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Experimental Platform for Teaching Control of Automotive Suspension

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Abstract: An experimental platform of a *Quarter of Vehicle* model was developed to improve the teaching-learning system of the Dynamics of Vehicle course; specifically, the suspension control systems topic. A fully instrumented 1:5 scale prototype was connected to a $dSpace^{TM}$ card and a Human Machine Interface (*HMI*) was implemented in $Matlab/Simulink^{TM}$. The *HMI* follows the *Plug* & *Play* philosophy that facilitates the design, implementation and validation of several control algorithms under different conditions. Early results show students obtained a better understanding by exploiting the *Research based Learning* approach, and stressing the practical application of what will be learned as a way to further motivate students.

Keywords: Control Education, Data-based Controllers, Suspension Control System

1. MOTIVATION

Mexican automotive and auto parts industries are leading the world, by the end of 2015, and are surrounded by good news: México is the 4^{th} largest exporter and 7^{th} largest vehicle manufacturer in the world. Furthermore, from 2013 to date over 23 billion dollars in new investments have been announced.

The competitive advantages of México are mainly the availability of highly qualified human capital, competitive operating costs, strategic geographical location, an attractive domestic market, legal certainty, an export platform to more than 45 countries, an extended supply chain and decades of experience.

This sector provides employment to over 66,000 people, representing 3 % of the *GDP* and generating 32 % of the total exports. México will be the 5^{th} largest producer by 2020, with 5 million vehicles a year. México has taken a change from a sector of advanced manufacturing towards a sector of development and innovation, with a better position in the global value chain. By December of 2013 the number of direct jobs in the Mexican automotive sector was just over 690,000 people, Cortés (2015)

Human capital is one of the main sources of competitiveness in Mexico's automotive industry, because of its high quality and specialization. Automotive plants in México have the highest levels of productivity in the world. Despite the great success of the Mexican automotive industry, important challenges for the future remain, such as the development of more research and development centers, local design for automotive components, and the attraction of high added value industrial processes.

The best way the *Tecnológico de Monterrey* contributes to the development of the Mexican automotive industry is by providing the needed leaders with an entrepreneurial spirit, committed to ethics and citizenship, and internationally competitive. *Tecnológico de Monterrey* made research its institutional priority in order to: (1) Form and educate, (2) Innovate and transform the scientific and technological knowledge into innovative solutions for the social welfare, and (3) Transcend, generate and transfer knowledge for the benefit of México.

Strategic research groups have been created and their scientific activity is centered on specific challenges related to their disciplines. Taking into consideration their strengths in scientific and educational fields, each group has focused on a few unique research lines. *Automotive Consortium* is a research group focuses on the development of modern transportation systems, particularly the ones associated with the automotive industry. This paper is about the development of an experimental platform to improve the teaching-learning system of vehicle dynamics course exploiting the *Research Based Learning* (*RBL*) approach.

This paper is organized as follows. Section 2 reviews the theoretical background. Section 3 describes the experimental platform. Section 4 presents the academic proposal. Section 5 shows some results. Section 6 discusses preliminary results. Section 7 concludes this research paper.

2. CONTROL SYSTEM FOR AN AUTOMOTIVE SUSPENSION

Vehicle dynamics is the study of vehicle whole body motion. It encompasses ride, handling, and braking behavior, although in practice, it is focus on ride and handling behavior. The fundamental goals of a car suspension are the isolation of the vehicle from the road and the improvement of road holding. The inherent limitations of classical suspensions have motivated the investigation of controlled suspension systems, both *Semi-Active* (*SA*) and active. Due to their higher reliability, lower cost and comparable performance *SA* suspensions have gained wide acceptance throughout the automotive engineering community.

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2.1 Quarter of Vehicle (QoV) model

A QoV model is the most basic automotive suspension, Fig. 1. Its use assumes an equivalent load distribution among the four corners and a linear dependency with respect to the translational and rotational chassis motions. The lateral and longitudinal wheel dynamics are not considered, while the wheel road contact is ensured.

This very simple one-dimensional model consists of a spring-damper-system representing the suspension strut and a single spring replacing the tire. The damper contributes the drive safety and the drive quality to the same extent. Its tasks are the prevention of an amplification of the body and the prevention of a skipping wheel. A non-skipping wheel is the condition for a good road-contact. The task of the spring is to carry the body-mass and to isolate the body from road disturbances maximally.

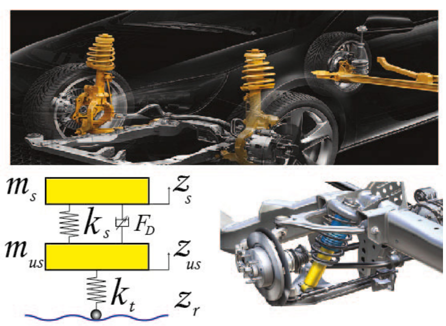

Fig. 1. QoV model

The dynamic behavior of a QoV model with a SA suspension is described by:

$$\begin{aligned} m_s \ddot{z}_s &= -F_D - k_s(z_s - z_{us}) \\ m_{us}\ddot{z}_{us} &= k_s(z_s - z_{us}) + F_D - k_t(z_{us} - z_r) \end{aligned} \tag{1}$$

where z_s, z_{us} and z_r are the sprung mass, unsprung mass and road profile vertical positions, respectively; m_s is the sprung mass which represents the chassis, m_{us} is the unsprung mass which represents the wheel, tire, etc.; k_s and k_t are the suspension and the tire stiffness, and F_D represents the damping force.

