbyszko Klockiewicz¹, Grzegorz Ślaski¹ and Hubert Pikosz¹

¹ Poznan University of Technology,

Maria Skłodowska-Curie Square 5, 60-965 Poznan, Poland

zbyszko.klockiewicz@put.poznan.pl

Abstract. The paper presents the method of kinematic road excitation reconstruction based on measured suspension dynamic responses and its reconstruction with use of estimated displacements of unsprung mass as a preliminary approximation of kinematic excitation and tracking control system with a PID controller that allows for faithful reconstruction of unsprung mass accelerations and, in turn, kinematic excitations. The authors performed an experimental verification of the method with use of one axle car trailer and measurements of road profile and acquiring signals of suspension dynamics responses. The signal processing methodology and obtained results are presented for random and determined excitations. The necessary requirements to use the method effectively were defined and its limitations were listed.

1. Introduction

The kinematic excitation is a primary type of vehicle vertical dynamics excitation, the other is a force excitation. The kinematic excitation forces the tread of the tire to move vertically as quickly as the actual vertical height of the road profile changes. It depends on road irregularities profile, vehicle speed and tire filtering properties and in some cases on whole vehicle vertical dynamics [1].

Due to this complexity of kinematic excitation it is not possible to just measure it as is possible in a case of road irregularities height profiles. It is possible to estimate kinematic excitation having given road profile and vehicle velocity and knowing filtering properties of a tire.

Due to these complications authors of this paper, like the other [2] proposed [3] to estimate kinematic excitation using measured signals of vehicle vertical dynamics responses and using proposed methodology to reconstruct kinematic excitation knowing vehicle vertical dynamics parameters. The method is similar to that known as Remote Parameter Control and used with electrohydraulic vibration excavators [4].

It is almost obvious task in case of using linear model of vehicle vertical dynamics and only simulated signals what authors proved in earlier papers [3,5]. In a case of using real measured signals of vehicle vertical dynamics and nonlinear vehicle model we obtain much complicated case, which was tested and described in this paper.
2. The method of kinematic excitation reconstruction

The proposed method for estimating (reconstructing) kinematic road excitations $z_r$ uses measured unsprung mass acceleration $\ddot{z}_{m,T}$ signal as an input for estimating procedure of kinematic excitations – the more thorough explanation can be found in [5], while the abbreviated version is presented here. Graphical presentation of the method can be seen in Figure 1.

The acceleration signal $\ddot{z}_{m,T}$ is first obtained in real life road experiments and is captured from accelerometers mounted as close to the wheel centre as possible. Wheel displacement estimate signal $z_{m,T,E}$ is obtained by integrating the acceleration signal $\ddot{z}_{m,T}$ twice. The resulting signal $z_{m,T,E}$ differs from kinematic excitation $z_r$ because of dynamics of a tire and also because of integration errors and other factors such as recording noise in the original signal.

Nonetheless it is then used as an input to the quarter car model with the output being unsprung mass acceleration from simulation $\ddot{z}_{m,S}$. This signal is different from real life test signal $\ddot{z}_{m,T}$ and the error $\dot{e}$ of accelerations between the two signals is calculated. After double integrating the error is processed by the PID controller which calculates correction $z_c$ trying to keep error $e$ equal to zero. This correction summed with the wheel displacement signal is creating an estimation of kinematic excitation signal $\hat{h}(t)$. The correction doesn’t apply to the iteration, in which the error was calculated. By having small time steps (in the case of this research 0.0001 s) the correction retains its relevance, as this allows the correction to occur after only a miniscule change in acceleration.

![Figure 1. The diagram of kinematic excitation reconstruction procedure.](image)

This procedure was tested in simulation using quarter car model and results were presented in a paper [3] in which IRI (International Roughness Index [4]) values were compared between original and reconstructed signals of road irregularities profiles. The biggest relative difference in IRI value was registered for the B class road and was equal to 3.0 % for input acceleration signal directly from quarter car simulation and 4.8 % for A class for simulation signal with added disruptions [6].

