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THE USAGE OF A LASER HEIGHT SENSORS FOR ESTIMATING ROAD UNEVENNESS PROFILE

WYKORZYSTANIE CZUJNIKÓW LASEROWYCH WYSOKOŚCI DO ESTYMACJI PROFILU NIERÓWNOŚCI DROGI

VYTENIS SURBLYS[1], GRZEGORZ ŚLASKI[2], HUBERT PIKOSZ[3]
Vilnius Gediminas Technical University, Poznań University of Technology

Summary

The paper presents results of simulation and experimental tests of proposed algorithm of compensation vehicle vertical and pitch dynamics in laser signals to get an estimation of road unevenness profile. In the beginning of the paper the problem of defining actual road unevenness profile height was described and a method to solve this problem was proposed. The described problem arises from the fact that measurement of the distance between laser height sensor and road is done with a sensor mounted to the vehicle body, which have its own dynamics. The method of compensation laser sensor signal for body movement – pitch and heave – was proposed and tested with simulation and experimental tests. For simulation tests half car model implemented in a Simulink and Matlab was used and for experimental test passenger car Opel Astra was used with algorithm implemented in dSpace electronic control unit prototyping system. Simulation test proved that the idea is correct and allows to fully compensate laser signal for body movement. Experimental test showed that method is easy to implement and fully effective in a simulation environment but

[1] Vilnius Gediminas Technical University, Faculty of Transport Engineering, Department of Automobile Transport, Saulėtekio al. 11, 10223 Vilnius; e-mail vytenis.surblys@vgtu.lt

[2] Poznan University of Technology, Faculty of Machines and Transport, Plac Marii Skłodowskiej-Curie 5, 60-965 Poznań; e-mail grzegorz.slaski@put.poznan.pl

[3] Poznan University of Technology, Faculty of Machines and Transport, Plac Marii Skłodowskiej-Curie 5, 60-965 Poznań; e-mail hubert.pikosz@put.poznan.pl

is much more complicated with a real application. It is because information about body movement is not accurate as in a simulation and a special signal processing methods need to be added to procedure working with a simulation signals. Acceleration signals must be integrated with use of a special band pass filtering, but with its use it is able to get good results of compensation also with a real car and real sensor signals.

Keywords: control suspensions, estimation of road unevenness, laser height sensors

Streszczenie

W artykule przedstawiono problem określania rzeczywistej wartości wysokości profilu nierówności drogi w czasie rzeczywistym i zaproponowano oraz przetestowano metodę rozwiązania tego problemu. Problem wynika z faktu, że zaproponowany pomiar odległości pomiędzy laserowym czujnikiem wysokości a drogą jest wykonywany czujnikiem zamontowanym do nadwozia samochodu, które ma swoją własną dynamikę. Zaproponowaną metodę kompensacji sygnału lasera dla ruchów nadwozia – przechyłu wzdłużnego i drgań pionowych – przetestowano z wykorzystaniem badań symulacyjnych i eksperymentalnych. W badaniach symulacyjnych wykorzystano model płaski połowy samochodu zaimplementowany w Simulinku i Matlabie, w badaniach eksperymentalnych wykorzystano samochód osobowy Opel Astra wraz z algorytmem kompensacji zaimplementowanym w systemie prototypowania elektronicznych jednostek sterujących firmy dSpace. Testy symulacyjne dowiodły, że idea kompensacji jest poprawna i pozwala na pełną kompensacje ruchów nadwozia w sygnale z czujnika lasera. Badania eksperymentalne wykazały, że metoda prosta do implementacji i w pełni efektywna w środowisku symulacyjnym jest znacznie bardziej skomplikowana w rzeczywistym pojeździe. Wynika to z tego, że informacja o ruchach nadwozia nie jest dokładna tak jak w symulacji i konieczne jest zastosowanie w procedurze pracującej z sygnałami symulowanymi dodatkowej specjalnej obróbki sygnałów z czujników. Sygnały przyspieszenia muszą być całkowane ale musi być też wykonana specjalna filtracja pasmowo-przepustowa. Po wykonaniu tych dodatkowych kroków można uzyskać dobre rezultaty także z rzeczywistym samochodem i sygnałami z rzeczywistych czujników.

