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Vibration control in semi-active suspension of the experimental off-road vehicle using information about suspension deflection

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The efficiency of vibration control in an automotive semi-active suspension system depends on the quality of information from sensors installed in the vehicle, including information about deflection of the suspension system. The control algorithm for vibration attenuation of the body takes into account its velocity as well as the relative velocity of the suspension. In this paper it is proposed to use the Linear Variable Differential Transformer (LVDT) unit to measure the suspension deflection and then to estimate its relative velocity. This approach is compared with a typical solution implemented in such applications, where the relative velocity is calculated by processing signals acquired from accelerometers placed on the body and on the chassis. The experiments performed for an experimental All-Terrain Vehicle (ATV) confirm that using LVDT units allows for improving ride comfort by better vibration attenuation of the body.

Key words: vibration control, magnetorheological damper, linear variable differential transformer, skyhook.

1. Introduction

Semi-active automotive suspension systems [9] have numerous applications, especially for vehicles used in significantly varying road conditions. This type of suspension is characterized by low energy consumption, inherent stability and ability to adapt to different road conditions. Generally, semi-active devices used in vehicles are magnetorheological (MR) dampers [11], in which the relationship between damping force and the piston velocity depends on the instantaneous viscosity of the MR fluid filling the damper. This viscosity can be adjusted by the magnetic field induced inside the piston. State of the MR fluid can be changed from liquid to semi-solid within milliseconds. Controlling current flowing through the coil allows for modifying the MR damper characteristics according to the ride conditions. In the recent literature numerous algorithms

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for the MR damper control can be found, such as, e.g., Skyhook or Groundhook [8]. In [6] linear and nonlinear feedback control algorithms for MR dampers are compared. Besides, information about the road profile which is obtained in advance can be applied in feed-forward control using, e.g., FxLMS approach [7].

Proper control of the damping parameters can be adjusted regarding to the information from different types of sensors, like LVDT [2], vision cameras [10], laser range scanners [1], or using other measurement methods like, e.g., structured light, RGB-D, infrared, ultrasonic sensors or multi-sensors approach [12]. Application of a laser range scanner in the experimental ATV [5] was tested during a special student program called PBL (Project Based Learning), but some disadvantages have been identified, e.g., changes of the vehicle position in the z-axis may result in replacing some of the scan lines, and produce incorrect values of the distance between the scanner and the road object. Besides, solutions based on image processing are computationally demanding, whereas the real-time processing imposes limits on the architecture of the system which should be simple, reliable and accurate. Thus, it is assumed that information about vehicle motion and, indirectly, about road roughness should be acquired from accelerometers and LVDT sensors, which measure the suspension stroke based on change of the position of the movable magnetic rod.

The paper is organised as follows. Section 2 refers to an experimental set-up together with the architecture of the measurement and control system applied in this research. In Section 3 Skyhook approach for vibration attenuation is described. Next, methods of vertical velocity estimation are analyzed in Section 4, and experimental results of vibration attenuation are presented in Section 5. Final conclusions are drawn in Section 6.

2. Description of the system

The experimental set-up is based on the off-road vehicle (see Fig. 1) modified by replacing the classical dampers by the MR ones produced by the Lord Corporation. Basic version of the test platform is equipped with the following devices: accelerometers from Freescale Semiconductor, peripheral measurement and control units, the main controller based on the Beaglebone-White single-board computer. In this research the measurement system has been extended by additional devices, i.e.: LVDT sensors and dedicated signal conditioners produced by Peltron, the National Instruments (NI) sbRIO platform which serves as a controller dedicated to LVDT units, and an IMU (Inertial Measurement Unit) assembled using the STMicroelectronics integrated circuit.

Transfer of measurement data from accelerometers to the main controller through the CAN bus is realized by a controller program written in C language. Software for LVDT sensors has been created using LabVIEW which supports NI platforms. A NI sbRIO platform is additionally connected to the main suspension controller via the RS-232 communication protocol. Communication with IMU has been established using the

