

## Skyhook Control of Front and Rear Magnetorheological Vehicle Suspension

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### Abstract

The paper presents an application of the Skyhook control of suspension MR dampers in a vehicular vibration control system. Experiments were conducted using an ATV (all-terrain vehicle) traversing a test route. The system elements were analyzed and calibrated paying special attention to the space orientation of sensors and MR dampers. Orientation data and inversed Bingham model, which maps dynamic behavior of MR damper, were included in the modified Skyhook control. Use of Skyhook control improved ride comfort in comparison to the use of passive suspension. It is stated that vibration control quality of front and rear part of the vehicle body significantly depends on the value of skyhook parameter.

*Keywords:* magnetorheological, control, bump test.

### 1. Introduction

Suspension system is the key element of the vibration mitigation system in a vehicle. Three types of suspension systems are distinguished: passive, semi-active and active. Parameters of passive suspension system are usually invariable and are optimized for specific driving conditions.

Active control scheme consists in mitigating vibration of the suspended body by using force generator and adding energy to the vibrating system. Active control is widely exploited in many research studies due to its control reliability and possibility of force excitation. However, active suspension systems are more complex than passive ones.

Semiactive systems are considered to be a promising trade-off between inadaptably passive and power-consuming active vibration control systems. These systems are failsafe; in case of system failure semiactive elements behave like passive ones. Control of semiactive elements changes suspension system characteristic depending on road conditions. Karnopp *et al.* in 1974 [8] firstly presented experimental results of an application of semiactive elements. It was stated that semiactive systems exhibit intermediate performance between passive and active systems. Application of semiactive

vibration control system implemented in vehicle was recently presented by Dong *et al.* [5].

Semiactive elements used in vehicular vibration mitigation systems can be divided into two classes *i.e.*: dampers and springs. However, due to discontinuous changes of resilience of currently available adjustable springs, mostly dampers are utilized. Recently commonly used types of adjustable dampers are MR (magnetorheological) and ER (electrorheological) dampers [15]. Application of MR damper is presented in [5]. An example of ER damper application can be reviewed in Choi *et al.* [3]. Another type of semiactive damper is SVD (servo-valve damper) [15]. According to Plaza [10] SVD exhibits higher reliability and wider operating temperature range in comparison to MR dampers. However, MR dampers are appreciated for their shorter time response. The difference between ER and MR dampers lies in maximum possible generated stress, which is higher for MR dampers [6].

Among many active and semi-active control algorithms there are Skyhook control [8], Groundhook control [15], Hybrid Control [12], On-Off control [16],  $H_\infty$  control [3], Fuzzy Logic control [9], Neuro control [11], HSIC [5].

The article is organized as follows. In chapter 2 the system setup is presented. Chapter 3 is dedicated to the MR damper modeling issue. In chapter 4 adaptation of Skyhook control scheme to the analyzed semiactive system is discussed. Chapter 5 presents the controller synthesis issue and implementation details. In chapter 6 the experiment results are presented and the efficiency of examined vibration control system is judged. Finally chapter 7 concludes achievements presented in the paper.

### 2. Semiactive vibration control system

All-terrain vehicle ATV Sweden CFMoto 500 Allroad is main part of the system (Figure 1). Axes X, Y and Z of the vehicle base coordinate system are parallel to directions of vehicle lateral, progressive and vertical motion, respectively. Angles  $\alpha$ ,  $\beta$ ,  $\gamma$  define rotations on axes X, Y and Z, respectively. Vehicle characteristic dimensions

describe the relative location of sensors and MR dampers with respect to the rear left vehicle sensor. Location of a sensor or a damper is assumed here to be the point of vehicle body – sensor/damper attachment.

Semiactive vibration mitigation system is controlled by a MRSC (MR suspension controller) which allows sampling acceleration measurement signals and controlling four MR suspension dampers. Control parameters as well as experiment results are stored in SD Card and are used in further analysis if necessary.

