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Adaptive Semi-Active Suspension Design Using Gain-Scheduling[★]

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Abstract: A novel approach to design a road adaptive semi-active suspension is proposed. Two scheduling parameters are considered: the road frequency and the type of road. A single corner vehicle model with a nonlinear dynamic model of the semi-active damper is considered. The suspension deflection and its derivative are used as feedback signals. Nonlinear simulations show that an adaptive suspension controller: *Frequency-Estimation-Based with road Adaptation (FEBA)* provides better comfort and road holding over different types of road. The improvement of the performance ranges from 5-10 %.

Keywords: Semi-active suspension, adaptive controller, experimental validation, *MR* damper.

1. INTRODUCTION

The automotive semi-active suspension control methods have been widely explored and different solutions have been proposed. There are several approaches in the control of semi-active suspensions that can be organized as (a) those with an experimental validation and (b) those with a simulation validation. In the first group, the free model controllers such as the *Sky-Hook*, Karnopp et al. [1974] and Mix-1-sensor, Savaresi and Spelta [2009] are the most efficient for comfort, and the *GroundHook*, Valasek et al. [1997] is the best for road holding. For comfort and road-holding, some of the nonlinear control techniques are a model predictive and sliding mode control, Dong et al. [2010], the human simulated intelligent controller, Yu et al. [2008], and the model-free controller named the Hybrid policy, Goncalves and Ahmadian [2003]. In the second group, the H_∞ , Choi and Sung [2008], using a linear *MR* damper model and the nonlinear control based on *LPV*/ H_∞ , Do et al. [2010] have been validated by simulation. Poussot-Vassal et al. [2012] shows a complete comparison of benchmark model-free controllers versus Model Predictive Control (*MPC*) and *LPV* approaches. However, the adaptation to the road profile type or the forward vehicle has not been widely explored.

The research of Huisman et al. [1993] and Muijderman et al. [1999] implemented a semi-active suspension control with a bulk of on-line computing and estimated the road profile using a Kalman Filter (*KF*). The results were good in simulation, but the experimental results were not. This problem resulted from the selection of several control laws on-line. Fialho and Balas [2002] applied this *LPV* con-

troller with gain-scheduling in an active suspension that complied with the comfort and suspension deflection goals and adapted to the road surface. The feasibility of this solution in practice was challenged by a set of ten controllers and the use of two scheduling parameters. The *LPV* controller potential under this concept was successfully shown. Hong et al. [2002] estimates the road roughness using a filter in order to gain-schedule a *SkyHook* controller. The voltage to be applied to the semi-active damper is obtained through a lookup table. This estimation needs a 5th order filter. A road profile estimator uses a deflection and shock absorber force as an input to the controller, Lu [2004]. The shock absorber force must be estimated or measured. Hence, this approach is a challenging task. A fact is that research efforts in the semi-active suspension control are including the road adaptiveness using complex algorithms, i.e. companies as *Peugeot*, Poilbout [2012], and *Honda*, Izawa and Kato [2012]. Mashadi and D. A [2005] shows the correlation of road roughness with the standard deviation of the side-slip angle, lateral acceleration and roll angle. A proposal, that combines the Frequency-Estimation-Based (*FEB*) controller with the adaptation of the manipulation limits according to the road profile, is presented Lozoya-Santos et al. [2012a].

This paper consists of six sections. Section 2 reviews the single corner of a vehicle, suspensions and *MR* damper models. The proposal is shown in Section 3. The simulation issues and performance criteria are described in Section 4. Section 5 presents and discusses the results. A conclusion is presented in Section 6.

