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VIBRATION CONTROL IN SEMI-ACTIVE SUSPENSION SYSTEM OF THE EXPERIMENTAL OFF-ROAD VEHICLE USING INFORMATION ABOUT ROAD ROUGHNESS

Summary. In the paper the main results of the Project-Based Learning (PBL) 2015/2016 semester project are presented. The project has been held by the Automatic Control Institute of the Silesian University of Technology. The studies concern on a vibration control application in an automotive semi-active suspension system which is based on the Magneto-Rheological (MR) dampers. The project has been divided into two related parts. First, two variants of Skyhook algorithm: on/off and proportional control were compared with soft and hard suspension setups. Second, software application for a laser scanner has been developed as well as for the Inertial Measurement Unit (IMU) and Linear Variable Differential Transducer (LVDT) that were additionally assembled in the vehicle.

TŁUMIENIE DRGAŃ W PÓŁAKTYWNYM ZAWIESZENIU POJAZDU Z WYKORZYSTANIEM INFORMACJI O NIERÓWNOŚCIACH DROGI

Streszczenie. W artykule zaprezentowano wyniki jednego z projektów Project Based Learning, prowadzonego w roku akademickim 2015/2016 w Instytucie Automatyki Politechniki Śląskiej. Przedmiotem badań było tłumienie drgań w półaktywnym zawieszeniu, opartym na tłumikach magnetoreologicznych (MR). W ramach projektu dokonano porównania rezultatów działania dwóch modyfikacji algorytmu Skyhook: on/off oraz sterowanie proporcjonalne, wraz z zawieszeniem miękkim i twardym. Druga część projektu obejmowała opracowanie oprogramowania dla laserowego skanera zamontowanego na pojeździe, a także montaż czujników orientacji IMU i przemieszczenia LVDT.

1. Introduction

Proposed PBL is a project-oriented learning approach which has been created for solving engineering problems in groups of a few students of the same Institute. This method of education allows the practical use of the scientific knowledge about a real object, not only on a simulated one. At the Silesian University of Technology PBL was initiated by Professor Marek Pawełczyk as a pilot program, which lasted from 2013 to 2016 year.

The project presented in this paper is based also on the two previous PBL projects. During the first and the second edition students compared several methods of road shape detection using a laser scanner, Microsoft Kinect sensor, vision cameras, infrared and ultrasonic sensors. Sensors have been mounted on the experimental vehicle which has been created during PBL projects, also numerous experiments have been performed. Especially, the precision and effectiveness of the proposed sensors have been evaluated.

The main goal of the PBL project presented in this paper was to implement and test basic vibration control algorithms in the experimental All-Terrain Vehicle (ATV) equipped with the semi-active suspension system. In the project the possibility of detection of road unevenness by the laser scanner installed on the ATV has been also evaluated. Finally, the possibility of application of LVDT sensors for measuring the shock absorber deflection and application of IMU sensor for measuring vertical acceleration affecting a vehicle driver has been analysed. The detailed block diagram of the developed system has been presented in Fig.1.