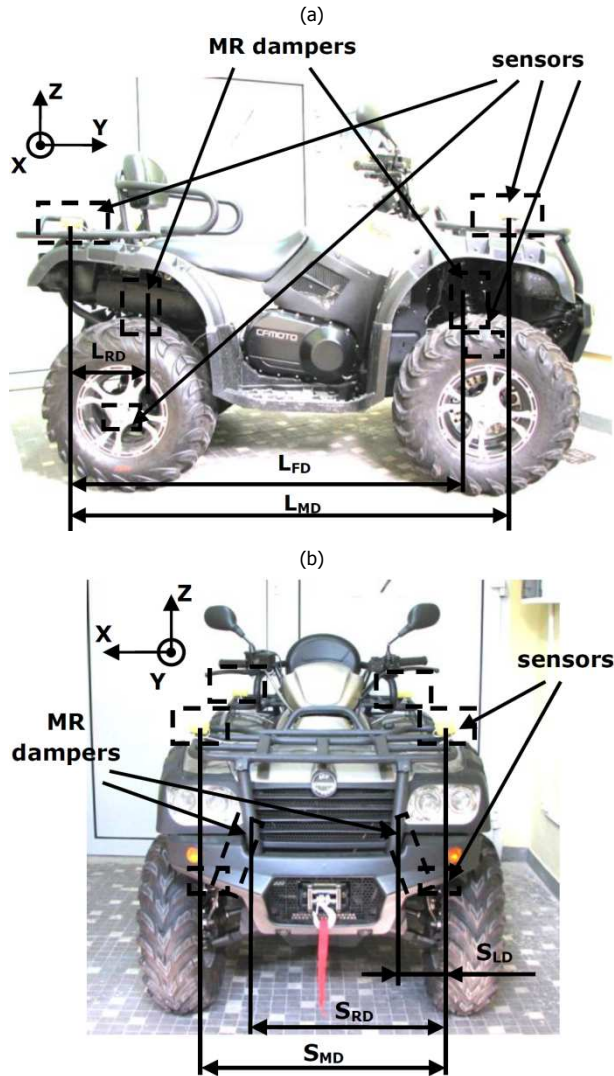


Figure 1. Characteristic dimensions of the experimental vehicle: (a) longitudinal, (b) transverse.

### 2.1. Elements of the semiactive suspension

The vehicle suspension system is equipped with four RD-8041-1 MR dampers made in Lord Corporation which were installed in a place of original suspension dampers.

In case of ATVs, front and rear suspension dampers are strongly leaning compared with the suspension system of typical passenger cars. Construction of ATV suspension system requires derivation of MR dampers' orientation to

unambiguously determine direction of MR damper real and desirable reaction. These orientation data were estimated based on vehicle certification papers.

Rotation matrices for the suspension dampers can be derived as follows:

$$\mathbf{R}_{D-U}(\beta_{IJ}, \alpha_{IJ}) = \mathbf{R}(y, \beta_{IJ}) \cdot \mathbf{R}(x, \alpha_{IJ}) \quad (1)$$

where  $\mathbf{R}(x, \alpha_{IJ})$  and  $\mathbf{R}(y, \beta_{IJ})$  are matrices describing the rotation on axis  $x$ ,  $y$  of the base coordinate system and angles  $\alpha_{IJ}$ ,  $\beta_{IJ}$  (Table 1) respectively.

Orientations of MR dampers are derived for unloaded experimental vehicle. Orientation of each MR suspension damper also depends of momentary suspension displacement what should be taken into account in more accurate analysis; however, it is neglected in the paper.

Tab.1.

Orientations defined with current angular coordinates relative to the vehicle base coordinate system

Notation	Description
IJ	Each element of the Cartesian product of sets {R (Rear), F (Front)} and {L (Left), R (Right)} respectively
$\alpha_{IJ}/\beta_{IJ}$	MR damper
$\alpha_{UIJ}/\beta_{UIJ}/\gamma_{UIJ}$	Sensors in the vehicle underbody
$\alpha_{SIJ}/\beta_{SIJ}/\gamma_{SIJ}$	Sensors in the vehicle body

### 2.2. Measurement elements

The system includes 8 motion sensors *i.e.* three-axis accelerometers ADXL335 made in Analog Devices. Each pair of sensors is meant to measure compression and rebound acceleration of dedicated MR suspension damper. Orientations of sensors were derived by measuring the gravitational acceleration sense and presented in the form of current angular coordinates (Table 1).