2. MODELS

The lumped parameter *single corner* model describes the sprung mass (m_s) corresponding to the vehicle chassis

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and components supported by the suspension, and the unsprung mass (m_{us}); it only captures vertical motions ($z_s, z_{us}, \dot{z}_s, \dot{z}_{us}, \ddot{z}_s, \ddot{z}_{us}$). The tire is modelled by a spring linked to the road (z_r) and represented with a stiffness coefficient (k_t) while the tire damping is negligible. A contact point between the road and the tire is always assumed. $z = z_s - z_{us}$ is the suspension deflection. The parameters of the lumped parameter *single corner* model are computed assuming a uniform distribution of the weight, two front passengers and mid-level fuel tank.

The passive suspension, typically modelled by a damper and a spring, exerts vertical resistive forces (F_c, F_{k_s}), Fig. 1a. The vertical forces are affected by the square of the motion ratio of the damper and spring, (η), Barak [1991], and reflect the projection of the force to the vertical axis in the wheel. A nonlinear *single corner* model with a passive damper will be used as a baseline model:

$$\begin{aligned} m_s \ddot{z}_s &= -\eta^2 F_{k_s}(z) - \eta^2 F_c(z, \dot{z}, \ddot{z}) \\ m_{us} \ddot{z}_{us} &= \eta^2 F_{k_s}(z) + \eta^2 F_c(z, \dot{z}, \ddot{z}) - k_t(z_{us} - z_r) \end{aligned} \quad (1)$$

$$z \in [z, \bar{z}], \quad \dot{z} \in [\dot{z}, \bar{\dot{z}}]$$

The controlled suspension uses a semi-active damper (F_{MR}) instead of the passive damper (F_c), Fig. 1b. The semi-active damper varies its damping force according to a manipulation (u_{sa}). The *single corner* model with a controlled suspension is derived as follows:

$$\begin{aligned} m_s \ddot{z}_s &= -\eta^2 F_{k_s}(z) - \eta^2 F_{MR}(z, \dot{z}, \ddot{z}, u_{sa}) \\ m_{us} \ddot{z}_{us} &= \eta^2 F_{k_s}(z) + \eta^2 F_{MR}(z, \dot{z}, \ddot{z}, u_{sa}) - k_t(z_{us} - z_r) \end{aligned} \quad (2)$$

$$z \in [z, \bar{z}], \quad \dot{z} \in [\dot{z}, \bar{\dot{z}}]$$

where u_{sa} is the input control of the system provided by the semi-active damper. Two dampers are considered: a

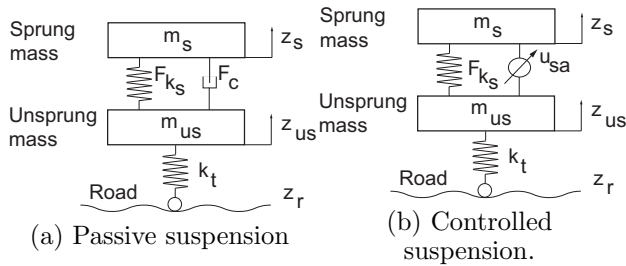


Fig. 1. Passive and controlled suspension schemes of a quarter of vehicle.

passive and *MR* damper. A lookup table of the a force-velocity plot models the baseline big-car damper. It has a damping force ratio of 3 to 1 between the rebound and compression zones, Gillespie [1992], Fig. 2. It presents a trade-off for road holding and comfort performances. The *MR* damper is modelled by a *full modified*

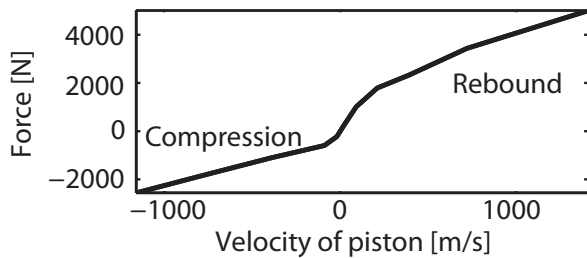


Fig. 2. Nonlinear passive damping force.

semi-phenomenological model, eqn. (3). It includes the friction, pre-yield and post-yield operation modes.