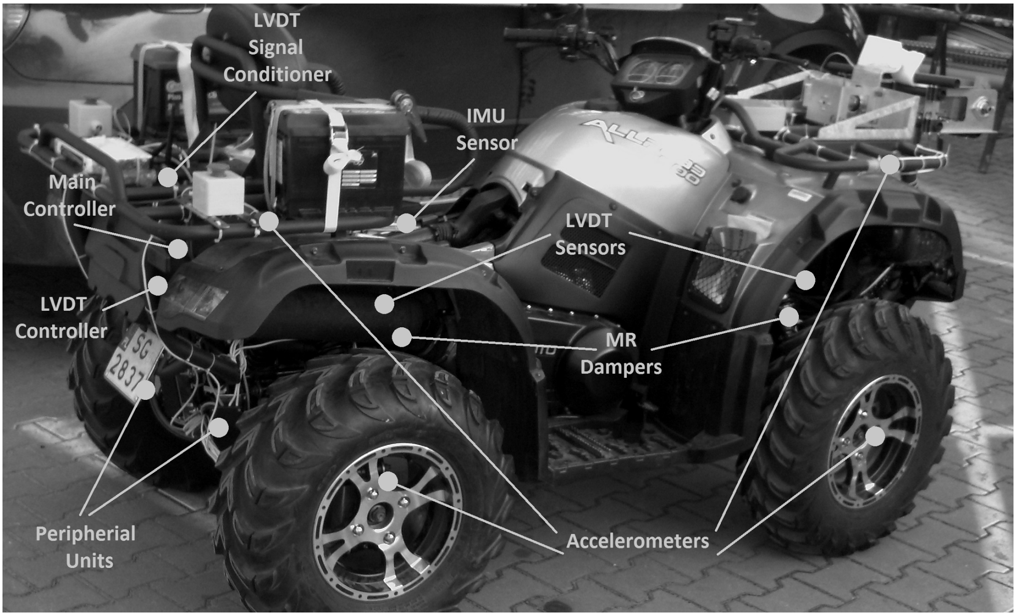

Figure 1: ATV with vibration control and vehicle motion measurement system

same NI controller. The developed measurement and control system is presented in the block diagram in Fig. 2.

Four three-axis accelerometers are installed on the vehicle body as well as four next to each wheel. They are used for measuring the absolute vertical acceleration of the ATV body (the sprung mass) and the chassis (the unsprung mass). However, the vibration control algorithm requires estimates of the absolute vertical velocity of the body and the relative velocity of the suspension system. Commonly, in order to obtain velocity estimates, the acceleration signals are integrated. Here, LVDT sensors have been also placed in the vicinity of the suspension shock-absorbers, on the same screws as dampers. They measure relative suspension displacement of the suspension system. Therefore, the LVDT signals can be differentiated and used instead of accelerometers for estimation of the relative velocity of the suspension elements.

3. Vibration control

The goal of vibration control is the minimisation of vibration of the selected vehicle part while driving through an obstacle, in this case a beam lying on the track. Shortly, it means that the suspension should be soft when wheels reach the beam, but when the ATV comes down, dampers should become harder to reduce oscillations of the vehicle body.

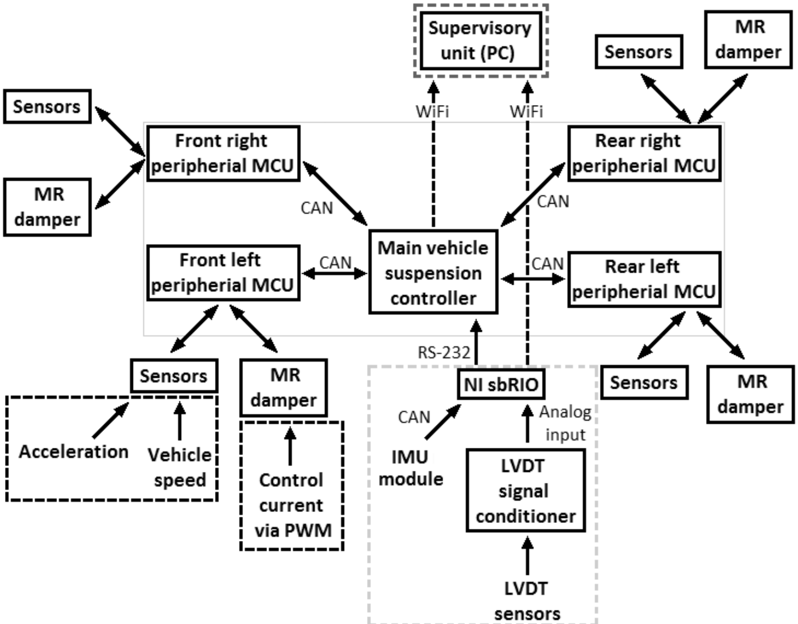

Figure 2: Architecture of the proposed measurement and control system

A classical approach to vibration control in the semi-active suspension system is based on the Skyhook algorithm [3], where the optimal control signal is able to isolate the sprung mass from the base excitation. It means that a force generated by the damper should be proportional to the absolute vertical velocity of the sprung mass v_s:

$$F_{alg} = -\delta \cdot v_s, \tag{1}$$

where the gain factor δ should be properly tuned to obtain good vibration attenuation.

