# Experimental Analysis of Vehicle Response

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**Abstract:** The present article deals with the experimental monitoring of the vehicle response when driving along the road and the subsequent processing of the measured signals. Describes the used technique, the properties of the sensors and the methodology of measurement. It shows the possibilities of statistical analysis of the obtained signals, correlation dependences and frequency composition of vibrations. Makes conclusions for possible applications in engineering practice.

**Keywords:** experiment; vehicle; dynamic response; analysis; signal processing.

## 1 Introduction

The behavior of the vehicle when driving on the road can be modeled numerically or monitored experimentally. The experiment represents the most objective possibility of assessing objective reality, therefore its results have more weight than the results of numerical solutions. As experimental technique develops, so experimental procedures are also improved, especially the possibilities of processing measured signals. Vehicle response monitoring has also been done in the past [1–7]. It was done by mechanical and civil engineers, each from their own point of view. Civil engineers are interested in the results related to the road load, driving comfort and the ability to verify the calculation models of vehicles.

## 2 Experimental measurements and instrumentation

The subject of the experiment was the measurement of vertical accelerations at selected points of the Tatra T815 truck at different speeds of its movement along the road. The accelerometers were located on the right side of the vehicle on the front and rear axles and at the center of gravity of the vehicle's sprung mass, Fig. 1.

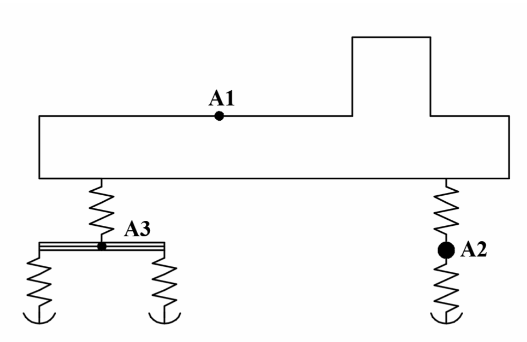


Fig. 1: Location of accelerometers on the vehicle.

The measuring line consists of the following components: sensor, amplifier, A/D interface, measuring center and data printer, Fig. 2. The signal transmission to the measuring center can be via cables (the center is located in the vehicle) or it is possible to use wireless transmission (the center is located outside the vehicle).

A piezoelectric miniature accelerometer Brüel & Kjær Deltatron 4508 B (Fig. 3) with the following parameters was used as a sensor: frequency range 0.4 – 8,000 Hz, measured range $\pm$70 m/s$^2$, temperature -54 – +100 °C, weight 4.8 gram, sensitivity 100 mV/ms$^{-2}$, output CCLD, resonance frequency 25 kHz.

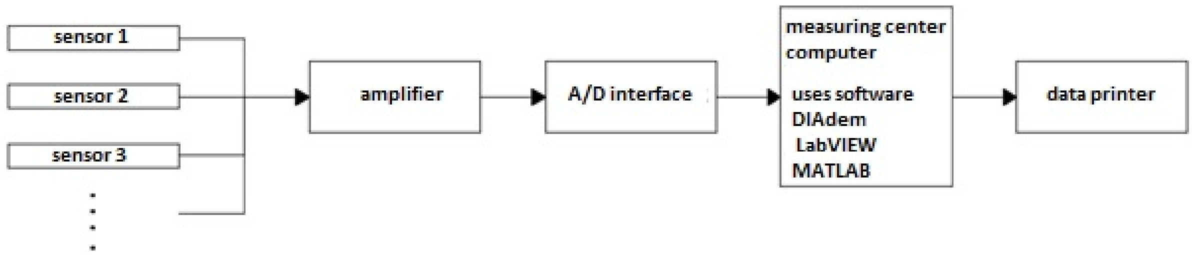


Fig. 2: Measuring line.


Fig. 3: Accelerometer Deltatron 4508 B.

M68D1 amplifier was used, Fig. 4. The amplifier is intended for connection of piezoelectric acceleration sensors. It enables functions such as amplification, low-pass or high-pass filtering, signal integration for speed or displacement measurement. It can be used in laboratory conditions as well as in the field.