Słowa kluczowe: zawieszenia sterowane, pomiar nierówności drogi, laserowe czujniki wysokości

1. Introduction

Knowledge about road surface is very useful for driver. This knowledge allows to predict the level of vehicle vertical dynamics response taking into account also vehicle longitudinal velocity. But the driver uses this knowledge in a other way than it can be used by vehicle dynamics control systems. As the driver only estimates the level of height of unevenness and uses of his wide experience about the relation between type of the surface, the level of vehicle velocity and a resulting vehicle dynamics vertical response the control systems rather needs to calculate the response using some model of vehicle dynamics structure and quantitive information about road unevenness profile.

One of the way to measure road unevenness is to use a laser height sensor allowing to measure a relative distance between road surface and sensor mounted to the vehicle body. The problem of this measurement is a dynamics (vertical and rotational) of a vehicle body which influence sensor signal. Therefore, the biggest problem is to compensate sensor signal for body movements signals. In Fig. 1. are shown simulated signals of sensor mounted on a vehicle body during travelling with small constant speed (10 km/h) over the 5 centimetre high speed lowering bump. There are presented signals for three cases:

1) for using a laser sensor sliding on a horizontal bar (without body movement) just for scanning road profile,
2) for using laser sensor mounted on a body in a 1 m distance to the vehicle front from front axle,
3) for using laser sensor mounted on a body exactly over front axle.

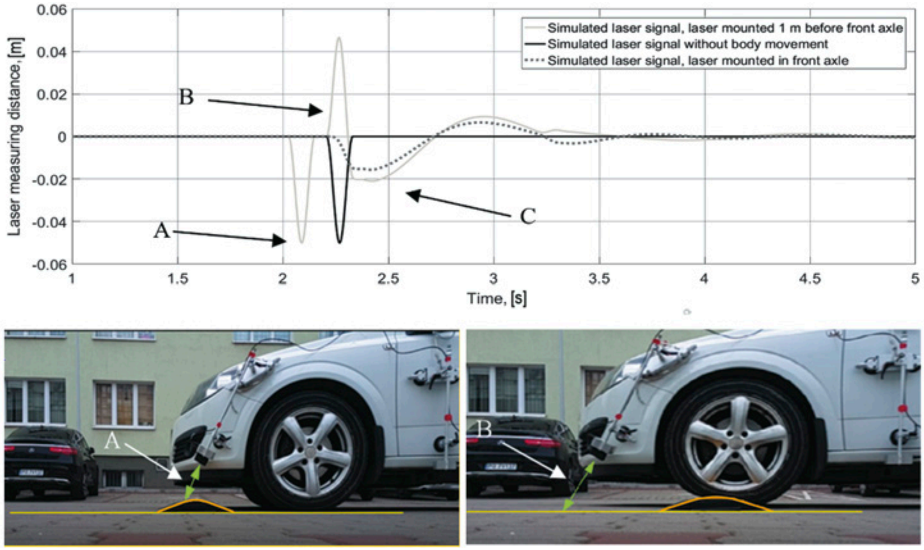

Fig. 1. Simulated laser signals without compensation (vehicle ride over a bump with speed 10 km/h)

As the direct signal form laser sensor is a distance between sensor and road surface (h_0), in a first case we get signal which after compensating it for h_0 has a negative values when laser is moved over a bump. It gives a mirror image of a road profile. Lower part of Fig 1. explains reason for signal values. Part A of laser signal for case 2) results from the situation similar to the case 1) until wheel enters the speed lowering bump – dimension A on a lower part of figure 1. Part B of laser sensor for the case 2) results from upwards movement of vehicle body. If a speed is a very small the body movement is almost equal to bump height, if a speed is a higher a suspension and a tire deflection occur and influence resulting signal. Part C of laser signal results from additional body movements after exiting speed lowering bump, although road under laser sensor is flat. In the case of additional longitudinal vehicle dynamics (vehicle acceleration or braking), the pitch angle will increase and lasers signals will be much more different from road unevenness profile.