Thus, the damper control signal (i.e. current controlling viscosity of the MR fluid in the damper) can be calculated as follows:

$$i_{ctrl} = \begin{cases} i\left(F_{alg}, v_{mr}\right) & \text{for } v_s(v_s - v_u) > 0, \\ \\ 0 & \text{for } v_s(v_s - v_u) \leqslant 0, \end{cases} \tag{2}$$

where: v_u is the velocity of the unsprung mass (the base excitation) and $v_{mr} = v_s - v_u$ denotes the relative velocity of the damper piston. The inverse model of the MR damper

$$i\left(F_{alg}, v_{mr}\right) = \left[\frac{-F_{alg} - c_0 \cdot v_{mr} - \alpha_0}{\alpha_1 \cdot \tanh(\beta_0 \cdot v_{mr}) + c_1 \cdot v_{mr}}\right]^2 \tag{3}$$

was identified in special experiments [4], where $\alpha_0 = 62.42$, $\alpha_1 = 1340$, $\beta_0 = 39.95$, $c_0 = 802.8$ and $c_1 = 488.5$.

It should be noticed that the following velocities are used in the above equations: the absolute velocity of the vehicle body v_s and under-body parts v_u as well as the relative velocity of the damper piston, v_{mr}. They should be estimated based on the appropriate measurement signals. Since each quarter of the vehicle suspension is controlled independently using the proposed Skyhook algorithm, the set of variables v_u, v_s, v_{mr}, F_{alg} reflects any part of the suspension.

4. Velocity estimation

Usually, in this type of applications, a vertical velocity of the vehicle body is estimated by integration of a signal acquired from an accelerometer mounted on the body, whereas the damper piston velocity is calculated as a difference between the estimated body velocity and the velocity of the unsprung mass estimated using a signal from an accelerometer mounted on the chassis, near a wheel. In order to improve the accuracy of the current calculation according to (3), and consequently the quality of vibration control, we propose to estimate the relative velocity v_{mr} based on differentiation of the signal from the LVDT sensor measuring the displacement of the damper piston.

4.1. Data preprocessing

Since, 3-axis accelerometers were used in this application, signals measured by the sensor was transformed into the vertical acceleration with respect to the vehicle's reference coordinate system. Typical measurements taken from the accelerometer and the LVDT deflection sensor located in the front right side of the vehicle are presented in Fig. 3. These signals were acquired with the sampling interval 2 ms while crossing the obstacle at zero control current of the MR damper. It can be stated that signal from the accelerometer exhibits an offset caused by the gravitational acceleration as well as a big noise induced by the vehicle engine. Also, the offset can be observed in the measured deflection of the suspension caused by the non-zero point of the LVDT operation, but influence of the engine noise is small.

Generally, two types of measurement disturbances can be distinguished in this case: sensor-induced and engine-induced. The sensor-induced noise is an inherent parameter related to the operating range of frequencies. Comparison of measurement noise and measured signals in frequency domain is presented in Fig. 4. The sensor-induced noise was acquired for a stationary vehicle with the engine off, whereas measurements were taken for the vehicle driving the test route. Based on presented power spectral densities it can be evaluated that signal-to-noise ratio for the whole 250 Hz frequency range is equal to 51 dB for the acceleration measurements and 57 dB for the suspension deflection measurements.

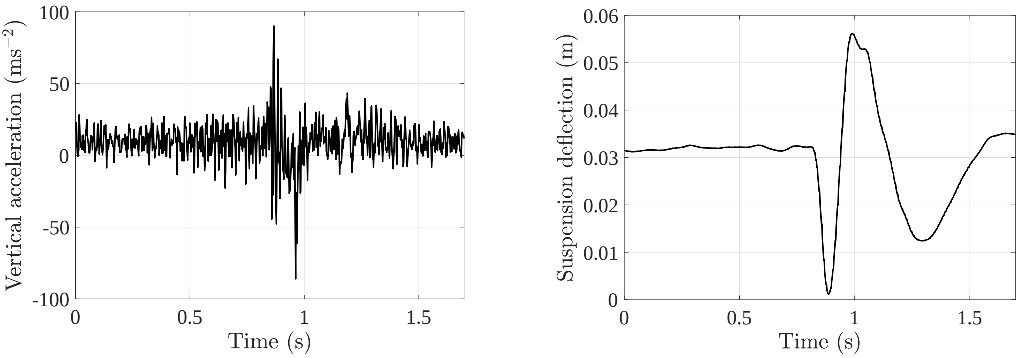

Figure 3: Sample measurement signals: body acceleration (left), suspension deflection (right).