$$\begin{aligned} F_D &= k_p z + c_p \dot{z} + m_d \cdot \ddot{z} + f_f \cdot \tanh(v_f \cdot \dot{z} + x_f \cdot z) \\ &+ c_{MR \text{ post-y}} \cdot I \cdot \tanh(v_{pre-y} \cdot \dot{z} + x_{pre-y} \cdot z) \end{aligned} \quad (3)$$

where F_D is the damping force, k_p is the stiffness coefficient, c_p is the viscous damping coefficient, m_d is the virtual mass of the damper, f_f is the friction force, v_{fric} and x_{fric} describe the damping and stiffness coefficients when friction is present, z, \dot{z}, \ddot{z} are the damper displacement, velocity and acceleration, $c_{MR \text{ post-y}}$ is the gain of damping force due to the electric current I , and v_{pre-y} and x_{pre-y} are the damping and stiffness coefficients when the *MR* damper operates in a *pre-yield* regime.

3. PROPOSAL

The main idea is to adjust the limits of upper and lower level of manipulation of the semi-active damper according to the road roughness. The low level of the road roughness agrees with a soft damped suspension, and viceversa. Thus, the controller output limits are changed according to a detected road profile.

The *FEB* controller chooses high/low damping at each sampling time to comply with comfort or road holding goals according to the suspension deflection frequency:

$$I = \begin{cases} I_1, & 0 < \hat{f} < f_1 \\ I_2, & f_1 < \hat{f} < f_2 \\ I_3, & f_2 < \hat{f} < f_3 \\ I_4, & f_3 < \hat{f} < f_4 \end{cases}, \quad \hat{f} = (\dot{z}_{rms}) / (2 \cdot \pi \cdot z_{rms}) \quad (4)$$

where I is the electric current to apply, I_i is the constant electric current to apply in the i^{th} bandwidth of interest, \hat{f} is the estimated frequency, f_i is the frequency thresholds that define bandwidth intervals, z_{rms} and \dot{z}_{rms} are the Root Mean Square (*RMS*) values of the suspension deflection and its derivative, respectively, in the last k samples; see Lozoya-Santos et al. [2012a] for details. A control system that meets both comfort and road holding is chosen: a hard damping in bandwidth intervals that contain the resonance frequencies ($0-2$ Hz and $12-14$ Hz), and soft damping for the others ($2-12$ and $14-20$ Hz). The road profiler consists in a proportional measure to the amplitude of the road profile. A quasi-linear relation can be assumed between the road profile and the suspension deflection, Lozoya-Santos et al. [2012b], in the content of frequency and variation of amplitude. Thus, the main assumption is: if the road profile roughness amplitude changes, the suspension deflection changes in the same magnitude and sense. Then, using the experimentally-validated correlation of the road roughness with the standard deviation of the road Izawa and Kato [2012], a road estimator can be used based on the standard deviation of the suspension deflection:

$$\sigma_i = \sqrt{\frac{\sum_{j=i-k}^i q_j^2}{k-1} - \frac{k}{k-1} \left(\frac{\sum_{j=i-k}^i q_j}{k} \right)^2} \quad (5a)$$

$$\bar{\Sigma} = \{\sigma_1, \dots, \sigma_\infty\} \quad (5b)$$

$$\bar{Q} = \bar{Z} - \frac{\sum_{j=i-k}^i z_j}{k} \quad (5c)$$

$$\bar{Z} = \{z_{i-k}, \dots, z_i\} \quad (5d)$$

where q is the suspension deflection displacement without the offset, σ_i is the q standard deviation of the i^{th} sample in the last k samples, $\bar{\Sigma}$, \bar{Q} , and \bar{Z} are data vectors. This way, it is expected that the standard deviation of the suspension deflection when exposed to a specific road will be different in range and magnitude. The road detection consists in:

$$R_p = \begin{cases} 1 & 0 < \sigma_i < \bar{\sigma}_{smooth} \\ 2 & \bar{\sigma}_{smooth} < \sigma_i < \bar{\sigma}_{rough} \\ 3 & \bar{\sigma}_{rough} < \sigma_i < \infty \end{cases} \quad (6)$$

where R_p is the type of detected road profile. R_p changes according to the thresholds of the standard deviation eqn. (5a). The thresholds are defined observing the standard deviations in the suspension deflection. A comparison of the statistic behavior of both the road profile and the suspension deflection validates the thresholds. In this case, two thresholds have been defined in order to differentiate three types of roads. Once the road is detected, the span of the *FEB* controller is adjusted according to Table 1:

Table 1. Span of the electric current according to the type of road.

Type of road	Range of I
Smooth runway	$\{I_{SRMin}, I_{SRMax}\}$
Highway with gravel	$\{I_{HGMin}, I_{HGMax}\}$
Pasture	$\{I_{PAMin}, I_{PAMax}\}$

where I_{max} and I_{min} are the electric current values to apply in the control law, eqn. (4). Smooth runways allow to use a vehicle in an sportive way; while in rough runways, the suspension must to provide comfort. This new *FEB* controller with road Adaptation is named : *FEBA*.

4. SIMULATION

The parameters of the vehicle *single corner* model correspond to the front corner of a F-Class vehicle, Table 2 following a distribution of the body weight of 60 % in the front and 40 % in the rear. Hence, a single front corner of the vehicle has a 30 % of the total body weight. Two suspensions are considered: an uncontrolled and a controlled suspension.

Table 2. *Single corner* model parameters.

Component	Value	Units
Sprung mass (m_s)	546.5	Kg
Unsprung mass (m_{us})	50	Kg
Spring stiffness (k_s)	83	kN/m
Tire stiffness (k_t)	230	kN/m
m_s resonance frequency (f_{m_s})	1.2	Hz
m_{us} resonance frequency ($f_{m_{us}}$)	11.5	Hz
Motion ratio (η)	0.614	-

The analysis criteria for the semi-active *suspension* systems in time domain consists of:

- (1) A qualitative analysis based on the following plots:
 - (a) *MR* damper Force versus Velocity.
 - (b) Acceleration of the sprung mass versus time.
 - (c) Deflection of the tire versus time.
- (2) A quantitative analysis of the controlled semi-active and passive suspension systems using the *RMS* criterion:

$$RMS(x) = \sqrt{\frac{1}{T} \int_0^T x^2 dt} \quad (7)$$

where x is the signal of interest, and T defines the interval of time to be analyzed.

Boxplots are used to analyze statistical behaviors. They consist of five-number summaries: the smallest observation (sample minimum), lower quartile, median, upper quartile, largest observation (sample maximum), and outliers. The spacings between the different parts of the box help indicate the degree of dispersion (spread) and skewness in the data, and identify outliers.

The simulation of three road profile sequences was done according to da Silva [2004] using the roughness coefficients proposed by Wong [2001] corresponding to a smooth runway, highway with gravel, and pasture. The simulations were done for the uncontrolled suspension and two controlled suspensions: *FEB* controller with $I_{max} = 5$ A and $I_{min} = 0$ A without a road adaptation mechanism, and the *FEBA* controller.

The uncontrolled suspension simulations have two purposes: (1) to define the thresholds in eqn. (6) and the electric current spans, Table 1, (b) to use as a reference for the suspension performance. Nine simulations were done. Each one consisted of a *single corner* model submitted to a given road profile under a given constant electric current. Three electric current values were tested, one per simulation. Then a comparison of the controlled suspensions simulations versus the uncontrolled in three different roads validates the proposal. The simulation was assumed to be in a distance of 100 m with a longitudinal speed of 40 km/h. The sample time was $1/512$ s, therefore, each road sequence consisted of 4,655 samples. For each road sequence, the standard deviation was computed according to eqn. (5a), and a vector $\bar{\Sigma}$ was obtained.

