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Experimental Validation of a Hierarchical Suspension Control via MR Damper

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Abstract: The suspension system has an important impact on vehicle dynamics, comfort and stability; these aspects are conflicting and the objective of an automatic control is to find a compromise. In this paper, the authors present an approach for the control of the vertical dynamics consisting of two layers: a low-level controller which fully exploits the properties of the magneto-rheological damper technology, and a high-level controller based upon a linearized skyhook for the full body control. The controller is experimentally validated on an actual vehicle in two road scenarios, which differ in their frequency excitation.

Keywords: Semi-Active Suspension, Vehicle Dynamics, Automotive Control, Magnetic Suspension, Skyhook

1. INTRODUCTION

The suspension system is the main responsible for the riding quality in a vehicle; electronically controllable suspensions are a tool that allows engineers to significantly improve the performance that can be obtained with a passive suspension. However, the design a control algorithm which can conjugate comfort and vehicle stability, two factors which usually clash against each other, is a challenging task.

Semi-active suspension systems are preferred over the more advanced active suspensions, since the latter require a significant amount of power to work at high bandwidth. Semi-active suspensions modulate the damping coefficient without introducing any active force; there exist several technologies that implement this idea: electro-hydraulic, where the fluid travels across an orifice, whose size is adjusted to modify the resulting damping; magneto-rheological and electro-rheological, where the viscosity of the fluid is modified by applying a magnetic or electric field. Among the cited technologies, MR dampers have interesting features: a wide controllability region, response time in the order of milliseconds, reduced device dimension and low voltages and currents.

The literature on semi-active suspension control of the vertical dynamics or, more generally, of vibrations is rich and diverse. In Savaresi and Spelta [2007], it has been shown that the skyhook logic approaches the filtering limit of a semi-active suspension; indeed, most of the literature is based on variations of this control logic which was first proposed in Karnopp [1995]. Variations of the skyhook logic can be found in Poussot-Vassal et al. [2006], Song [2009], Yao et al. [2002], Savaresi and Spelta [2008], Li et al. [2009], Nie et al. [2017]. The other aspect is the literature regarding the control of the damping force in a magneto-rheological damper; in Sims et al. [1997, 2000], the authors developed a scheme to track a reference damping force in a MR damper by controlling the input current, regardless of the application (*e.g.*, automotive). The closest related work is Corno et al. [2019] where the authors designed a skyhook control scheduled to undergo extreme dynamic maneuvers, whereas the control of the MR Damper was not thoroughly investigated.

The novelties of this work consist in

- an experimental analysis on the design of passive damping curves and their influence on the vertical dynamics;
- a mid-layer *morphing* strategy which allows the high-level controller to exploit the properties of the underlying damping curves.

These objectives are achieved within a hierarchical scheme, where the control of the vertical dynamics and the control of the MR damper are decoupled but work together to achieve a better filtering of the vibrations due to road excitation. The two main building blocks consist of:

- an *ad hoc* low-level controller which emulates a passive characteristics by modulating the current of a MR damper;
- a skyhook variant which is decoupled from the underneath hardware.

Furthermore, most of the referenced bibliography lacks an experimental validation on an actual vehicle, which means the algorithms are never proven to be applicable in real working conditions. Indeed, in Corno et al. [2019], the authors show how the state-of-the-art skyhook logic, when implemented on a real vehicle, suffers from vertical jerk which significantly deteriorates performance. Therefore, all results presented in this article have been validated on an actual vehicle.

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The remainder of this paper is as follows. In Section 2, the vehicle setup used to validate the proposed algorithms is presented. Section 3 gives a broader picture of the general control framework, which is thoroughly elaborated in its sub-systems in Sections 4-5. Eventually, the final controller is validated on two meaningful road scenarios in Section 6. The paper is ended by some concluding remarks. Throughout the document, for confidentiality matters, the axes of all Figures have been normalized.