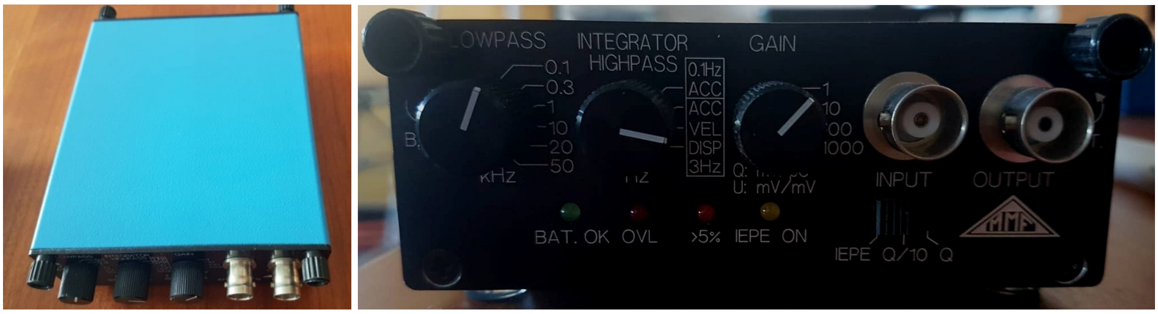


Fig. 4: Amplifier M68D1.

A/D converter NI 9215 was used, Fig. 5. The module contains four simultaneously sampled analog input channels, a sequential approximation register SAR and a 16-bit analog-to-digital converter ADCs.


Fig. 5: A/D converter NI 9215.

The response of the vehicle was monitored on a selected section of road 100 m long. The vehicle moved at different speeds in the range from 15.18 to 52.95 km/h. The total weight of the vehicle was 21,500 kg. The sampling frequency of 200 Hz was used for the measurement. The measurement was performed in a LabVIEW environment using the DIAdem system.

## 3 Processing of measured signals

Signal processing was done in MATLAB. Examples of possible analyzes are documented in the following text. In Fig. 6 is an example of time courses of vertical accelerations at test No. 4, vehicle speed $V = 33.84$ km/h, from sensors A1 – gravity center and A2 – front axle.

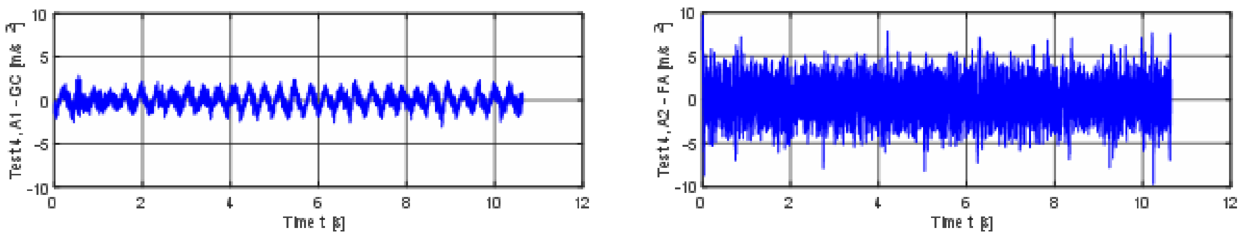


Fig. 6: Time courses of accelerations A1-GC, A2-FA, test No. 4, vehicle speed $V = 33.84$ km/h.

It is possible to make a basic statistical analysis of each record. For example the basic statistical characteristics of records A1 – gravity center, A2 – front axle and A3 – rear axle at test 4, vehicle speed $V = 33.84$ km/h are in Tab. 1.

Tab. 1: Basic statistical characteristics of records, test 4, speed $V = 33.84$ km/h.

| Test 4, $V = 33.84$ km/h | A1-GC | A2-FA | A3-RA |
|---|---|---|---|
| Mean value $\bar{a}$ [m/s$^2$] | 0.012876 | 0.009878 | 0.030961 |
| Arithmetic mean deviation $R_a$ | 0.710678 | 1.494229 | 1.658621 |
| Root mean square average deviation $R_q$ | 0.857459 | 1.885612 | 2.083721 |
| Dispersion $\sigma^2$ | 0.735236 | 3.555535 | 4.341895 |
| Effective value $RMS$ | 0.857555 | 1.885638 | 2.083951 |
| Asymmetry coefficient $R_{sk}$ | -0.105586 | 0.011212 | 0.024257 |
| Kurtosis $R_{ku}$ | 2.456701 | 3.144322 | 3.033628 |
| The greatest depth of record | -3.114865 | -8.202233 | -8.036912 |
| The largest height of record | 2.431183 | 7.859604 | 8.499235 |
| Overall height of the record | 5.546049 | 16.061838 | 16.536148 |