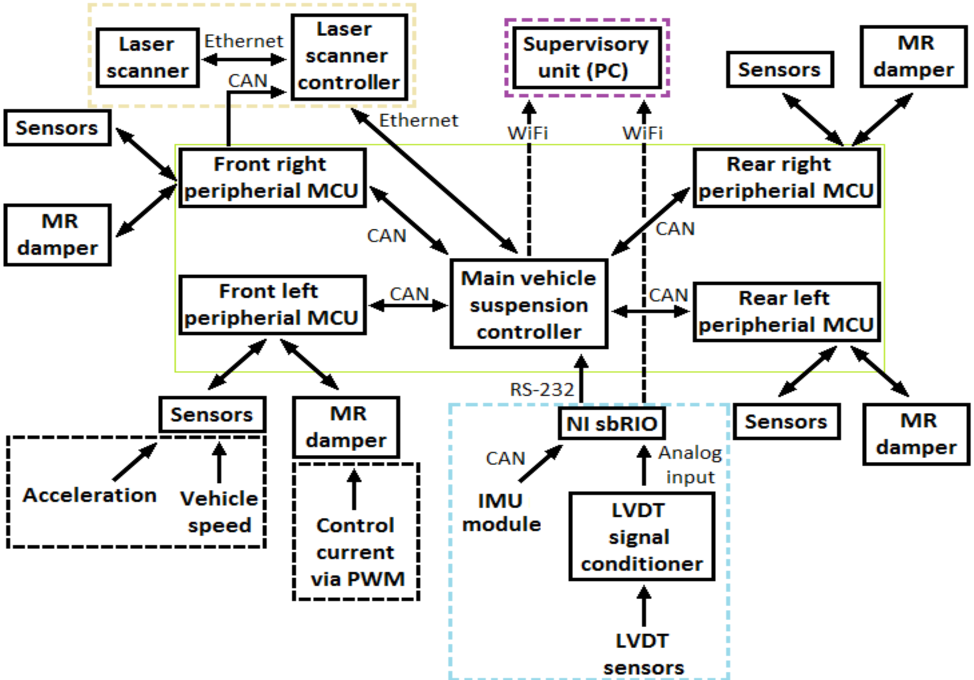

Fig.1. Architecture of the proposed measurement and control system

The paper is organised as follows. In Section 2 related works are presented. Main information about the experimental vehicle and implemented algorithms are included in Section 3. Results are described in Section 4. Finally, a short summary is presented in Section 5.

2. Related works

Semi-active vehicle suspension systems [8] 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, operation of the MR damper [12] is based on the relationship between damping force and its piston velocity, i.e. viscosity of MR fluid filling the damper. The viscosity can be adjusted by magnetic field induced inside the damper's piston. State of MR fluid can be changed from liquid to semi-solid within milliseconds. Controlling the MR damper allows for modifying its characteristics depending on varying ambient conditions. In the recent literature numerous methods of controlling MR dampers can be found such as, e.g. Skyhook and Groundhook [7], neural networks [4] or fuzzy control [5].

Proper control of the damping parameters can be adjusted regarding to the information about the road profile which is obtained in advance using, e.g. vertical velocity or distance between the vehicle body and the ground. This distance can be measured by different types of sensors, like LVDT [2], vision cameras [11], laser range scanners [1,9] and using methods of measurement like, e.g. structured light, RGB-D, infrared, ultrasonic sensors or multi-sensors approach [13,6]. Mostly, fusion of visual images and laser range scanner information is used in the multi-sensors approach. Generally, approaches can be divided into two separate groups. First, information about road roughness and objects in the front of the vehicle can be obtained in 2D/3D form such as images, points cloud – in this case the shape of the road in front of the vehicle can be predicted to 4 meters. Second, the information about the vertical distance between the vehicle and the ground can be gathered in 1D form using LVDT sensors which measure the suspension stroke based on change of position of the movable magnetic rod.

Acquiring information about road roughness is performed often using 2D digital cameras. Unfortunately, it has many disadvantages, images can be deteriorated by dark areas, shadows, reflections which in result lead to problems with determining the distance to the analysed object. Another literature configuration uses two digital cameras in order to acquire the image with 3D point clouds in the result. In this case all cameras should be initially calibrated, both, internal and external parameters need to be evaluated, based on epipolar geometry which is a fundamental of stereo vision. In consequence, large amount of calculation should be performed in real-time. Laser range scanners which are less sensitive to changes in the illumination, object colour, and texture represent the other solution to the problem of road roughness detection. They exhibit high accuracy, however, it is dependent on the scanning frequency and vehicle velocity. Also, some disadvantages have been identified, e.g. changes of the vehicle position on 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. The real-time processing used in the experimental ATV imposes limits on the architecture of the system which should be simple, reliable and accurate.

3. Proposed solution

3.1. Experimental vehicle

In the presented project the experimental vehicle has been used. The vehicle has been modified during previous projects which were focused on vibration control of the semi-active suspension. Basic version of the test platform consists of the ATV with MR dampers produced by Lord Corporation, Freescale accelerometers from Texas

Instruments, peripheral measurement and control units and the main controller based on Beaglebone White. During previous PBL projects the laser scanner LMS400 from SICK has been mounted (Fig. 2) with the quad-core Freescale controller in the front part of the vehicle.