2. Literature review

In literature, use of road surface estimation in a front of vehicle to control suspension is sometimes called as "Preview Control" [4, 6]. Some of scientist already have used lasers sensors for road surface estimation. Göhrle et. al. [5] used sensors mounted on vehicle's front window to measure distance from vehicle body to road to change active shock absorbers parameters. In that article scientist, met the same problem with laser signal compensation for body dynamics and sensor's signal filtering. In another paper [2] authors described the use of laser sensors mounted in the car's radiator grill to generate 3D road surface description. Authors mentioned that obtained signal could be used for control active suspension parameters and also for others automotive systems. Scientists in another paper [1] described scanning road profile ahead vehicle using LIDAR (Light Detection And Ranging) sensors. By using the trigonometric relations of the sensor with respect to the vehicle motion, the road profile was calculated. Authors used 7 Degrees Of Freedom (DOF) full vehicle vertical model for simulations and quarter-car test rig for experimental tests. They get better results than using the other known semi-active control algorithms. Sugai et. al. [8] tried to use Preview Control to enhance ride comfort in vehicle with electric active suspension. They adopted preview ride control into electric active stabilizer suspension system and have improved ride comfort and road holding over a wide frequency range and reduced the energy consumption of the system. Authors of the next analyzed article [9] used another novel road estimation method. They used a Fourier analysis to compute online the road roughness condition and perform an ISO 8608 classification. Another estimation method was proposed in [3] which was based on statistical analysis of dynamic suspension response to kinematic excitation. Authors used body and wheels vertical acceleration and after calculation, they could estimate road type.

3. Idea of compensation

Body oscillations appear when vehicle is moving. Vehicle body is moving vertically up and down and also rotating about 3 axes with origin at body gravity center. The most important for laser compensation is rotation about transverse axis called pitch. Thus proposed laser compensation algorithm consists of three main parts (Fig. 2) designed to remove from laser signal (representing distance between sensor and road) a components due to:

- body vertical displacement measured at the body center of gravity;
- body vertical displacement at laser mounting point resulting from pitch angle and a distance between sensor mounting point and the body center of gravity;
- laser mounting position compensation (especially the angle).

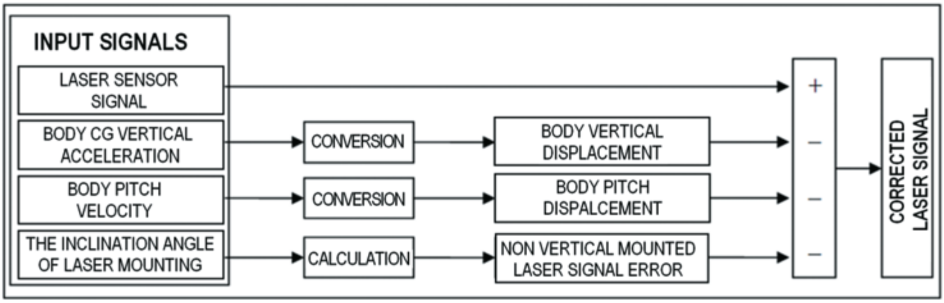

Fig. 2. Laser height sensor signal compensation for vehicle body dynamics

Body vertical displacement in center of gravity point

This part of compensation algorithm uses acceleration data from accelerometer mounted in the vehicle center of gravity to calculate vertical movement of a body. Numerical integration was used with additional lowpass and highpass filtering before integration due to many noises in the signal and a presence of signal drift due to not always purely vertical measuring axis.