All statistical characteristics depend on the speed of the vehicle movement. Such a theoretical dependence has a large number of local maxima and spikes. It is a characteristic property for each quantity expressed on the speed of vehicle movement when solving the effects of moving loads on structures. The dependence of the RMS values of acceleration A-GC on the vehicle speed is shown in Fig. 7.

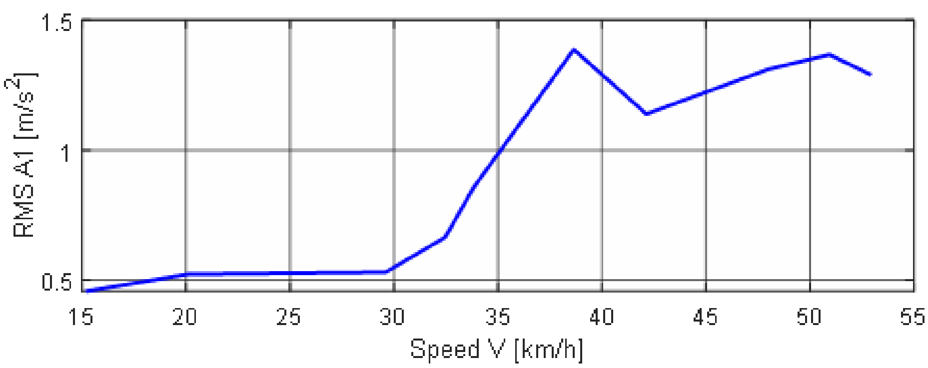


Fig. 7: RMS values of acceleration A1-GC on the vehicle speed.

The probability distribution histograms of acceleration from sensors A2-FA and A3-RA satisfy very well with Gaussian distribution law (red line), Fig. 8. The probability distribution histograms of acceleration from sensor A1-GC have in some cases the character of a bimodal distribution, Fig. 9.

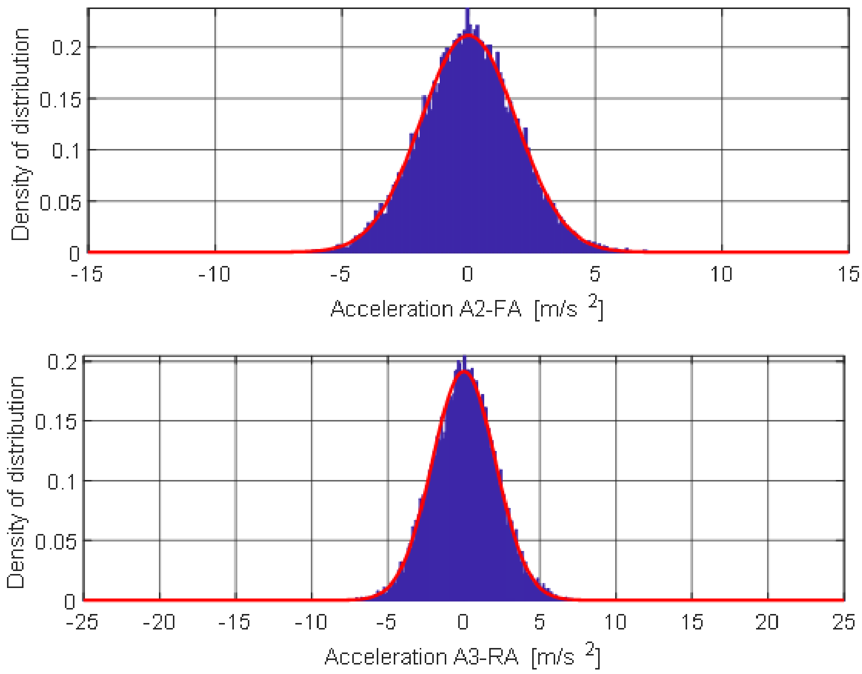


Fig. 8: Histograms of acceleration from sensors A2-FA and A3-RA, test 4, speed $V$ = 33.84 km/h.