2. EXPERIMENTAL SET-UP

The research in this article is validated on a sports-car, equipped with MR dampers, with a sprung and unsprung mass of $1800\,Kg$ and $200\,Kg$ respectively.

The vehicle is fully instrumented:

- 4 corner single-axis body accelerometers (used for control);
- 4 corner suspension potentiometers (used for control);
- a central inertial measurement unit with an integrated gyroscope (used for analysis and validation);

The control algorithm is uploaded onto a prototypal ECU which controls the MR dampers; the ECU is also in charge of logging every signal from the sensors.

The experiments have been carried out in a professional proving ground to ensure a fair evaluation of the controller.

3. HIERARCHICAL CONTROL FRAMEWORK

This section elaborates the development of a hierarchical control scheme which considers both the vehicle dynamics control and MR force tracking; the two control problems shall work together to achieve a better filtering of vibrations due to road excitation. In this section, the general framework of the control scheme is introduced, whilst each subsystem is further elaborated in the remainder of the article.

The damping characteristics of a MR damper is known to be highly nonlinear; the most troublesome property is the steepness at low stroke speeds, equivalent to having an extremely high damping: although this is favorable in dynamic maneuvers (*e.g.*, cornering), it significantly degrades the filtering capabilities when considering purely vertical dynamics (driving straight). It is therefore desirable to be able to shape this characteristics to achieve desired performance; the shape of this curve is a design parameter which is further discussed in Section 4.

With this aim, the low-level controller allows the MR damper to emulate a *passive damper*: given a reference damping curve, in terms of a Force-Speed relationship, this subsystem is in charge of delivering the correct amount of current I, so that the MR damper exerts the desired damping force. There are several ways one can design such system, the easiest being making use of an inverse model of the MR damper.

The high-level controller implements a linearized variant of the classic skyhook, thoroughly discussed in Section 5, which outputs a normalized $C \in [0, 1]$ where 0 indicates the lowest damping curve, and 1 the highest. This value corresponds to a desired damping curve which the low-level controller must follow. The association between C and a particular curve is elaborated in Section 5.

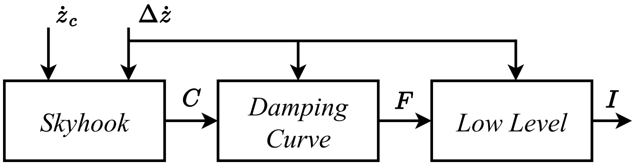

Fig. 1. Hierarchical control scheme.

Summarizing, the control scheme is depicted in Figure 1, where $\dot{z}_c$ indicates the vertical corner velocity and $\Delta\dot{z}$ the stroke speed. From a top-down perspective, the high-level controller, according to the present body excitation, outputs a reference C which is encoded as a real number in the interval $[0, 1]$; this value is transformed into a damping curve and forwarded to the low-level controller which generates the appropriate control current I which drives the MR damper to track the desired force.

The advantage of this decoupling lies in the fact the skyhook control law does not depend upon the underlying hardware, since the low-level controller has the purpose of hiding the mechanism which generates the current I.

The aforementioned scheme operates independently on each corner of the vehicle, *i.e.* it is replicated four times.

4. LOW-LEVEL CONTROLLER

The low-level controller transforms a force request into a control current I; this allows the MR damper to change its natural damping characteristics into any desired curve, which must lie within the physical limits of the device.

Hence, the term *Virtual Damper* was coined to suggest the capacity to emulate a passive damper (*i.e.* having a constant force-speed relationship) with a semi-active suspension. This fact itself is a tool in the hands of a calibration engineer who is given the possibility to shape a (passive) damping curve electronically, whereas doing so on a passive damper would require much more time and resources. The actual implementation of such system is out of the scope of this article. A possible solution to achieve such goal can be found in Sims et al. [1997].