During this project the measurement system has been extended by adding LVDT sensors and a dedicated signal conditioner produced by Peltron, a National Instruments sbRIO platform which serves as a controller dedicated to LVDT as well as an STMicroelectronics IMU sensor (Fig. 3).

Fig. 2. Laser scanner and a wooden beam used as an obstacle during the tests

Software for LVDT sensors has been created in NI LabVIEW platform, with FPGA based acquisition from NI sbRIO digital inputs. Serial communication with IMU has been established using the same controller, which was additionally connected with the main unit via RS 232. Measurements from accelerometers were sent through the CAN bus to the main unit using software written in C language while data from the laser scanner were sent to the dedicated Freescale controller via Ethernet.

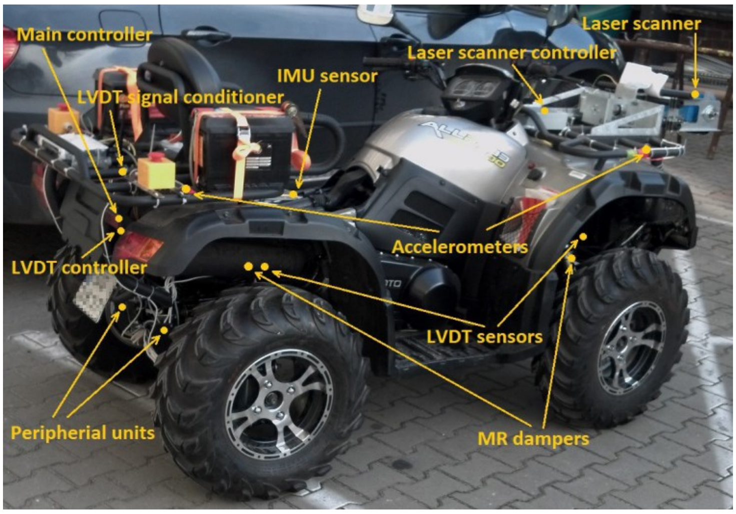

Fig. 3. ATV with vibration control and road roughness detection system

Generally, upper and lower accelerometers are used for estimation of the vertical relative acceleration of the ATV body (sprung mass) with respect to the chassis (unsprung mass), although, LVDT sensors installed in the vehicle measuring relative displacement can be used instead. Skyhook algorithm requires velocity measurements, therefore the LVDT signal should be differentiated contrary to the accelerometer related case, in which signal has been integrated. LVDT sensors have been placed near the suspension shock-absorbers, on the same screws as dampers. Each LVDT sensor requires an individual conditioner (Fig. 4).

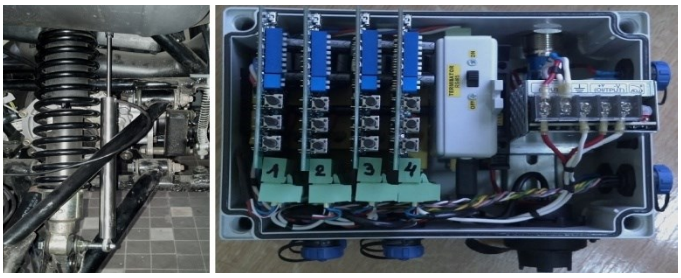

Fig. 4.LVDT sensor (left) and LVDT signal conditioner (right)

3.2. Tested control algorithms

In the project two main vibration control algorithms have been tested. Both of them are based on a law of control parameter switching. The Bang-bang algorithm, called in the literature also as on/off control [10] is described by undesirable spikes due to high speed switching of the damper control force. However, its advantage is the minimal time to achieve the desired value. Based on the equation (1) it should be noted that in this type of control only the sign of multiplication of the sprung mass velocity and the velocity of the damper piston is important. The damper control signal u in the on/off algorithm is defined as follows:

$$u_{on/off} = \begin{cases} i_{max} & \text{for } \dot{y}_2(\dot{y}_2 - \dot{y}_1) > 0, \\ 0 & \text{for } \dot{y}_2(\dot{y}_2 - \dot{y}_1) \leq 0, \end{cases} \tag{1}$$

where i_{max} is the maximum value of the MR current, $\dot{y}_1$ is the unsprung mass velocity, whereas $\dot{y}_2$ denotes the velocity of the sprung mass.