Pitch compensation part

This part of compensation algorithm is designed to estimate this part of a laser signal which is produced by a pitch rotation and a distance from center of pitch rotation (body center of gravity is assumed). Micromechanical sensor produces the pitch rotational velocity signal so the only one integration step is necessary to estimate pitch angle. The displacement at a laser sensor mounting point can be calculated using the equation:

$$\Delta z_{\varphi} = l_{laser} \tan \varphi \qquad (1)$$

where:

Δz_{φ} – vertical (z) displacement of a body at sensor mounting point,

l_{laser} – the distance from body center of gravity to laser,

φ – vehicle pitch angle.

Laser mounting position compensation part.

The last part of the compensation algorithm is used when there is an angle between laser measuring axis and a road surface. Then the only a vertical component of a laser sensor signal is useful for compensation purposes. If laser is mounted not perpendicular to road, angle must be compensated by equation:

$$z_{lc} = z_l \cos\alpha \quad (2)$$

where:

z_{lc} – corrected laser signal;

z_l – measured laser signal,

α – laser-mounting angle to vertical axle.

4. Simulation testing of proposed algorithm of compensation

The goal of simulation test of proposed algorithm was to test the idea of compensation with use of artificial but ideal signals and ideal road surface with only one bump. No additional noises were added to simulated laser height sensors signals – only vehicle body movement was some kind of noise.

Simulation was performed with use pitch oriented "half-car" model [7] - figure 3. Its parameters are defined in a table 1. Simulated laser sensor was "mounted" on vehicle body (sprung mass) 1 meter in front of the vehicle front axle (Fig. 3). Laser position was perpendicular to the surface of the road.

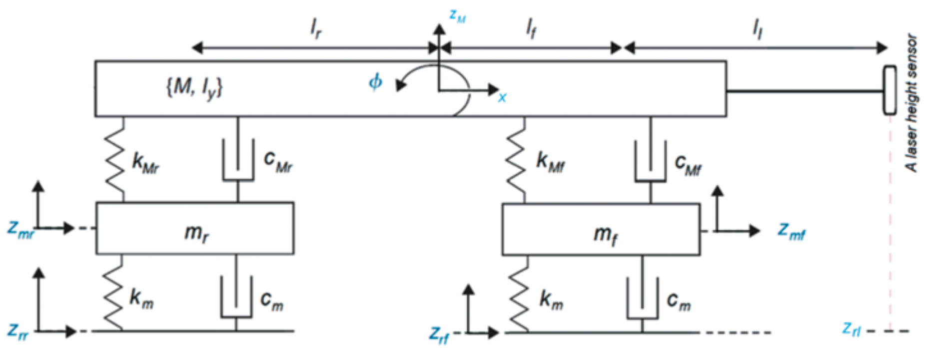

Fig. 3. Pitch oriented "half-car" model

The "half-car" model (Fig. 3) consists of three bodies: M – vehicle's body (sprung mass), m_f ir m_r – the front and rear wheels with axles (unsprung masses). This model has 4 degrees of freedom: the vertical displacement of sprung mass z_M and transverse about the transverse axis φ, the displacements of the unsprung masses z_{mr} and z_{mf}.

Independent excitations from the road are marked by displacements z_{rr} and z_{rf}.