2.2 Comfort and Road Holding

Comfort is measured with the vertical chassis acceleration ($\ddot{z}_s$) response to road disturbances (z_r), between 0 and 20 Hz. This is the acceleration felt by the passengers. *Road holding* is measured with the vertical wheel deflection ($z_{us} - z_r$) response to road disturbances (z_r), between 0 to 30 Hz. It represents the ability of the wheel to stay in contact with the road.

The common goal is the minimization of either the energy transfer from z_r to $\ddot{z}_s$ (comfort), or the energy transfer from z_r to $(z_{us} - z_r)$ (road holding) or a tradeoff of these two energy transfers over a frequencies bands. Four *Frequency Bands* (FB) are defined based on the resonance frequencies of the masses of the QoV model, Bastow et al. (2004):

(1) FB_1: [0-2] Hz range, the goal is comfort. People can feel dizziness and motion sickness. This bandwidth includes the resonance frequency of the sprung mass, typically in 1-2 hz.
(2) FB_2: [2-9] Hz range, the goal is comfort. High gains of vertical accelerations generate an overall discomfort.
(3) FB_3: [9-16] Hz range, the goal is road holding. It contains the unsprung mass frequency resonance into the 10-15 Hz, affecting the road holding and increasing the discomfort.
(4) FB_4: [16-20] Hz range, the goal is road holding. Dangerous vibration of the head with respect to shoulders could generate internal damage.

2.3 Data-based Controllers

The most representative algorithm for comfort is the *Sky-Hook* (SH). The principle is to *link* the chassis to the *sky* by a virtual damper and put a controlled damper among the masses to reduce the vertical oscillations of the chassis. The SH algorithm has two-states, Karnopp et al. (1974):

$$c_{sky} = \begin{cases} c_{min} & \text{if } \dot{z}_s(\dot{z}_s - \dot{z}_{us}) \le 0 \\ c_{max} & \text{if } \dot{z}_s(\dot{z}_s - \dot{z}_{us}) > 0 \end{cases} \tag{2}$$

where c_{min} is the minimum damping coefficient in a SA damper and c_{max} its counterpart. Based on the acceleration measurement instead of the velocity of the sprung mass, the named *Acceleration Driven Damper* (ADD) control and its improved version, *SH-ADD*, have become efficient comfort-oriented algorithm, Savaresi and Spelta (2007):

$$c_{SH-ADD} = \begin{cases} c_{max} & \text{if } ((\ddot{z}_s^2 - \alpha\dot{z}_s^2) \le 0 \wedge (\dot{z}_s\dot{z}_{def}) \ge 0) \\ & \vee\ ((\ddot{z}_s^2 - \alpha\dot{z}_s^2) > 0 \wedge (\ddot{z}_s\dot{z}_{def}) \ge 0) \\ c_{min} & \text{if } ((\ddot{z}_s^2 - \alpha\dot{z}_s^2) \le 0 \wedge (\dot{z}_s\dot{z}_{def}) < 0) \\ & \vee\ ((\ddot{z}_s^2 - \alpha\dot{z}_s^2) > 0 \wedge (\ddot{z}_s\dot{z}_{def}) < 0) \end{cases} \tag{3}$$

where α is the crossover frequency, at which the frequency responses of closed-loop systems using SH and ADD algorithms intercept. Reducing the number of measurements that are used to control the damping force, the *Mix-1-Stroke* algorithm shows similar performance as the *SH-ADD*, but with only one measurement. Its control law is, Spelta (2008):

$$c_{Mix1} = \begin{cases} c_{max} & \text{if } (\ddot{z}_s^2 - \nu^2\dot{z}_s^2) \le 0 \\ c_{min} & \text{if } (\ddot{z}_s^2 - \nu^2\dot{z}_s^2) > 0 \end{cases} \tag{4}$$

where ν is the cut-off frequency of the sprung mass acceleration of the QoV model, between the low/high damping curve.

The *Ground-Hook* (GH) algorithm has been proposed to reduce the road holding by including a virtual damping between the wheel and road and a SA shock absorber, whose damping coefficient is, Valasek et al. (1997):

$$c_{GH} = \begin{cases} c_{min} & \text{if } -\dot{z}_{us}(\dot{z}_s - \dot{z}_{us}) \le 0 \\ c_{max} & \text{if } -\dot{z}_{us}(\dot{z}_s - \dot{z}_{us}) > 0 \end{cases} \tag{5}$$

To manage the compromise between comfort and road holding, Ahmadian (1997) proposed a hybrid strategy that weights the SH and GH control outputs:

$$c_{hybrid} = \lambda c_{SH} + (1 - \lambda)c_{GH} \tag{6}$$

where λ is a parameter of design used to weight the comfort and road holding performances. The control strategy for any data-based algorithm is shown in Fig. 2.