The proportional control is the next tested algorithm, where the damper control signal u is defined as follows:

$$u_{pro} = \begin{cases} i(F_{alg}, v_{mr}) & \text{for } \dot{y}_2(\dot{y}_2 - \dot{y}_1) > 0, \\ 0 & \text{for } \dot{y}_2(\dot{y}_2 - \dot{y}_1) \leq 0, \end{cases} \tag{2}$$

where:

$i = \sqrt{\frac{\frac{1}{\tanh(\beta_o \cdot v_{mr})}(-F_{alg} - c_o \cdot v_{mr}) - \alpha_0}{\alpha_1}}$ is the inverse model of the MR damper [3] with

$v_{mr} = (\dot{y}_2 - \dot{y}_1)$

$F_{alg} = -\delta \cdot \dot{y}_1$

$\delta = \begin{cases} 3000 & \text{for front dampers,} \\ 5000 & \text{for rear dampers,} \end{cases}$

$\alpha_0 = -23$
$\alpha_1 = 1215.2$
$\beta_0 = 36.5$
$c_0 = 1202.7.$

4. Results of experiments

Proposed algorithms should be tested for standardised parameters such as track dimensions and the vehicle velocity. Thus, the wooden construction of 0.08 m high was prepared as an obstacle track and the vehicle velocity was assumed as 5.5 m/s.

Fig. 5.Three consecutive video frames of an ATV ride over the obstacle

The goal of vibration control is the minimisation of vibration of the selected vehicle part while driving through the wooden beam. Shortly, it means that the suspension should be soft when wheels reach the obstacle, but when the ATV comes down, dampers should become harder to reduce oscillations of the vehicle body. It was stated based on results presented in Fig. 6 that predominance of proportional control can be observed in comparison to other suspension parameters. However, in the case of on/off control the better results are obtained while the wheels are reaching the ground. For the rear vehicle body part difference between Skyhook variants was hardly observable and the advantage of on/off control in suppression of vehicle body vibration has been observed (Fig. 7).

Generally, application of Skyhook control variants presented in the article was based on measurements from accelerometers installed in the off-road vehicle. However, other available sensors, such as laser scanner, LVDT or IMU were used during implementation of presented control schemes including their debugging. Such additional sensors are the source of possible independent observation of vehicle motion during experimental rides despite the fact they were not directly applied in the control schemes. The LVDT sensors measure the damper motion just in their vicinity and offer higher relative accuracy in comparison to accelerometers installed in the vehicle. Thus, they can be used for improvement of measurement quality as redundant to accelerometers in the estimation of the relative damper piston velocity. Application of the laser scanner gave additional information of traversed obstacles which can be used for data synchronisation. Furthermore, future improvement of the stabilisation system for the laser scanner position should improve its contribution to data pre-processing. Finally, application of the IMU sensor mounted under a driver seat allows for tracking the motion of the vehicle body, analysing vibration affecting the driver and validating measurements given by accelerometers installed in the vehicle body part.