The optimal shape of a passive damping curve is very much application dependent and, to the authors' knowledge, it has never been addressed by the scientific community. Test engineers rely upon experience and trial-and-error calibration to accomplish desired performance. When calibrating a passive suspension, several aspects must be considered:

- *harshness*, high frequency vibrations at low stroke speeds ($\Delta\dot{z} < 20\,mm/s$) which are transmitted to the body due to stick-slip effects in the damper; the damping characteristics should be flat in this speed region to avoid high friction forces;
- *soft handling*, low frequency depressions and steering maneuvers must be dampened to achieve good stability of the body; the damping characteristics should be steep in the range $\Delta\dot{z} \in [20, 100]\ mm/s$ to generate high damping forces.

- *comfort*, when the terrain is rough, the damper shall absorb the impact to minimize the vertical accelerations passed onto the body; the damping characteristics should be flat for high stroke speeds ($\Delta\dot{z} > 100\,mm/s$).
- *balance*, the vehicle shall remain parallel (*i.e.*, attenuate the pitch dynamics); balance can be adjusted by partitioning the front and rear damping forces according to the mass distribution of the vehicle.

Three sets of damping curves have been tested and compared against in order to highlight the benefits of the best solution which embraces the aforementioned aspects; the curves are shown in Figure 2.

Curve I has a steep slope to tackle *soft handling*, but it does not implement any distribution between front and rear to deal with *balance*. *Curve II* is more *comfort* oriented, delivering lower forces with respect to the previous solution, and it enforces a higher characteristics in the rear. *Curve III* has a steep slope for the stroke speed range $(20, 100)\,mm/s$ guaranteeing a good stability of the body for low frequencies, whereas for higher speeds the curve flattens out to improve *comfort*; further, the rear characteristic is scaled by a factor of 60% with respect to the front in order to improve *balance*.

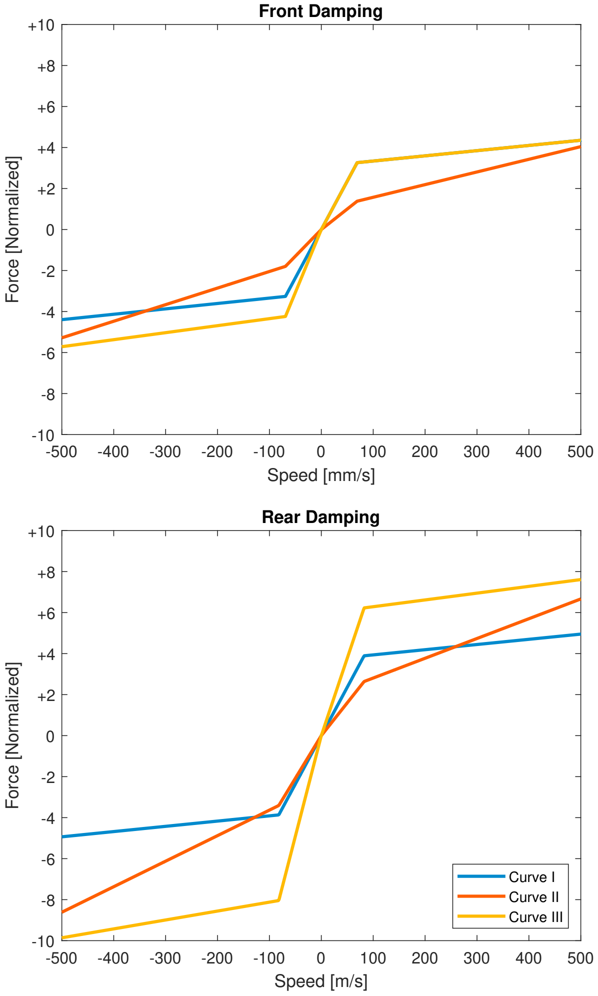

Fig. 2. Virtual passive curves tested.