Table 1. Parameters of vehicle used in simulations

The parameter	The value
Half of the vehicle body mass	M = 765 kg;
Vehicle front unsprung mass	m_f = 45 kg;
Vehicle rear unsprung mass	m_r = 35 kg;
Stiffness of front suspension	k_{Mf} = 22000 N/m;
Stiffness of rear suspension	k_{Mr} = 18000 N/m;
Damping of front suspension	c_{Mf} = 2000 N·s/m;
Damping of rear suspension	c_{Mr} = 1600 N·s/m;
Stiffness of tire	k_m = 182000 N/m;
Damping of tire	c_m = 200 N·s/m;
Vehicle wheelbase	wb = 2.703 m;
Distance from center of gravity to front axle	l_f = 1.021 m;
Distance from front axle to laser sensor	l_l = 1 m;
Inertia moment	I_y = 900 kg·m^2;

Equations of motion of this model are described by the equations:

$$\begin{cases} M\ddot{z}_M = -k_{Mf}\left(z_{Mf}-z_{mf}\right)-k_{Mr}\left(z_{Mr}-z_{mr}\right)-c_{Mf}\left(\dot{z}_{Mf}-\dot{z}_{mf}\right)-c_{Mr}\left(\dot{z}_{Mr}-\dot{z}_{mr}\right) \\ I_y\ddot{\varphi} = -l_f\left(k_{Mf}\left(z_{Mf}-z_{mf}\right)-c_{Mf}\left(\dot{z}_{Mf}-\dot{z}_{mf}\right)\right)+l_r\left(k_{Mr}\left(z_{Mr}-z_{mr}\right)+c_{Mr}\left(\dot{z}_{Mr}-\dot{z}_{mr}\right)\right) \\ m_f\ddot{z}_{mf} = k_{Mf}\left(z_{Mf}-z_{mf}\right)-k_m\left(z_{mf}-z_{rf}\right)+c_{Mf}\left(\dot{z}_{Mf}-\dot{z}_{mf}\right)-c_m\left(\dot{z}_{mf}-\dot{z}_{rf}\right) \\ m_r\ddot{z}_{mr} = k_{Mr}\left(z_{Mr}-z_{mr}\right)-k_m\left(z_{mr}-z_{rr}\right)+c_{Mr}\left(\dot{z}_{Mr}-\dot{z}_{mr}\right)-c_m\left(\dot{z}_{mr}-\dot{z}_{rr}\right) \end{cases} \tag{3}$$

where:

$$\begin{cases} z_{Mf} = z_M + l_f\sin\varphi - z_{mf} \\ z_{Mr} = z_M - l_r\sin\varphi - z_{mr} \\ \dot{z}_{Mf} = \dot{z}_M + l_f\sin\dot{\varphi} - \dot{z}_{mf} \\ \dot{z}_{Mr} = \dot{z}_M - l_r\sin\dot{\varphi} - \dot{z}_{mr} \end{cases} \tag{4}$$

Simulations were processed on the computer with use the Matlab and Simulink software. Model was excited by speed lowering bump (Fig. 4). Obstacle shape for simulation purposes was described by equation 5:

$$z_r(x_L) = \frac{H}{2}\cdot\left(1-\cos\left(2\pi\cdot\frac{x_L}{L}\right)\right) \tag{5}$$

where:

H – the height of speed lowering bump (50 mm),

L – the length of speed lowering bump (350 mm),

x_L – longitudinal dimension of the road used for description of the shape of road shape, the value is in a range of 0 to L.

Bump parameters in model is like a real bump used later for experimental tests. The changes of the road height in a time – kinematic excitation – $z_r(t)$ were interpolated after calculating traveled distance x first and later interpolating for this distance current height of the road profile $z_r(x_L)$. The duration time of the kinematic excitation related to traveling over speed lowering obstacle depends on a vehicle longitudinal velocity. For a higher velocity the kinematic excitation duration will be shorter and also the velocity $\dot{z}_r$ of a height change will be bigger as well as vertical acceleration of the wheel will be higher.