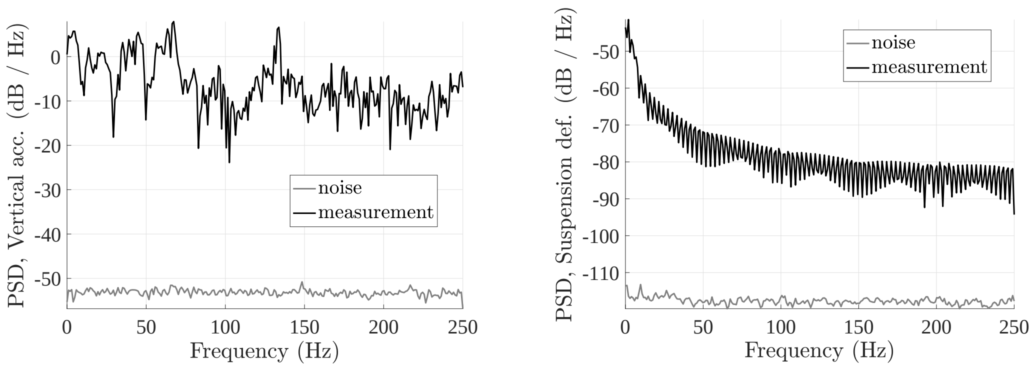

Figure 4: Power spectral density of measured signals and measurement noise for accelerometer (left), LVDT (right).

Because integration of signals may lead to problems with an offset and a signal drift, so invariant influence of the gravitational acceleration was excluded from the resultant acceleration signal a_j by subtracting an estimated averaged acceleration $a_{avg,j}$ from the raw measurement $a_{sensor,j}$:

$$a_j(n) = a_{sensor,j}(n) - a_{avg,j}(n), \tag{4}$$

where n denotes the time instant, and the averaged acceleration is the result of low-pass filtering in the discrete-time domain:

$$a_{avg,j}(n) = \left[H_{lp}(z^{-1})\right]^2 \cdot a_{sensor,j}(n) = \left[\frac{0.001}{1-0.999z^{-1}}\right]^2 \cdot a_{sensor,j}(n), \tag{5}$$

where z^{-1} is the delay operator. Here index j refers to the relevant part of the vehicle body: front or rear, and left or right.

In the case of vehicle vibration control the frequency-range-in-interest of the acceleration signals varies from about 1 Hz to 25 Hz [9], so time constant of the low-pass digital filter denoted here as $H_{lp}(z^{-1})$ was set to 2 seconds resulting in a cut-off frequency equal to 0.5 Hz.

Finally, the velocity estimation can be implemented as integration with inertia according to the following formula:

$$v_j(n) = H_{int}(z^{-1}) \cdot a_j(n) = \frac{T_s}{1 - 0.99z^{-1}} \cdot a_j(n), \tag{6}$$

where T_s denotes the sampling interval and dynamics of the inertial part of the filter $H_{int}(z^{-1})$ can be characterized by a time constant set to 0.2 seconds. The estimated velocity of the vehicle parts are used in the Skyhook algorithm directly according to (2), or they are used for estimation of the relative velocity applied in the inverse model (3).

In the second approach the relative velocity can be estimated by differentiation of the signal from LVDT sensor measuring the displacement of the damper piston:

$$v_j(n) = \frac{(1 - z^{-1}) \cdot x_j(n)}{T_s}, \tag{7}$$

where x_j denotes a deflection of a suspension.

4.2. Experimental results

Both methods of velocity estimation were compared in experiments performed as individual trips by a beam with a height of 0.08 m and for a vehicle speed of about 20 km/h. Vehicle vertical movement was recorded by 8 accelerometers and 4 LVDT sensors positioned as shown in Fig. 1. Operation of the suspension system was tested for the different levels of current controlling the MR dampers: 0, 0.07, 0.13, 0.27, and 0.53 A. Here only a few examples of experimental results can be presented.