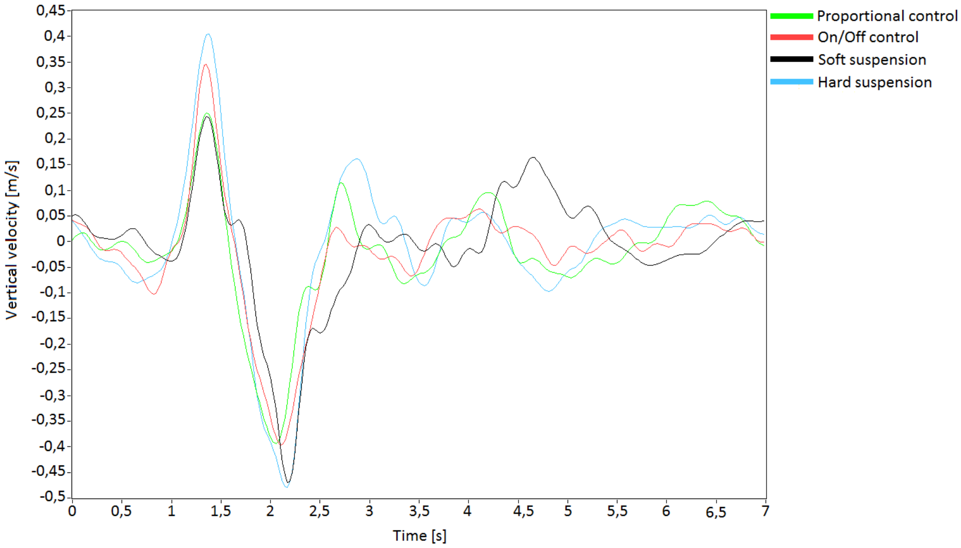

Fig. 6. The vertical velocity of the front vehicle body part (sprung mass)

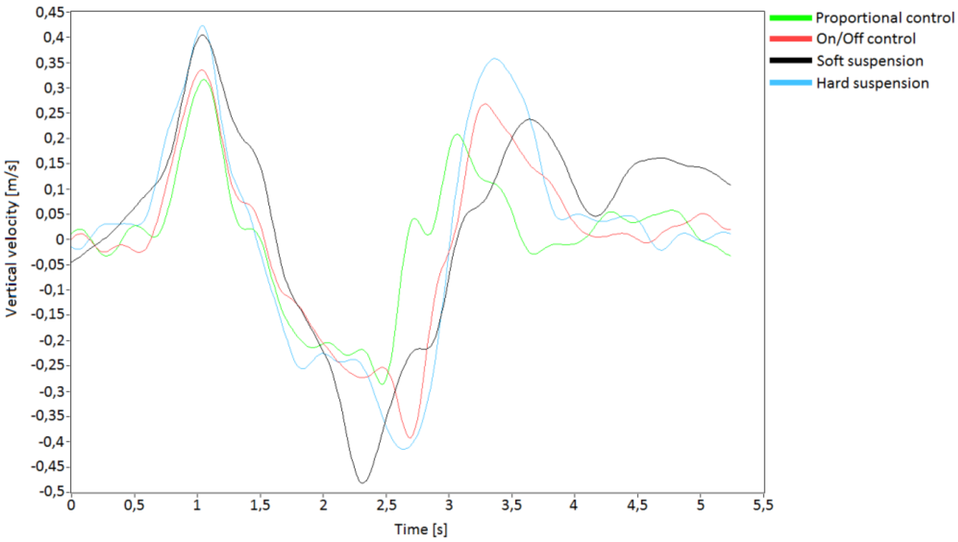

Fig. 7. The vertical velocity of the rear vehicle body part (sprung mass)

5. Conclusions

Comparison of two variants of Skyhook control, i.e. proportional and on/off control, as well as soft and hard suspension setup is presented in the article. The control algorithms were implemented using a suspension control system installed in the off-road experimental vehicle equipped with MR dampers. All configurations of vehicle suspension were tested while the vehicle was traversing a single road obstacle.

Presented results suggest that both variants of Skyhook control are more effective than passive soft or hard suspension. The effectiveness of Skyhook control depends on a phase of a drive through an obstacle. During experiments, it was additionally observed that certain mechanical parts of the vehicle, e.g. a drive shaft, or electrical parts, e.g. an alternator or an ignition system can decrease quality of measurements. Thus, the on/off Skyhook algorithm, which is considered more robust, is favoured over the proportional variant in such severe control conditions. The proportional control is more complex and simultaneously less resistant to interference.

Future works will be focused on two issues. The first one is related to applying the additional sensors, i.e. the laser scanner, LVDT sensors and IMU not only for data off-line processing, but also for on-line control. Besides, the measurement part of the system will be enhanced by improving accuracy of sensors as well as by modifying the architecture of the system and a way of communication of different units.

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