5. RESULTS

The statistic behavior of the $\bar{\Sigma}$ vector for each road profile shows the maximum standard deviation according to each road profile and has its own range of variability, Fig. 3. Therefore, σ_i can be used as a road profile detector.

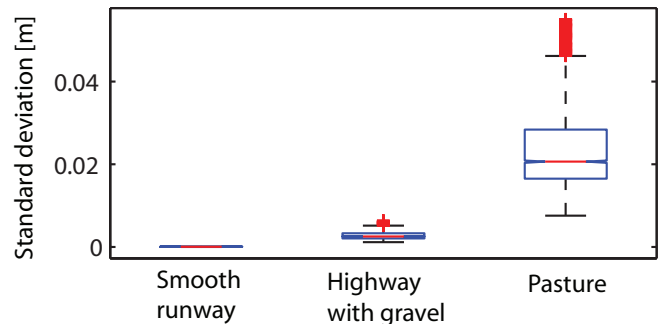


Fig. 3. Boxplots of standard deviations of road profiles for a receding horizon of 200 samples.

It is shown that the use of the suspension deflection under several electric currents and a specific road profile is valid. It can be observed how the suspension deflection decreases when the electric current increases from the nine simulations of the uncontrolled suspension, Fig. 4. However, the goal is to observe if the standard deviation ranges of the suspension deflection remain independent

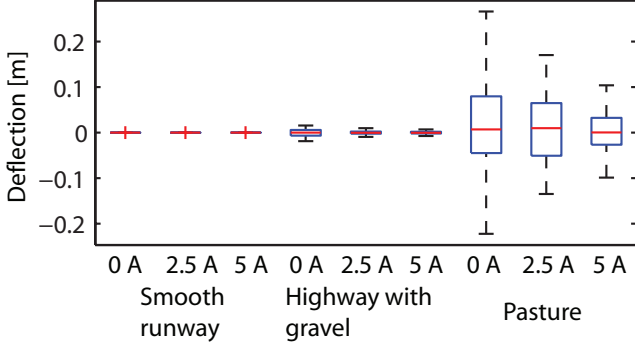


Fig. 4. Boxplots of the suspension deflection for three roads and several currents.

from each other, regardless of the applied electric current, Fig. 4.

The results allow to infer that the standard deviation ranges of the suspension deflection for the three tested roads can be used in a control system of a semi-active suspension. This is because the standard deviation ranges keep their upper and lower limits. According to the ob-

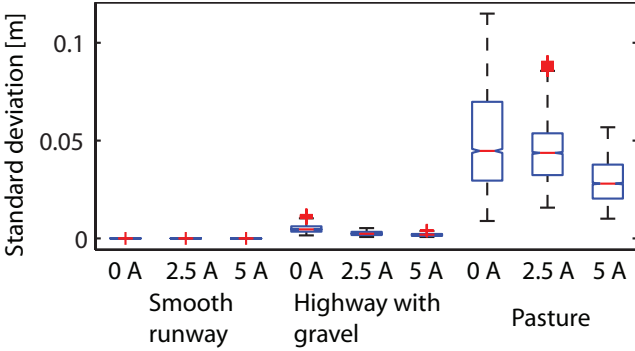


Fig. 5. Boxplots of standard deviations for the suspension deflection for a receding horizon of 200 samples under several roads and electric currents.

served results for the standard deviation spans of the suspension deflection for a given road, which is independent of the applied electric current, the limit values (thresholds) were defined. The thresholds for the road detection were defined as:

$$R_p = \begin{cases} 1 & 0 < \sigma_i < 0.0005m \\ 2 & 0.0005m < \sigma_i < 0.009m \\ 3 & 0.009m < \sigma_i < \infty \end{cases} \quad (8)$$

where $R_p = 1$, $R_p = 2$, $R_p = 3$ corresponds to the smooth runway, highway with grave and pasture roads, respectively. Hence, the road detection will be done according to the thresholds of the eqn. (8). The detection was proven using a road profile containing the three types of roads, one behind the other. Fig. 6 shows the simulation result of the detection mechanism showing a good qualitative detection efficiency. Although an exhaustive validation of the mechanism under several roads and conditions is needed, this mechanism will be used to show its potential application.