Sample plots of the relative velocity estimated by both methods for 5 consecutive runs for the same control current are shown in Fig. 5. This confirms the greater impact of errors caused by subtraction of two estimates calculated by integration. It may suggest that using LVDT-based estimates gives the opportunity to get better results of control in comparison with the acceleration-based approach.

Repeatability of experiments was validated performing 5 runs for the same configuration of the suspension system. In order to exclude disturbances generated by the vehicle engine signals were additionally filtered by the 20th-order Chebyshev low-pass filter of first type with the cut-off frequency equal to 35 Hz. Next, the velocity was estimated and time diagrams of velocity signals were averaged as follows:

$$v(n) = \frac{1}{5} \sum_{k=1}^{5} v_k(n), \tag{8}$$

where k refers to a consecutive experiment.

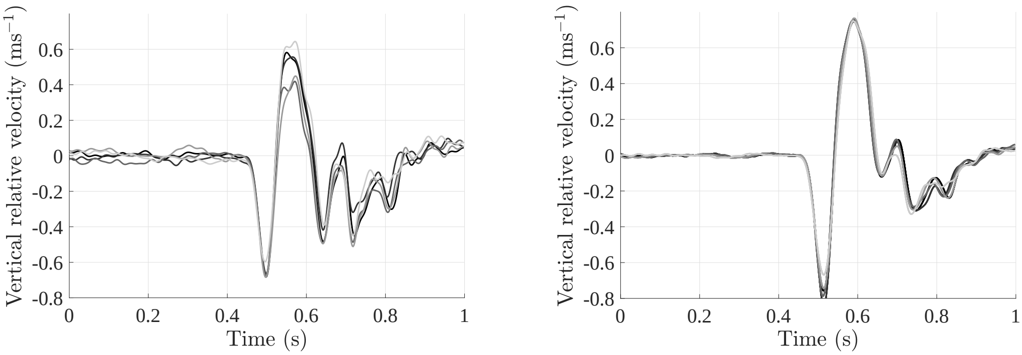

Figure 5: Vertical relative velocity of the left front part of the suspension for 5 consecutive rides for current 0.07 A, estimated using: accelerometers (left), LVDT (right).

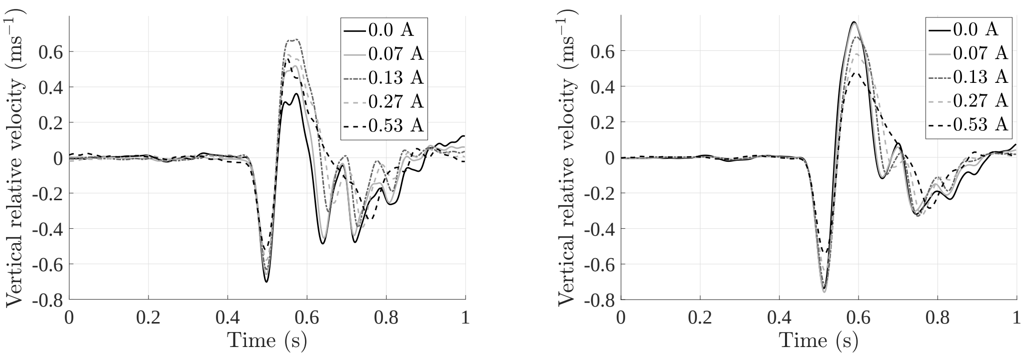

Figure 6: Vertical relative velocity of the right front part of the suspension estimated for different control currents using: accelerometers (left), LVDT (right).

The averaged values of velocity estimates are shown in Fig. 6 and 7. They depict the relative movement of the right and left front part of the suspension, respectively. Reduction of the maximum amplitude of the relative velocity according to increase of the control current can be easily noticed for results obtained by using LVDT measurements. This is in line with expectations, that the higher current should result in better damping. Plots of the velocity estimated using acceleration measurements indicate some irregularities in waveforms, not existing in reality, as well as occurrence of the offset. Furthermore, in the case of acceleration-based estimates, decreasing of the amplitude for increasing control current is not met which confirms greater deterioration of these estimates in comparison to the LVDT-based results.