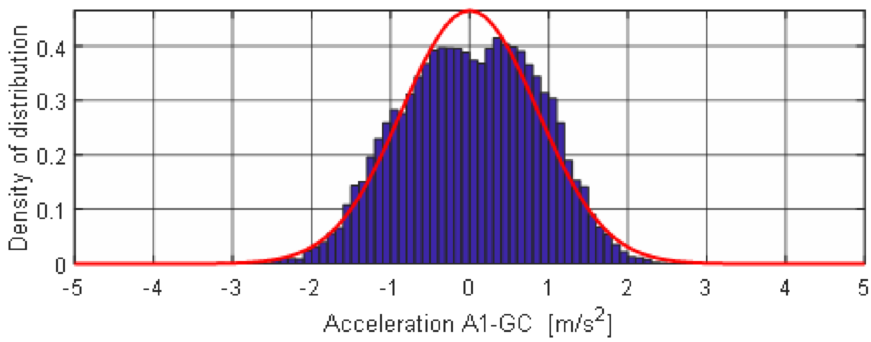


Fig. 9: Histogram of acceleration from sensor A1-GC, test 4, speed $V$ = 33.84 km/h.

Auto-correlation functions (ACF) and cross-correlation functions (CCF) can be quantified from acceleration records. It is suitable to work with standardized correlation functions, where the value of the correlation function at the zero point (lag = 0) is equal to zero. The maximum value $C_{\max}$ of CCF oscillates in a wide interval. Under certain circumstances and under certain mutual lag, the CCF value can be more than 40 times higher than when the records are not lagged relative to each other. For example, test 12, $V$ = 52.95 km/h (14.7091 m/s) the lag is +0.2375 s, what is 3.493 m and $C_{\max}$ = 40.4969. The theoretical distance between the front axle wheel and the front wheel of the rear axle is 3.55 m. The rear axle wheel follows the same road profile as the front axle wheel, but with a lad of 0.2375 s, which results in a high $C_{\max}$ value, Fig. 10.

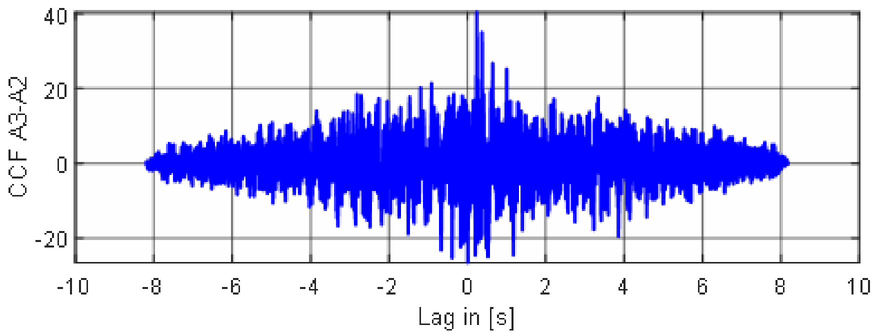


Fig. 10: Cross-correlation function A3-A2, test 12, speed $V$ = 52.95 km/h.

To solve dynamic problems in the frequency domain, it is necessary to know the frequency spectra. A fast Fourier transform (FFT) is used to calculate the frequency spectra. The number of $2^n$ samples is used. The spectra can be amplitude or phase. It is worked with different types of amplitude spectra. The difference between them is only in scale. Power spectral densities (PSD) are often used to provide information on the power of individual frequency components. PSD of accelerations from sensors A1, A2, A3 for test 12, speed $V$ = 52.95 km/h in the frequency range 0-50 Hz are shown in Fig. 11–13.