In this paper authors presents the experimental test of using this procedure for reconstructing kinematic excitation on the base of response signals measured on a single axle trailer for passenger car driving over two types of road profile – deterministic and stochastic.

3. Verification of the method

3.1. Experimental vehicle and measured variables

Test subject was single-axle trailer of gross vehicle weight 750 kg, meant to be towed by passenger vehicles. The trailer did not have brakes installed. Its technical characteristics are shown in Table 1.

In order to run simulations inside reconstruction procedure it was imperative to specify trailer’s parameters, which were then in turn implemented in a vertical dynamics suspension quarter-car model in Matlab-Simulink – Figure 2.
Table 1. Test trailer’s parameters.

| Model               | TEMA-MARTZ PREMIUM PRO 2012W |
|---------------------|-------------------------------|
| Type                | Single-axle car trailer      |
| Curb weight         | 161 kg                       |
| Maximum payload     | 589 kg                       |
| Gross Vehicle Weight| 750 kg                       |
| Wheel track         | 1515 mm                      |
| Length              | 3170 mm                      |
| Width               | 1680 mm                      |

A series of measurements of sprung and unsprung mass displacements were done, which were then used to calculate stiffnesses of the tire and suspension spring [7]. Damping coefficient was estimated based on the time it took the trailer to stop oscillating after being dropped from a curb. Tire coefficient was assumed based on similar types of tires that were previously examined. This data is shown in Table 2.

Table 2. Characteristics of a trailer used for a quarter-car model in Matlab.

Figure 2. Quarter car model used in reconstruction process.
### Measured variables

During the experimental phase of the research vertical dynamics responses were measured to be used as an input into the kinematic excitation procedure and also to comparative purposes. Those variables included:

- longitudinal distance travelled during measurement,
- suspension deflection $z_s - z_u$
- sprung mass vertical acceleration $\ddot{z}_s$
- unsprung mass vertical acceleration $\ddot{z}_u$.

### Experimental trials and tested road profiles

In order to verify the kinematic excitation reconstruction method a series of test rides was conducted and reconstruction was carried out for the data collected during those experiments. Signals were collected for two types of road irregularities:

1. **determined** – associated with a drop down from a curb of 9 cm with velocity of 4-7 km/h.
2. **random** – associated with rides with velocities of 10 and 20 km/h over randomly irregular pavement.

Those road surfaces are presented in the pictures in **Figure 3**, and the profile for determined irregularity measured with laser distance sensor is shown in **Figure 4**, as well as the version after the filtration modeling filtration properties of a tire. The filtration involved first subtracting the linear trend followed by using a constant track length tire model of 16 cm length. After accounting for vehicle velocity, the profile was then transformed into kinematic excitation and fed as an input to the Matlab-Simulink model.

**Figure 3.** Road irregularities used during tests a) deterministic, b) stochastic.
3.3. The signal processing methodology

Due to the different nature of the input signals (comparing to earlier simulation verification) to the road kinematic excitation reconstruction procedure – measurement signals with noise from real object (not a rigid body) – proved in earlier research [3,5] procedure had to be modified.

Measured signals were processed as follows:
- mean value was subtracted;
- linear trend was subtracted;
- highpass filter with the cutoff frequency of 15 Hz was applied;
- acceleration signal (after those transformations) were then integrated twice, and after each integration a lowpass filter with the cutoff frequency of 1 Hz (determined irregularity) or 0.3 Hz (random irregularity) was applied;
- reconstructed kinematic excitation signal was then, in addition to previous steps, filtered using a moving mean for a number of samples corresponding to 0.5 s for each vector’s element.

3.4. Results of kinematic excitation reconstruction

After modelling kinematic excitation based on measured irregularities’ profiles and carrying out the reconstruction process using author’s method, it was possible to compare both kinematic excitation signals.