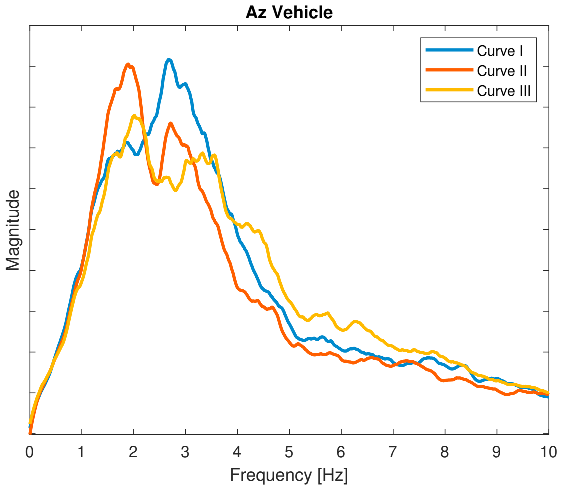

Fig. 3. Spectrum of the vertical acceleration in *Virtual Damper* mode.

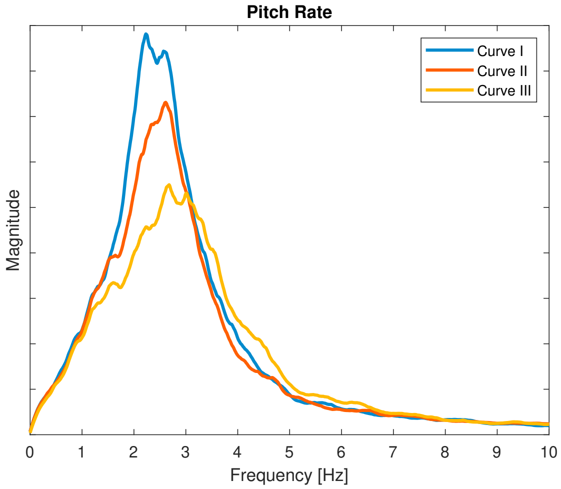

Fig. 4. Spectrum of the pitch rate in *Virtual Damper* mode.

In order to assess the filtering qualities of the three curves, we drove the vehicle at constant speed over a road stretch to excite frequencies up to $10Hz$; the results are represented via the estimated spectrum of the signals of interests (vertical acceleration and pitch rate) shown in Figure 3-4, which confirm the good practices listed above in the bullet points. The spectrum of the vertical acceleration shows that *Curve I* has a good damping of the heave resonance $\sim 2Hz$ (*soft handling*) but very poor *balance* performance, captured by the pitch rate spectrum. *Curve II* shows the best filtering for higher frequencies, but it is very poor in *soft handling*. *Curve III* combines the properties of the first two to the (little) detriment of comfort.

These curves are the result of a fine tuning where the goal consisted in finding the optimal *Virtual Passive Damper*. A passive damper must inevitably compromise between comfort and stability; this downside will be overcome by the high-level controller which upgrades *de facto* the logic from passive to semi-active.

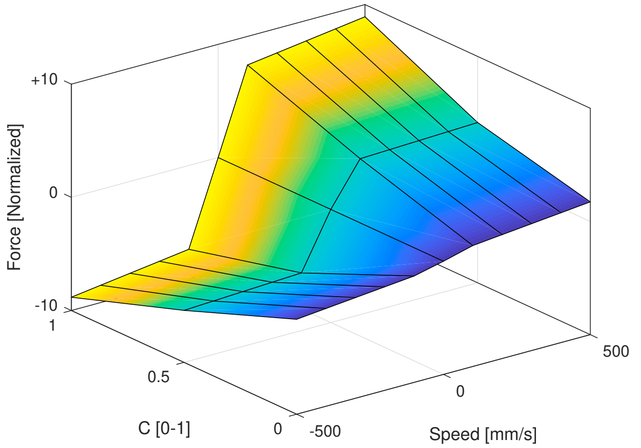

Fig. 5. Morphing 3D view.