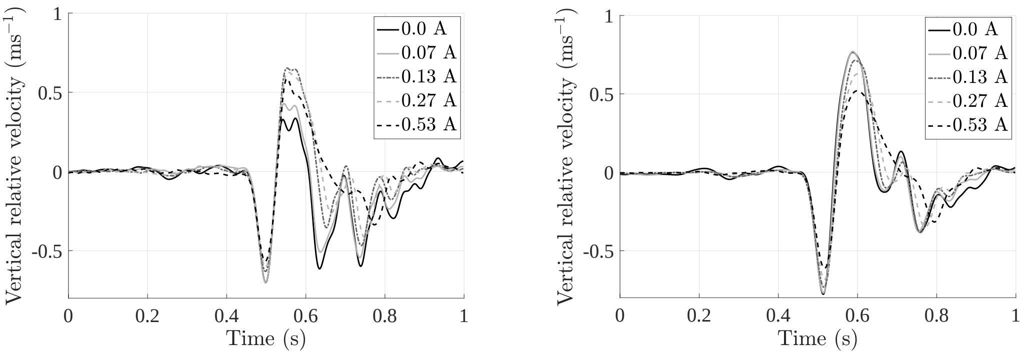

Figure 7: Vertical relative velocity of the left front part of the suspension estimated for different control currents using: accelerometers (left), LVDT (right).

5. Results of vibration attenuation

Effectiveness of vibration attenuation was tested for both methods of the relative velocity estimation. Control current was calculated according to equation (2) independently for each MR damper. Generally, the ride comfort is assessed on the basis of the acceleration acting on the driver or the passenger, so we propose to evaluate the effectiveness of control algorithms using a signal from IMU situated near the driver seat. The main problem in implementation of the Skyhook algorithm is the proper choice of the gain δ. The mathematical model of the system is non-linear and the optimisation procedure for δ selection is very difficult to perform, so the gain factor in (2) was determined experimentally by the trial and error method. For each part of the suspension δ was changed within the range defined on the basis of previous research. It was found that the best results for control algorithm using estimation of the relative velocity based on acceleration sensors can be obtained for δ equal approximately 3000, whereas for estimation based on the LVDT sensors the gain factor δ was a little smaller and was 2500. However, it was also stated that effectiveness of vibration attenuation is not very sensitive to δ, which can vary over a fairly wide range.

Exemplary results of the acceleration measured by IMU obtained for both methods of the relative velocity estimation are shown in Fig. 8. It can be easily observed that the maximum value of the acceleration, having the greatest impact on the feeling of comfort ride, reaches about 18 ms^{-2} for control using accelerometers, whereas it reaches about 12 ms^{-2} for control using LVDT. Thus, this confirms the supposition that using LVDT sensors for estimation of the relative velocity may improve effectiveness of vibration attenuation in this case.

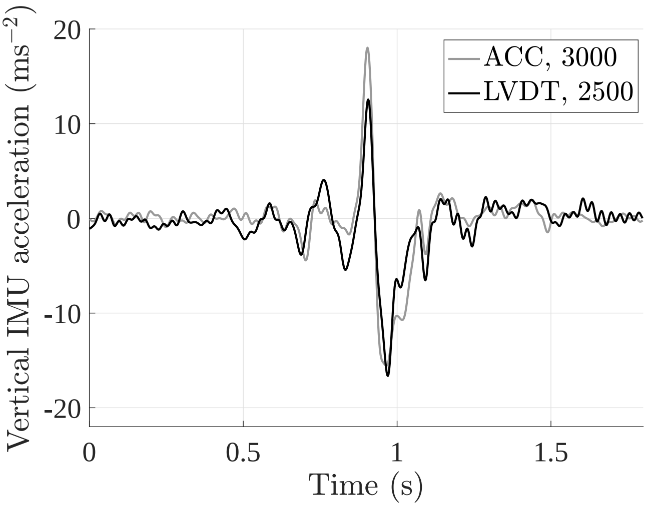

Figure 8: Acceleration measured by IMU for both methods of relative velocity estimation, averaged over different vehicle rides

6. Conlusions

In this paper vibration control in the semi-active automotive suspension using two ways of the relative velocity estimation has been considered. One method represents classical approach based on subtracting the velocity of sprung and unsprung masses, estimated on the basis of signals acquired from accelerometers. The other method uses signals from LVDT units. It was shown that LVDT-based estimates are less susceptible to measurement noise and using them in the inverse model of the MR damper to calculate the control current may lead to better vibration attenuation of the vehicle body. It also seems that estimation of the body velocity required in equation (1) based on some kind of combination of signals from accelerometers and LVDT sensors may improve the results of vibration control. This will constitute the next stage of the research.

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