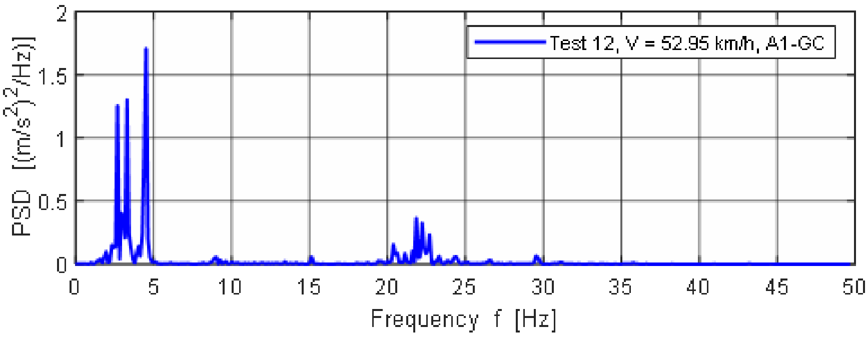


Fig. 11: PSD of accelerations, sensor A1-GC, test 12, speed $V$ = 52.95 km/h.

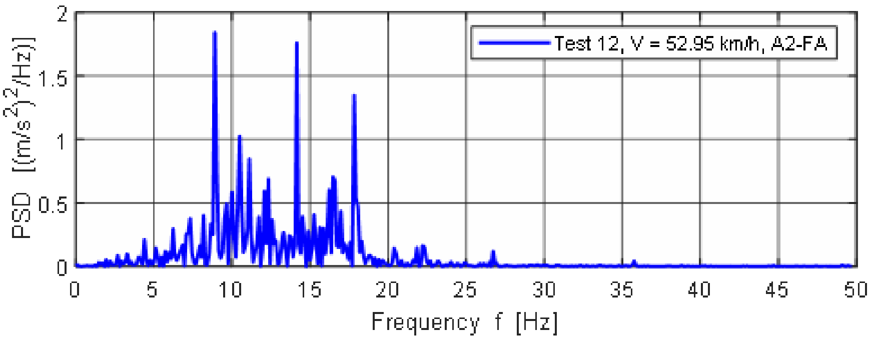


Fig. 12: PSD of accelerations, sensor A2-FA, test 12, speed $V$ = 52.95 km/h.

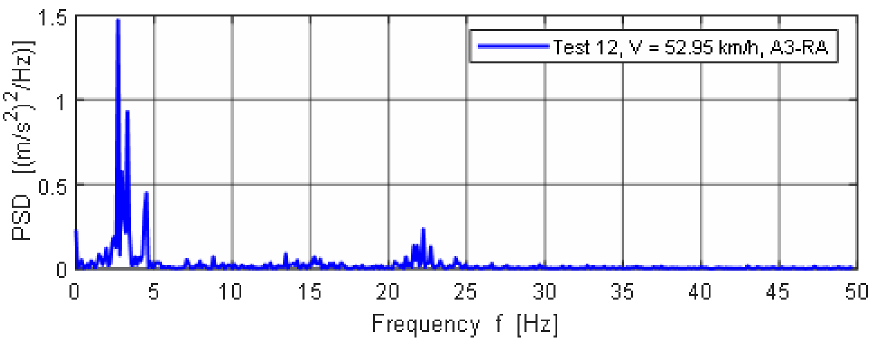


Fig. 13: PSD of accelerations, sensor A3-RA, test 12, speed $V$ = 52.95 km/h.

## 4 Conclusion

The experiment is the only tool for finding objective reality. It is advantageous to measure accelerations when monitoring the vehicle response when driving along the road. There are many suitable sensors for this purpose. The signal from the sensor to the measuring center can be transmitted via cables or wireless transmission can be used. There are also many tools for time and frequency domain signal analysis, such as DIAdem or MATLAB. The quality of the results when using these tools is high. Numerical methods are currently making great progress. Current computing and numerical simulation methods make it possible to simulate real operating states in real time. However, we need to be sure that the calculation model is in line with reality. Therefore, these type of experiments will need to be carried out in the future. Once the computational model is in line with reality, many analyses will be able to be done numerically. This is the progress of these procedures. It saves time, energy, finances and moves knowledge one step further.

## Acknowledgement

This work was supported by the Grant National Agency VEGA of the Slovak Republic, G1/0006/20.

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