When the road profiler detects a given road, the limits of the *FEB* controller output will vary in order to assure the comfort and road holding goals regardless of the unevenness of the road. Several simulations in a closed loop using the *FEB* controller and the road profiles were done in order

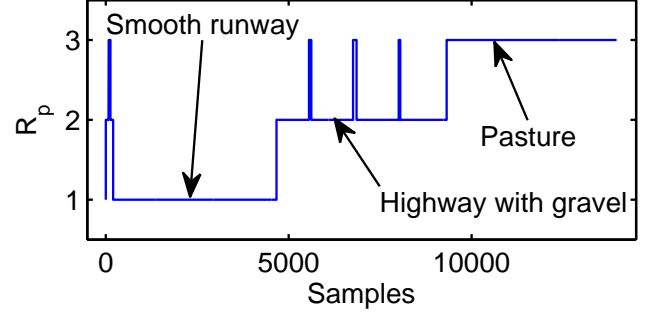


Fig. 6. Validation of the road detection mechanism when the suspension is submitted to the three roads.

to define the limits of the electric current. Hence, observing the *RMS* improvement of the vertical acceleration and tire deflection controlled suspension *RMS*s, both relative to the same criteria from baseline suspensions, the limits of the electric currents for each detected road profile were defined as:

Table 3. Lookup table values for road adaptive mechanism in *FEB* Adaptive controller.

Type of road	Limits for I of <i>FEB</i>
Smooth runway ($R_p = 1$)	0.2, 0
Highway with gravel ($R_p = 2$)	3, 1
Pasture ($R_p = 3$)	5, 2.5

Once the road profile detection and the electric currents were defined, the *FEB* controller was tested in the *single corner* model with and without the road detection. Nine simulations were done, three for the original *FEB* control, three for the *FEB* control with Adaptation to road (*FEBA*), and three for the baseline suspension. Each of the three simulations correspond to a given road.

The quantitative results indicate that *FEBA* controller maintains the comfort and road holding goals when compared with the baseline suspension, Fig. 7. Between 5–10 % is achieved in all roads. The *FEB* does not have a good performance in smooth roads for both goals, not even in highways with gravel road, where the road holding is key. In pasture, both controllers are better than the passive suspension, since here the road demands the comfort and road holding. The mechanisms for the controller adaptation to the road increases the efficiency of the *FEB* controller to a wider suspension operation.

The different electric current exerted by the *FEB* and *FEBA* controllers has the same shape, however, the limits in the *FEBA* controller changes due to the adaptation. This way, for smooth roads, the road holding and comfort is achieved by the softer suspension according to the *FEBA*, while the *FEB* computes an electric current to maintain a hard suspension. The difference is to allow more suspension deflection to maintain such goals, as it can be seen in the deflections of the suspension for each road, Fig. 7.

The *Force-Velocity* (*F-V*) diagrams of *MR* damper model show a linear behavior for a smooth runway, a sigmoid shape in a highway with gravel, and a sigmoid shape with a high friction component, Fig.9. The *FEBA* controller shows the optimum damping characteristics for each road