Acceleration relative to the vehicle base coordinate system can be determined using rotation matrices derived as follows:

$$\mathbf{R}_{M-(U,S)IJ}(\gamma_{(U,S)IJ}, \beta_{(U,S)IJ}, \alpha_{(U,S)IJ}) = \mathbf{R}(z, \gamma_{(U,S)IJ}) \cdot \mathbf{R}(y, \beta_{(U,S)IJ}) \cdot \mathbf{R}(x, \alpha_{IJ}) \quad (2)$$

where  $\mathbf{R}_{M-UIJ}(\alpha_{UIJ}, \beta_{UIJ}, \gamma_{UIJ})$  and  $\mathbf{R}_{M-SIJ}(\alpha_{SIJ}, \beta_{SIJ}, \gamma_{SIJ})$  are matrices describing the space rotation dedicated to sensors located in the vehicle body and underbody part respectively.

### 3. MR damper modelling

Maghetorheological fluid, which is one of smart materials, is usually made of oil in which magnetizable particles are suspended. MR fluid changes its viscosity when subjected to magnetic field. One of MR fluid applications are MR dampers in which build-in coils induce magnetic field. Unfortunately parameters of MR fluid are dependent of magnetic field magnitude and damper piston velocity in significantly nonlinear manner.

So far many MR damper models have been proposed which take into account nonlinear and bi-viscous dynamic behavior. Coulomb damping and viscous damping are modeled by Bingham model presented by Stanway et al. [14]. Stanway et al. [13] presented a bi-viscous model which takes into account yield and post-yield regions of ER damper behavior. Both models [14] and [13] was proposed for ER dampers, however, they can also capture behavior of MR dampers. Moreover, in the force-velocity characteristic of MR damper strong hysteresis behavior is revealed which is captured by the bi-viscous hysteresis model presented by Guo et al. [7]. More sophisticated multi-parameter models of MR dampers such as Bouc-Wen model formulated based on the Bouc [2] and Wen [17] papers, the polynomial model presented by [4], neural network model, heuristic model modified by Plaza [10] much better map the MR damper behavior due to their complexity.

The Bingham model is favored for its simplicity. According to the Bingham model, which is adopted in this study, force generated by MR damper is given by Equation (3):

$$F_{BM}(\mathbf{v}, V) = a(V) \cdot \mathbf{v} + b(V) \cdot \text{sign}(\mathbf{v}) + c(V) \quad (3)$$

where  $\mathbf{v}$  is velocity of damper piston;  $V$  is voltage controlling MR damper;  $a$ ,  $b$  and  $c$  depend of control voltage and are viscous damping, Coulomb damping and absolute term parameters respectively. The relationship between Bingham model parameters and control voltage is assumed linear:

$$k(V) = k_1 + k_2 \cdot V \quad (4)$$

Substituting Equation (4) into Equation (3) yields Equation (5).

$$F_{BM}(\mathbf{v}, V) = (a_1 + a_2 V) \cdot \mathbf{v} + (b_1 + b_2 V) \cdot \text{sign}(\mathbf{v}) + (c_1 + c_2 V) \quad (5)$$

Two approaches are proposed in control systems for the problem of MR damper nonlinearity. Firstly, the additional closed-loop controller can be involved to reliably determine the level of control voltage corresponding to required force. Second approach is an open-loop control where the inverse model can be used to linearize MR damper characteristic.

MR damper inverse model included in the discussed system is derived from Equation (5). Control voltage needed for MR damper to generate a specific force is defined as follows:

$$V_{BM}(\mathbf{v}, F) = \frac{F - a_1 \mathbf{v} - b_1 \text{sign}(\mathbf{v}) - c_1}{a_2 \mathbf{v} + b_2 \text{sign}(\mathbf{v}) + c_2} \quad (6)$$

The exceptional case of the inverse model is causes by division by zero:

$$a_2 \mathbf{v} + b_2 \text{sign}(\mathbf{v}) + c_2 = 0 \quad (7)$$

When the Exception (7) is met, according to the Bingham model (5), MR damper is uncontrollable. In

such a case it is recommended to set the output of the inverse model (6) to the minimum permissible value. Both the Equation (6) and the Exception (7) inseparably constitute the inversed Bingham model.