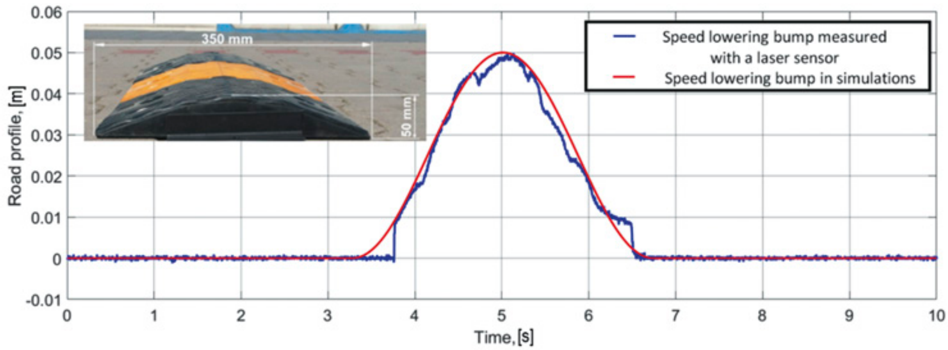

Fig. 4. The shape of speed lowering bump used for tests

A laser height sensor signal was calculated by equation 6:

$$z_l = z_M + (l_f + l_l)sin\varphi - z_{rl} \tag{6}$$

where z_M is a displacement of the vehicle body center of gravity, l_f and l_l are distances described in the table 1 and figure 3, z_{rl} is a road profile height in a point of laser sensor measurement. Results of simulation tests are presented on a figure 5. The simulation was done for vehicle moving with constant speed 30 km/h.

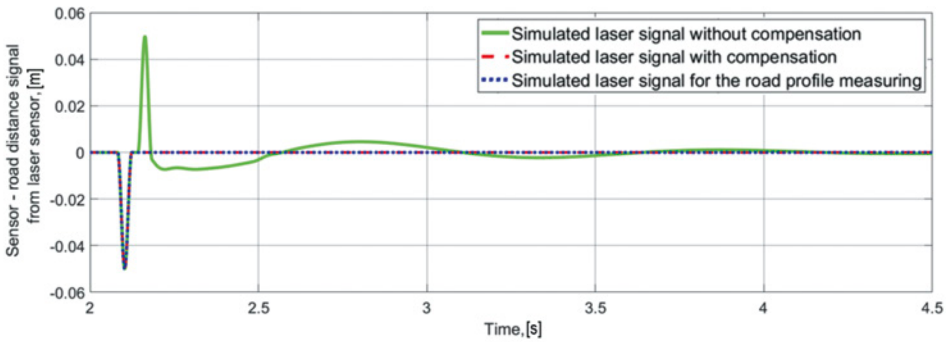

Fig. 5. Simulated signals of laser height sensor for riding over a speed lowering bump with velocity 30 km/h without and with compensation

In first part of signal, laser sensor captures a bump, after that front wheel drives over a bump and then some oscillations from sprung and unsprung masses dynamics occurs. After using for this signal algorithm of compensation we get compensated signal the same like signal from measuring road profile. It proves that proposed algorithm works correctly and laser signal components from body pitch and bounce oscillations are successfully compensated.

5. Experimental tests of algorithms

Experimental tests were performed to verify the compensation algorithm in a practice. For experimental tests passenger car Opel Astra was used. The weight of the car during the tests was 1350 kg, the overall dimensions – length 4430 mm, width 1814 mm, height 1510 mm, wheel base 2685 mm, tires were 205/55 R16 size. For measuring variables of vehicle dynamics the following sensors where mounted on a vehicle:

- 2 Kistler Group height lasers measurement sensors Corrsys-Datron HF-500C (Fig. 6),
- 8 acceleration sensors Analog Devices ADXL327 (4 for wheels and 4 for sprung masses in vertical axes),
- vehicle inertia measurement unit Bosch YRS3 for X and Y axis accelerations and pitch, roll and yaw velocities,
- 5 Hz Garmin GPS module for vehicle speed measuring.

All of the measured parameters were recorded at the frequency of 200 Hz with the dSpace system and later processed on the computer using the Matlab software.