3.4.1. Results for a determined excitation

In the reconstructed kinematic excitation the curb height the curb height was estimated to be between 7 and 10 cm (the height from filtered laser distance sensor after tire filtration was 8.4 cm) – Figure 5. The signal was shifted by 0.06 m down, as the method cannot account for the difference in height between two level planes.

**Figure 4.** Profile of a determined irregularity.
After the drop the reconstructed signals show a drop of around 0.04 m, that isn’t present in the signal from laser sensor, after which the low-frequency oscillations begin, which differentiates them from a laser sensor signal. Statistical data from the four tests can be found in Table 3.

**Table 3. Statistical data for determined irregularity**

| Road kinematic excitation | Calculated on the base of road profile measurement and tire filtered [m] | Reconstructed from vehicle responses – road test no 1 [m] | Reconstructed from vehicle responses – road test no 2 [m] | Reconstructed from vehicle responses – road test no 3 [m] | Reconstructed from vehicle responses – road test no 4 [m] |
|---------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| Minimum                   | -0.010                                          | -0.038                                          | -0.056                                          | -0.047                                          | -0.023                                          |
| Maximum                   | 0.074                                           | 0.049                                           | 0.044                                           | 0.044                                           | 0.049                                           |

Besides the reconstruction of the profile itself, it is equally as important to achieve similar levels of suspension’s dynamic responses for the resulting profiles, as they are then used to calculate the suspension performance criteria like safety and comfort criterion or the construction load.

Because of how the method works, the signal that is reconstructed almost flawlessly is unsprung mass acceleration (**Figure 6**), as the whole procedure was designed to minimize the error between the signals from experiment and the one using excitation reconstructed based on accelerations from experiment. Because of that the accuracy of reconstruction is very high – over 95%. The signal based on the profile created by filtering the laser sensor data has the minimal acceleration values twice as high as the aforementioned two signals.
Figure 6. Comparison between unsprung mass acceleration signals from experiments and one reconstructed from accelerations.

Figure 7 shows the comparison of suspension deflections from three sources:
- signal from real life tests (red line),
- suspension response for kinematic excitation based on the profile from laser sensor data that was subjected to tire filtration (blue line),
- suspension response for kinematic excitation based on the profile reconstructed using proposed method (yellow line).

In cases for both sprung mass accelerations from simulation the oscillation amplitudes were greater than experimental ones, which suggests the suspension parameters were not fully consistent with their real-life counterparts – especially the asymmetry of the damping force was not accounted for. The results still match well with the experimental results in the time domain, as the simulation results are 25% higher than minimum values and 70% higher than maximum values.

Figure 7. Suspension deflection values for determined irregularity.
Table 4. Statistical data for suspension deflections for determined irregularity

| Suspension deflections [m] | Simulated response to the reconstructed kinematic excitation | Road test signal |
|----------------------------|------------------------------------------------------------|------------------|
|                            | Test 1 Test 2 Test 3 Test 4 Test 1 Test 2 Test 3 Test 4    |                  |
| Minimum                    | -0.041 -0.047 -0.047 -0.033 -0.033 -0.033 -0.033 -0.033 |                  |
| Maximum                    | 0.056 0.055 0.056 0.048 0.031 0.030 0.032 0.030          |                  |

Figure 8 shows sprung mass accelerations for determined irregularity. Acceleration signals were compared for three sources:
- signal from real life tests (red line),
- suspension response for kinematic excitation based on the profile from laser sensor data that was subjected to tire filtration (blue line),
- suspension response for kinematic excitation based on the profile reconstructed using proposed method (yellow line).

The results from simulations show high qualitative accuracy when it comes to the signals in time domain. The minimum values were reconstructed with 85% accuracy, while the maximum ones were reconstructed with 50% accuracy. Once again, the blame for this can be put on the lack of damping force asymmetry that was not implemented in the model.