### 3.1. MR damper model identification

The model of Lord RD-8041-1 MR damper installed in the experimental vehicle was examined during identification experiments carried out in Tenneco Automotive Poland, Gliwice. Excitation signals were define and experiments were supervised by Plaza [10]. MR damper was excited by the sinusoidal velocity signal of MR damper piston and the random control voltage values. Parameters of the Bingham model were estimated and verified through the comparison of MR damper and Bingham model responses by the author of the current paper.

## 4. Control scheme

Skyhook control algorithm for semiactive systems was firstly presented by Karnopp [8]. Skyhook control was analyzed based on 2 DoF (degree of freedom) Quarter-Car model which consists of two vertically vibrating masses: sprung and unsprung mass modeling part of vehicle body and vehicle wheel respectively; passive elements model damping and resilience of the suspension and the tire. Skyhook control emulates behavior of abstract skyhook damper which is attached with its ends to the vehicle body and to the inertial reference point. Skyhook scheme is ride comfort related control algorithm *i.e.* it is used in mitigation of vehicle body vibration.

In the current paper an extension of Skyhook control is presented, where each part of the experimental vehicle suspension dedicated to specific wheel is controlled independently using Skyhook control scheme. Vertically oriented skyhook dampers are attached to vehicle body in points  $DP_{Sij}$  as presented in Figure 2.

### 4.1. Skyhook control scheme

Skyhook control exploited in active system causes generation and dissipation of energy in turns. In the semiactive system only the energy dissipation can be controlled using adjustable dampers. Above mentioned feature of semiactive system requires the energy dissipation and generation regions to be distinguished. Energy dissipation region is marked by the sense equality of force vectors generated by adjustable damper and skyhook damper (notations in Table 2):

$$F_{SH-ij} \cdot F_{D-ij} > 0 \quad (8)$$

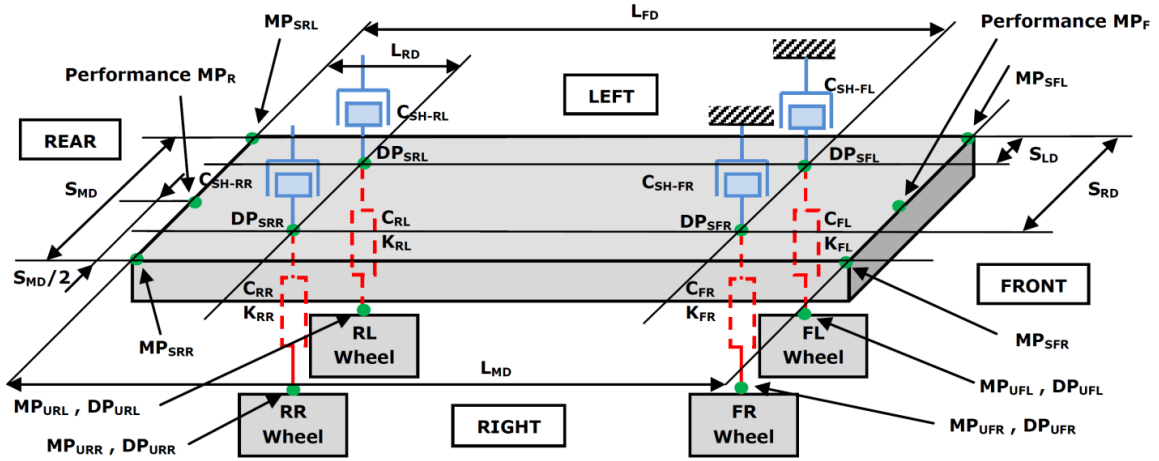


Figure 2. Quadruple Skyhook Control based on Full-Car Model, notations in Figure 1 and Table 2.