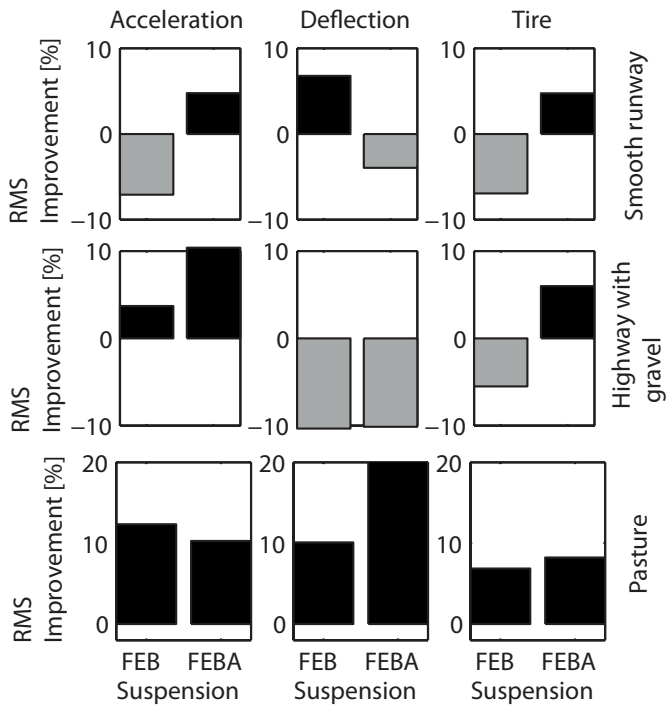


Fig. 7. Comparison of the *RMS* improvement of the controlled suspensions versus the passive suspension for three different roads. A positive value means that the controlled suspension has a smaller *RMS* than the baseline suspension, and viceversa.

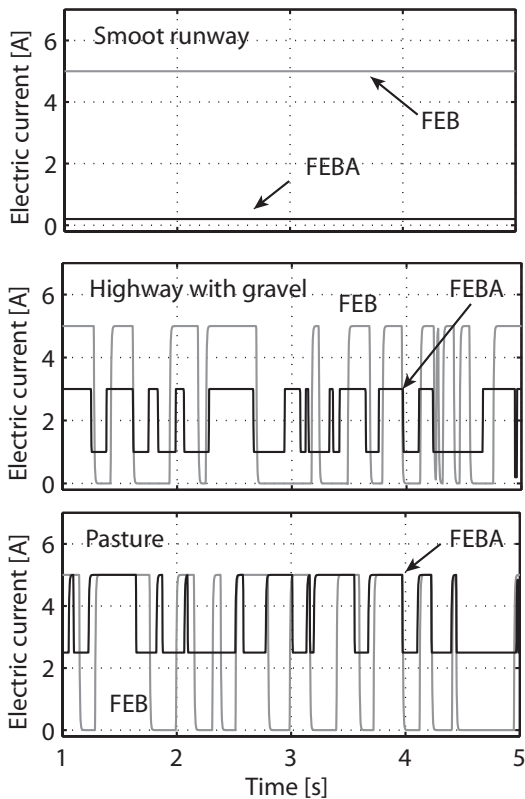


Fig. 8. Comparison of the electric current of the controlled suspensions for three different roads. The dark line is the *FEBA* controller and the grey one corresponds to the *FEB*.

in order to comply with the goals: soft for a smooth runway, a trade-off between soft and hard for a highway with gravel, and a harder suspension for the pasture (off road). The higher difference was in a highway with gravel road, where a trade-off between a soft and hard damping suspension is applied, while the *FEBA* explores the limits in the damping suspension affecting the road holding but maintaining the comfort.