Figure 8. Sprung mass accelerations for determined irregularity

3.4.2. Results for reconstruction of stochastic road kinematic excitation
During tests various velocities were used but analysis of results proved that the best results were obtained for velocity equal to 20 km/h. Due to this reason in the paper results for this velocity are presented. The kinematic excitation reconstructed from unsprung mass accelerations for a ride with velocity of 20 km/h is shown in Figure 9.
Figure 9. Kinematic excitations for random irregularity for velocity of 20 km/h

Statistical parameters for resulting signals for random irregularity were compared and shown in Table 5. Those parameters show around 85% of reconstruction accuracy when it comes to RMS of the signals and standard deviations. The errors for minimum excitation value is 13% and 4% for maximum one. Those results are visualized in Figure 9 – it can be observed that the qualitative representation of the original signal is satisfying – the characteristic changes in both signals are visible, however it seems like the test vehicle’s velocity was not kept constant throughout the recording, which caused time-series to differ at the end.

Table 5. Statistical data for kinematic excitations for random irregularity for velocity of 20 km/h

|                        | RMS from laser sens. | RMS from acc. recons. | STD from laser sens. | STD from acc. recons. | MIN from laser sens. | MIN from acc. recons. | MAX from laser sens. | MAX from acc. recons. |
|------------------------|----------------------|-----------------------|---------------------|-----------------------|---------------------|----------------------|---------------------|----------------------|
| Mean value for 3 tests [m] | 0.0074               | 0.0080                | 0.0074              | 0.0080                | -0.0183             | -0.0172              | 0.0149              | 0.0170               |
| ratio between profile form laser sensor and VRPC reconstruction [%] | -                   | 84.1                  | -                   | 86.0                  | -                   | 87.5                 | -                   | 104.2                |

Figure 10 shows the suspension deflection signals for the test ride, as well as the reconstructed ones. Table 6 shows the statistical data for those signals.
Figure 10. Suspension deflection signals for random irregularity for velocity of 20 km/h

Compared to the deflection values from experimental data, the signals for reconstructed profiles gave around 40% higher values for all statistical data analyzed. For the minimum and maximum values they were around 30 and 60% higher, respectively, compared to signal from experiments.

Table 6. Statistical data for suspension deflection for random irregularity for velocity of 20 km/h

|               | RMS from exper. | RMS from acc. recon. | STD from exper. | STD from acc. recon. | MIN from exper. | MIN from acc. recon. | MAX from exper. | MAX from acc. recon. |
|---------------|-----------------|----------------------|-----------------|----------------------|----------------|----------------------|-----------------|----------------------|
| Mean value for 3 tests [m] | 0,0061 | 0,0085 | 0,0061 | 0,0085 | -0,0167 | -0,0214 | 0,0088 | 0,0143 |
| ratio between VRPC reconstr. and exp. data [%] | - | 139,43 | - | 139,58 | - | 128,46 | - | 161,86 |

Figure 11 shows the unsprung mass acceleration signals for the test ride, as well as the reconstructed ones. Table 7 shows the statistical data for those signals.

The accuracy of both RMS and STD for unsprung mass accelerations is very high – the error is between 2 and 3 % between experimental data and signals using profile reconstructed from unsprung mass accelerations. Minimum and maximum values for reconstructed unsprung mass accelerations are similarly close to the ones from the experiments – they differ by 3 to 7%.
Figure 11. Unsprung mass acceleration signals for random irregularity for velocity of 20 km/h

Table 7. Statistical data for unsprung mass accelerations for random irregularity for velocity of 20 km/h

|                  | RMS from exper. | RMS from acc. recons. | STD from exper. | STD from acc. recons. | MIN from exper. | MIN from acc. recons. | MAX from exper. | MAX from acc. recons. |
|------------------|-----------------|-----------------------|-----------------|-----------------------|-----------------|-----------------------|-----------------|-----------------------|
| Mean value for 3 tests $[m/s^2]$ | 3.64            | 3.74                  | 3.65            | 3.73                  | -14.19          | -14.58                | 19.88           | 18.64                |
| Ratio between VRPC reconstr. and exp. data [%] | -               | 102.71                | -               | 102.44                | -               | 102.78                | -               | 106.68               |

Figure shows the sprung mass acceleration signals for the test ride, as well as the reconstructed ones. Table 8 shows the statistical data for those signals.