Tab.2. Notations describing the semiactive vibration control system

Notation	Description
MP <sub>Sij</sub> /MP <sub>Uij</sub>	Sensor location in the IJ part of the vehicle body/wheel
DP <sub>Sij</sub> /DP <sub>Uij</sub>	Damper attachment point in the IJ part of the vehicle body/wheel
P-MP <sub>I</sub>	Performance examination point in the I part of the vehicle body
C <sub>SH-IJ</sub>	Coefficient of the Skyhook damper attached in DP <sub>Sij</sub>
C <sub>IJ</sub> /K <sub>IJ</sub>	Resultant nonlinear damping/resilience coefficient of the IJ part of the vehicle passive suspension attached in DP <sub>Sij</sub> and DP <sub>Uij</sub>
F <sub>SH-IJ</sub> /F <sub>D-IJ</sub>	Vertical force exerted by skyhook/MR damper in DP <sub>Sij</sub>
z <sub>M-Sij</sub> /z <sub>M-Uij</sub>	Vertical displacement in MP <sub>Sij</sub> /MP <sub>Uij</sub>
s <sub>M-Sij</sub> /s <sub>M-Uij</sub>	Space displacement in MP <sub>Sij</sub> /MP <sub>Uij</sub>
z <sub>D-Sij</sub> /z <sub>D-Uij</sub>	Vertical displacement in DP <sub>Sij</sub> /DP <sub>Uij</sub>
z <sub>PM-I</sub>	Vertical displacement in P-MP <sub>I</sub>

The Equation (8) can be simplified for an ideal adjustable damper to the well-known Skyhook formula [8] as follows:

$$\dot{z}_{D-SIJ} \cdot (\dot{z}_{D-SIJ} - \dot{z}_{D-UIJ}) > 0 \quad (9)$$

However, real semiactive elements exhibit more sophisticated behavior (Chapter 3) which needs to be modelled. On the basis of the fundamental expression (8) including information about inversed Bingham model of MR damper (6) and rotation matrices (1), an expression (10) can be formulated, which is modification of the Equation (9) dedicated to MR dampers and the discussed control system.

Assuming that permissible values of signal controlling MR damper are positive and are in the range between  $V_{MIN}$  and  $V_{MAX}$  the Equation (10) is as follows:

$$V_{BM}(\dot{z}_{MR-IJ}, F_{MR-IJ}) \in (V_{MIN}, V_{MAX}) \quad (10)$$

and

$$\delta = V_{BM}(\dot{z}_{MR-IJ}, F_{MR-IJ}) \quad (11)$$

where:

$$\begin{bmatrix} 0 \\ 0 \\ \dot{z}_{MR-IJ} \end{bmatrix} = \mathbf{R}_{D-IJ}^{-1}(\alpha_{IJ}, \beta_{IJ}) \cdot \begin{bmatrix} \dot{x}_{D-SIJ} - \dot{x}_{D-UIJ} \\ \dot{y}_{D-SIJ} - \dot{y}_{D-UIJ} \\ \dot{z}_{D-SIJ} - \dot{z}_{D-UIJ} \end{bmatrix} \quad (12)$$

$$\begin{bmatrix} 0 \\ 0 \\ F_{MR-IJ} \end{bmatrix} = \mathbf{R}_{D-IJ}^{-1}(\alpha_{IJ}, \beta_{IJ}) \cdot \begin{bmatrix} F_{D-IJ}^x \\ F_{D-IJ}^y \\ F_{D-IJ}^z \end{bmatrix} \quad (13)$$

$$F_{D-IJ}^z = F_{D-IJ} = F_{SH-IJ} = C_{SH-IJ} \cdot \dot{z}_{D-SIJ} \quad (14)$$

Based on the expression (10) and the definition (11) modified Skyhook control scheme can be formulated:

$$F_{D-IJ} = \begin{cases} F_{SH-IJ}, & \delta \in (V_{MIN}, V_{MAX}) \\ F_{SH-IJ-MIN}, & \delta \leq V_{MIN} \\ F_{SH-IJ-MAX}, & \delta \geq V_{MAX} \end{cases} \quad (15)$$

where  $F_{SH-IJ-MIN}$  and  $F_{SH-IJ-MAX}$  are maximum and minimum possible forces, respectively, generated by MR damper for certain piston velocity. Controller implementation also needs to include the Exception (7).