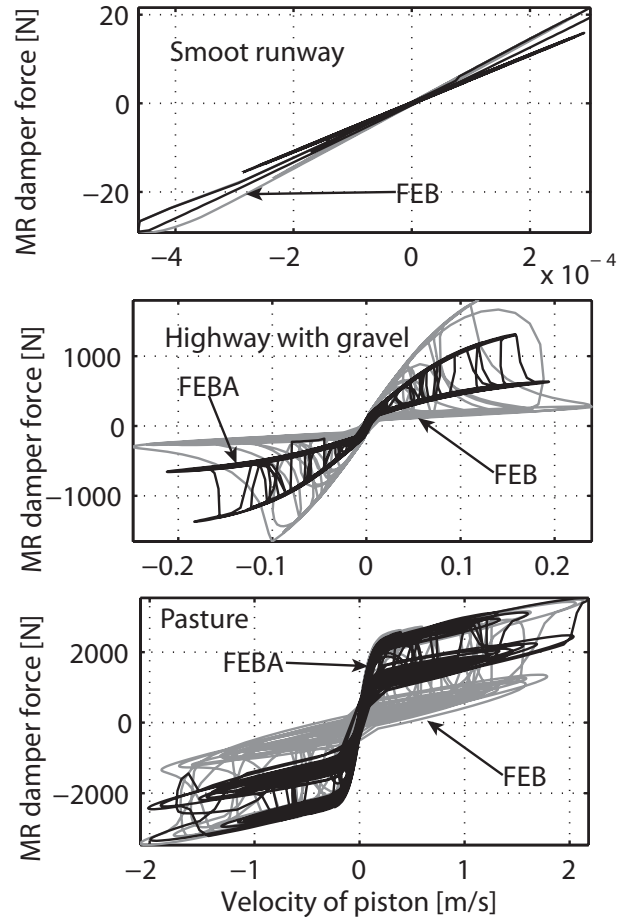


Fig. 9. Comparison of force-velocity diagrams of the controlled suspensions for three different roads. The dark line is the *FEBA* controller and the grey one corresponds to the *FEB*.

Examples of the vertical acceleration and tire deflection for a highway with gravel are shown in Figs 10-11. The avoidance of higher values of these key variables is achieved by the *FEBA* controller in a better way than by the *FEB*.

6. CONCLUSIONS

A road adaptive controller for an automotive suspension with a semi-active damper has been proposed. The approach uses the suspension deflection standard deviation of a window of samples moving in time in order to detect the type of road. The detection mechanism was used to move the limits of the applied electric current in an *FEB* controller, hence a new *FEBA* controller is proposed. The results show that the detection of the road improves the *RMS* performance in comfort and road holding under

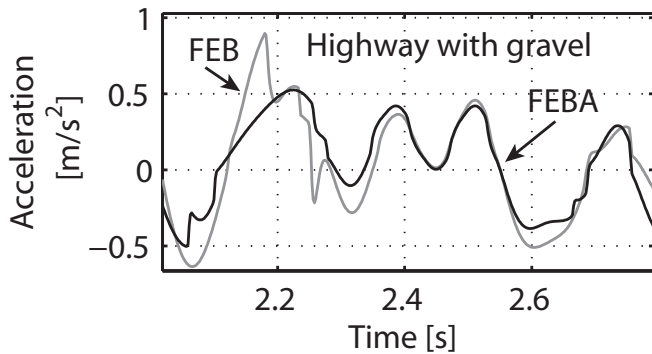


Fig. 10. Chassis acceleration comparison of controlled suspensions. The dark line is the FEBA controller and the grey one corresponds to the FEB.

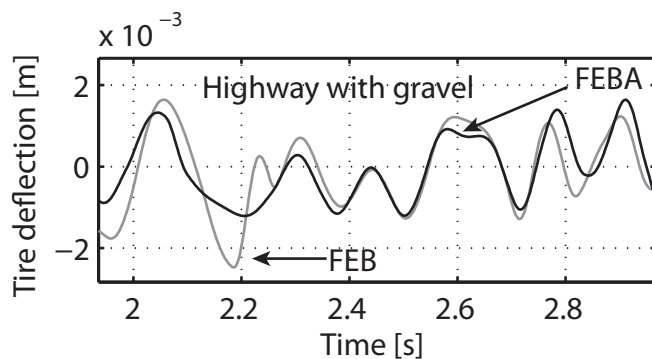


Fig. 11. Tire deflection comparison of controlled suspensions. The dark line is the FEBA controller and the grey one corresponds to the FEB.

several types of road in a 5-10 %. The proposed algorithm is simpler and allows lower computation than others presented in literature.

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