Analysis of those statistical parameters show that the accuracy of RMS and STD for sprung mass accelerations between experimental data and signal from simulation using profile reconstructed based on unsprung mass accelerations is around 80%. Same level of accuracy can be observed for minimum and maximum values of those accelerations in comparison with experimental data.
Figure 12. Sprung mass acceleration signals for random irregularity for velocity of 20 km/h

Table 8. Statistical data for sprung mass accelerations for random irregularity for velocity of 20 km/h

|                  | RMS from exper. | RMS from acc. recon. | STD from exper. | STD from acc. recon. | MIN from exper. | MIN from acc. recon. | MAX from exper. | MAX from acc. recon. |
|------------------|-----------------|----------------------|-----------------|----------------------|----------------|----------------------|----------------|---------------------|
| Mean value for 3 tests $\frac{m}{s^2}$ | 1,87            | 1,48                 | 1,87            | 1,48                 | -3,66          | -2,87                | 7,09           | 5,54                 |
| ratio between VRPC reconstr. and exp. data [%] | -               | 79,48                | -               | 79,29                | -              | 78,34                | -              | 78,14                |

4. Conclusion
The results achieved in the study confirmed that the proposed algorithm can potentially be used to reconstruct kinematic excitations, but at the same time showed the shortcomings that need to be overcome in further research. The results for unsprung mass accelerations are very promising, being 95 to 98% accurate compared to the experimental data for all analyzed cases, as they were the signal the algorithm was reconstructing directly. This meant that the inaccuracies between quarter car model and the real test object played the smallest role for those signals.

For the kinematic excitation there is no possibility of directly comparing the reconstructed signal with the real-life one, with the exception of stationary tests using actuators, where such measurement is doable. That is why for comparison signal based on laser distance sensor was used, after taking into account the filtration of the tire and the velocity at which the vehicle was travelling.

For the determined irregularity – falling from a curb – the results in time domain are very similar for real-life experiments and simulation based on recreated profile. The curb height was estimated to
be between 7 and 10 cm, while the real value was 8.4 cm. The accuracy of suspension deflection in terms of time and amplitude is high. The results from simulation are around 25% higher for minimum values and 70% higher for maximum ones, but this stems from not accounting the damping force asymmetry in the quarter-car model. Minimum sprung mass accelerations in simulations were 85% accurate compared to the experiments, while the minimum values were 50% accurate.

For the random irregularity satisfying results were achieved for rides of velocities of 10 and 20 km/h. Analysis of statistical data showed that the error of kinematic excitation reconstruction’s RMS was 15% for both velocities. The minimum and maximum value errors were between 4 and 25%. For sprung mass accelerations, the error was 5% for the RMS and 20% for both extreme values.

The achieved reconstruction accuracy was deemed satisfactory at this preliminary stage of road test. Further improvements in the quality of reconstruction can be done by:

- improving the stiffness of the test vehicle – the closer it is to the rigid body model, the more registered acceleration signal are to the ones in the simulation model,
- improving the trailer (test vehicle) suspension’s parameter estimation, like the asymmetric damper model,
- developing more sophisticated filtering methods for the signals to be used before and after applying the procedure.

Developed method allows to generate kinematic excitation signals for real road surfaces for the purposes of research in the field of suspension construction, assessment of the fatigue strength as well as the effectiveness of applied suspension control algorithms.

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