To validate laser mounting position compensation two laser sensors were mounted on testing vehicle – figure 6. First one was mounted perpendicularly to the road surface in a front of vehicle – 1.0 m before front axle, the second sensor was mounted 0.61 m before front axle and with 70.4° angle to road surface.

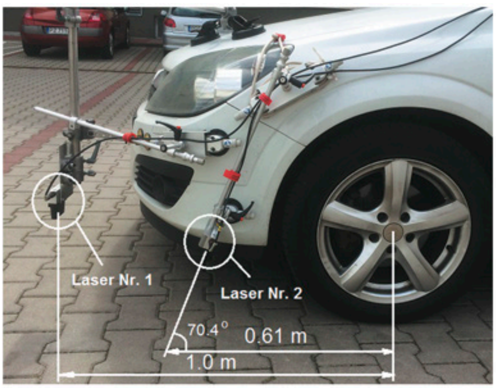

Fig. 6. Laser sensor mounting positions

Dry concrete road section of length of 70 m was chosen for the experimental tests. As a source of kinematic excitation was used transportable speed lowering bump with dimensions: length 350 mm, height 50 mm (figure 4).

The car during the tests was driven at almost steady speed of 30 km/h. To additionally examine the body's oscillations tests were made with different shock absorbers settings – the most comfortable (the biggest body's oscillations) and the most stiff (the smallest oscillations).

In real world appears many additional effects – among other problems with estimation of body and wheel displacements. It could be made only in an indirect way – integrating accelerations (for vertical displacements) or velocities (for angular displacements). The additional problem were noises of acceleration and angular velocity signals. To solve this problems additional procedures were necessary to apply:

- numerical signal filtering,
- numerical signal integration.

For a filtering and integrating signal in a real time the transfer function with characteristics of the low-pass filter was used [7]:

$$Int(s) = \frac{1}{s + \beta_i} \tag{7}$$

where β – the cut-off frequency of the filter (in test for acceleration β_i = 1Hz was used). The effect of use formula 11 on the estimated body vertical displacement is presented on a figure 7. One can see that filtering helps to avoid displacement signal constantly descend after integration process.

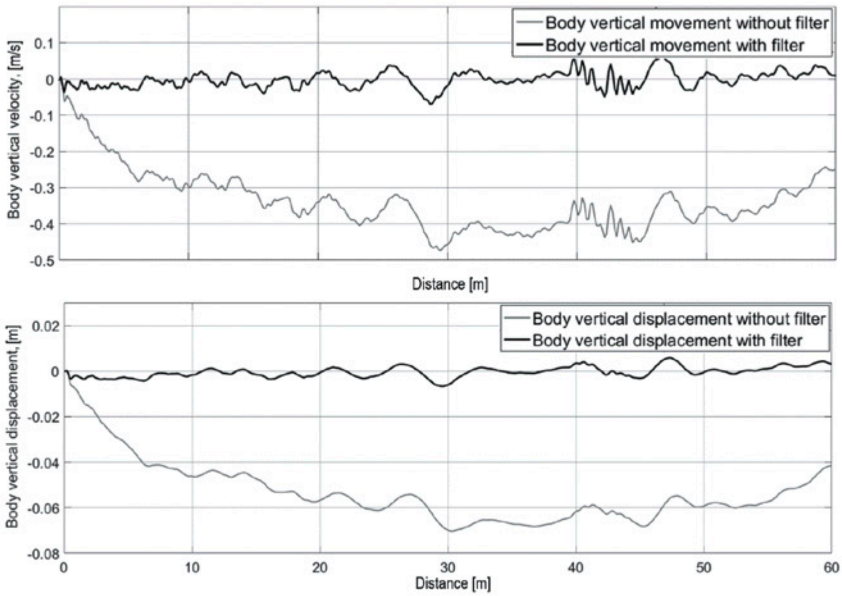

Fig. 7. Estimation of the vehicle body displacements

The algorithm of a compensation with added blocks for filtering and integrating was implemented in a dSpace real time computer for prototyping electronic control systems. The obtained results, after processing the experimentally measured data, are presented on the figure 8 (soft damping) and the figure 9 (stiff damping).