#### 4.2. Estimation of velocity signals

Acceleration measurements in the vehicle underbody are taken in the vicinity of MR dampers so they can be directly utilized in control algorithm. However, velocity estimations in points DP<sub>Sij</sub> in the vehicle body are not known explicitly but need to be judged using velocity signals estimated in MP<sub>Sij</sub>:

$$\begin{aligned} \dot{z}_{D-SIJ} = & \dot{z}_{M-SRL} + \frac{L_{DI}}{L_{MD}}(\dot{z}_{M-SFL} - \dot{z}_{M-SRL}) + \\ & + \frac{S_{DJ}}{S_{MD}}(\dot{z}_{M-SRR} - \dot{z}_{M-SRL}) \end{aligned} \quad (16)$$

All notations used in Equation (16) are explained in Table 2 and presented in Figure 1 and Figure 2.

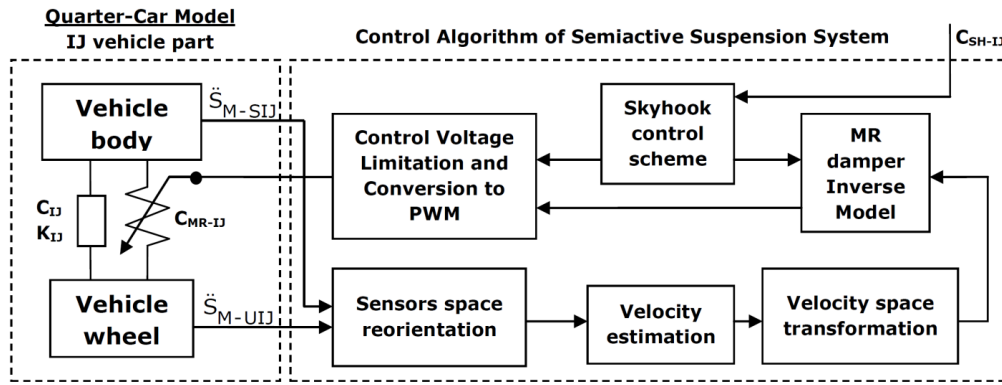


Figure 3. Block Diagram of Semiactive Vehicle Suspension Control, notations in Table 2

## 5. Controller synthesis

Voltage signal controlling each suspension MR damper is updated with frequency of 100 Hz as well as acceleration signals are sampled with frequency of 100 Hz. Vibrations in the vehicle body are to be mitigated in range of 0 – 25 Hz what gives the sampling frequency of 100 Hz to be satisfying.

Each part of vehicle suspension can be modelled using Quarter-Car Model presented in block diagram in Figure 3 where “Vehicle wheel” block corresponds to the mass of vehicle wheel, resilience and damping of the tire. The vehicle suspension presented in Figure 3 consists of resultant nonlinear resilience, viscous damping of the quarter of vehicle suspension system and MR damper marked as  $K_{IJ}$ ,  $C_{IJ}$  and  $C_{MR-IJ}$  respectively.

Damping coefficient of skyhook damper  $C_{SH-IJ}$  is the input parameter of semiactive control scheme presented in the second part of the block diagram. Measurement data are processed starting from estimating oriented acceleration signals using orientation data presented in chapter 2.2. Secondly offset value induced mainly by gravitational acceleration is filtered and velocity signals are estimated by integration of acceleration. This problem can be also solved using state observers such as Kalman [1] or Luenberger. However, state observers are not considered in the current paper. Next space transformation of measurements is exploits (as stated in chapter 4.2) to obtain velocity in  $DP_{SIJ}$  measurement points.

Skyhook control scheme affects operation of the MRSC in two ways (figure 3). First of all expected force generated by MR damper depends directly on the skyhook damper coefficient. Secondly the idea of modified skyhook control (17) requires limiting the control voltage.