The obtained signals show that compensation procedure reduces body vertical oscillations influences and allows to estimate real road profile. For both damping setting, road tests shows that the obstacle height estimated with laser height sensors signal after body movement compensation, reflects real bump height. Some additional road height changes remains in the graph what is difficult to judge as the road surface during the test was not ideally flat and the vehicle speed was not ideally constant.

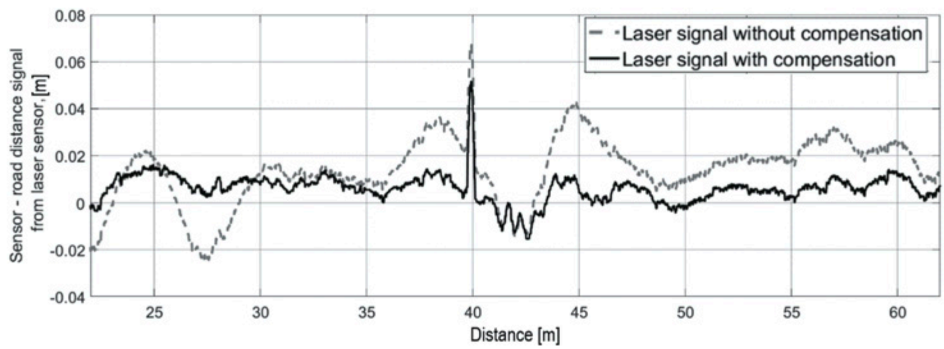

Fig. 8. The road profile estimation using laser sensor No. 1 – comparison of a raw sensor signal and compensated with proposed algorithm – soft damping case

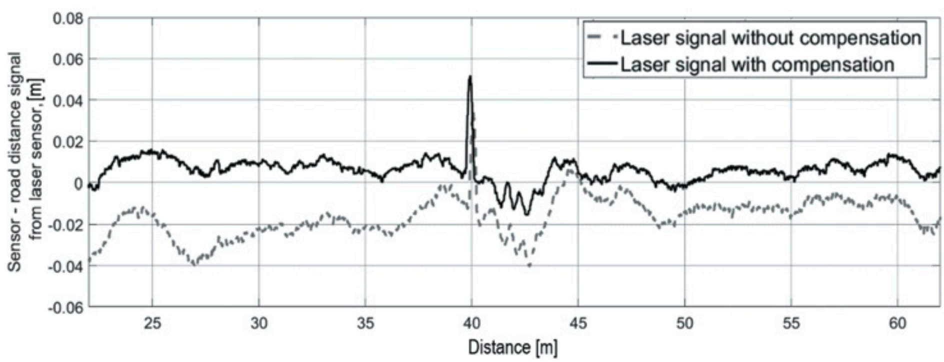

Fig. 9. The road profile estimation using laser sensor No. 1 – comparison of a raw sensor signal and compensated with proposed algorithm – stiff damping case

6. Recapitulation

In this paper, the usage of laser sensors for estimating road profile was presented. Laser sensor mounted on vehicle body could be used for road unevenness profile measurement but it needs taking into account vehicle body vertical and angular oscillations. That means a special procedure needs to be used to compensate laser height sensor signal for these oscillations influences. Presented in the paper simulation test proved that such a compensation could be fully successful if we know body vertical and angular displacements. But as far as in an ideal world, where body vertical and angular movement are accessible directly and without noises, in a real world there is only a possibility to estimate these displacement in an indirect way filtering and integrating acceleration and velocity signals. Experimental tests results for a procedure with added estimation of body displacements, confirmed compensation method efficacy. Proposed method of road profile estimation can be used to improve suspension performance using it with a special damping control algorithm. In a future work of authors compensated laser signal will be used for variable damping suspension control algorithm.

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