## 6. Results

Efficiency of vibration deterioration in the rear and front part of the experimental vehicle was determined based on acceleration measurements taken in points  $PMP_R$  and  $PMP_F$  respectively (Figure

2). These acceleration signals are estimated based on acceleration measurements in two adjacent points  $MP_{SRR}$ ,  $MP_{SRL}$  and  $MP_{SFR}$ ,  $MP_{SFL}$  respectively:

$$\ddot{z}_{PM-I} = \ddot{z}_{M-SIL} + \frac{1}{2}(\ddot{z}_{M-SIR} - \ddot{z}_{M-SIL}) \quad (17)$$

where all notations are defined in Table 2 and presented in Figure 2. Vibration control quality is estimated for specific control conditions using performance index defined as follows:

$$PI_I = \frac{\sum_{i=1}^n [\ddot{z}_{PM-I}(i) - \ddot{z}_{PM-I-MEAN}]^2}{n} \quad (18)$$

where  $\ddot{z}_{PM-I-MEAN}$  is the mean value estimation of acceleration  $\ddot{z}_{PM-I}$ .

Tests of vehicular vibration control system were taken for the experimental vehicle traversing a test route including bumps at constant progressive velocity of approximately 10 km/h. Ride quality experiments were carried out for 7 test conditions *i.e.*: soft suspension, hard suspension and the vehicle suspension controlled using Skyhook control scheme with skyhook parameters of 2000, 5000, 7000, 10000 and 15000  $Nsm^{-1}$  for both front and rear vehicle suspension simultaneously. Each test ride was performed three times for specific test conditions.

Based on experiment results, relationship between efficiency of vibration mitigation and skyhook parameter was estimated. Comparison of performance index values is presented in Figure 4. The worst cases of the possible suspension control correspond to soft and hard suspension. Use of Skyhook control improved ride comfort in comparison to the passive suspension. Vibration control quality of the vehicle body significantly depends on the value of skyhook parameter.

## 7. Conclusions

In this paper, the vehicular vibration control system based on installed magnetorheological suspension dampers has been presented. The experiment results have shown the improvement of

vibration deterioration efficiency for specific values of skyhook parameter concerning front and rear vehicle part separately. Moreover, experiments proved the advantage of semiactive suspension over passive soft and hard suspension if the value of skyhook parameter is well-suited to the suspension characteristic. Measurement acquisition part of the system was analyzed and calibrated paying special attention to the orientation of sensors and MR dampers as well as to the proper identification of the MR damper dynamic behavior. Identified Bingham model included in the semiactive control and modifications of Skyhook control scheme contribute to the performance of presented system. It will be interesting to examine the impact of others MR damper models and control schemes on vibration mitigation. Future works will also concern preview vibration control systems.

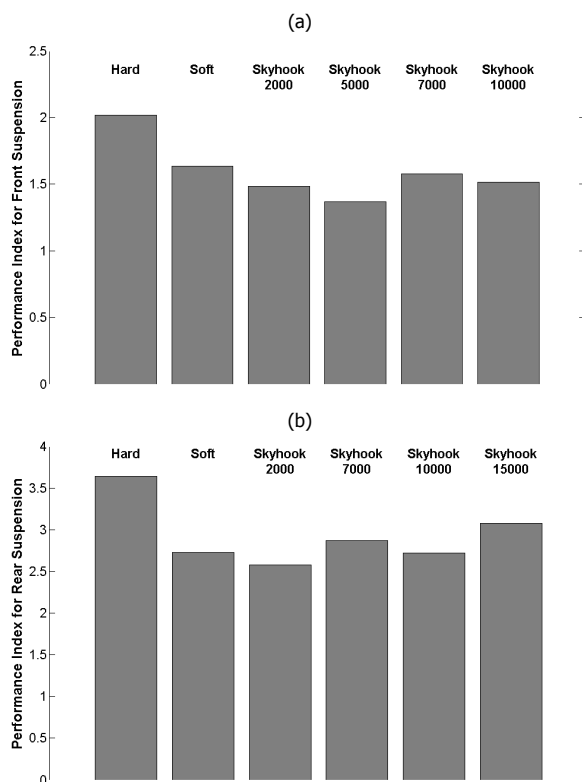


Figure 4. Vibration control efficiency for different test conditions: (a) front vehicle body, (b) rear vehicle body.

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