5. HIGH-LEVEL CONTROLLER

The high-level controller has the task to control the vehicle dynamics. This research focuses only on the heave and pitch dynamics (*comfort* and *balance*) due to road disturbance; it is not in the scope of this paper to address longitudinal and lateral dynamics (*i.e.*, braking and steering maneuvers).

The control law is a modified skyhook expressed as

$$C = C_{nom} + K\dot{z}_c\Delta\dot{z} \tag{1}$$

where C_{nom} and K are design parameters, $\dot{z}_c$ is the vertical corner velocity and $\Delta\dot{z}$ is the stroke speed; each one of the four corners works independently from the others.

The skyhook control law in Equation (1) has two main design parameters: C_{nom} defines the base curve which the low-level controller uses in absence of perturbation, while K delineates how sensitive the controller should be when the sprung mass is moving ($\dot{z}_c \neq 0$). If $K = 0$, the skyhook logic is turned off and the system runs in *Virtual passive damper* mode, where the damping curve is specified by C_{nom}. On the other extreme, as $K \to \infty$ the control law tends to the ideal two-state skyhook; as thoroughly investigated in Corno et al. [2019], the ideal logic introduces a vertical jerk when switching between minimum and maximum damping which significantly deteriorates the riding comfort.

The damping request C is normalized in the range $[0, 1]$ and each value must be associated to a virtual curve to be tracked by the low-level controller. Naturally, the relationship between C and the damping force must be monotonically increasing.

The problem consists in designing a *morphing* strategy, namely the mid-layer in between the low-level controller, where the *Virtual Damper* is defined, and the high-level skyhook control logic, which determines the reference damping. This interface is the algorithm through which the virtual passive curve, discussed in the previous section, is scaled with respect to C.

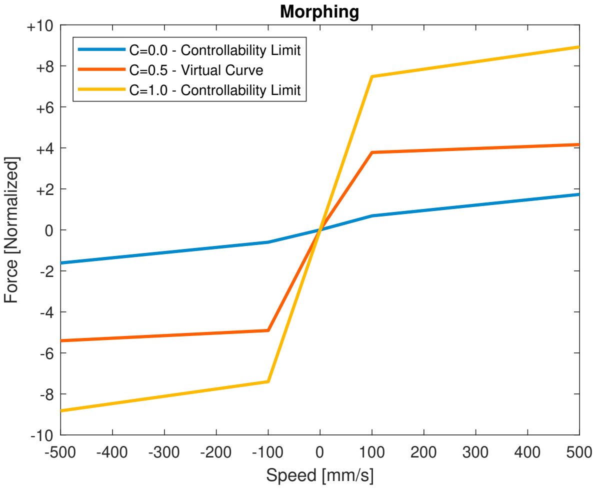

Fig. 6. Morphing 2D view.

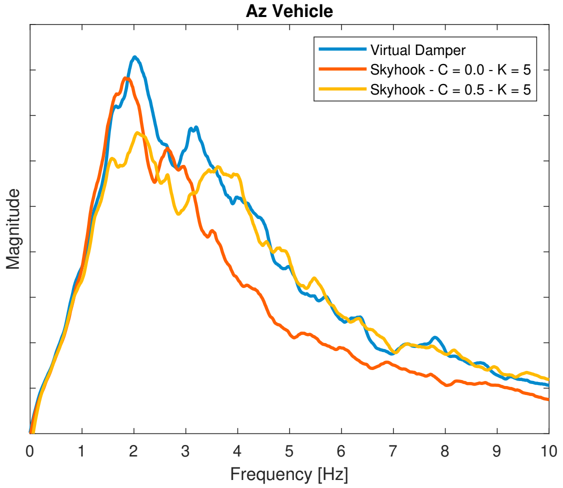

Fig. 7. Spectrum of the vertical acceleration with semi-active skyhook.

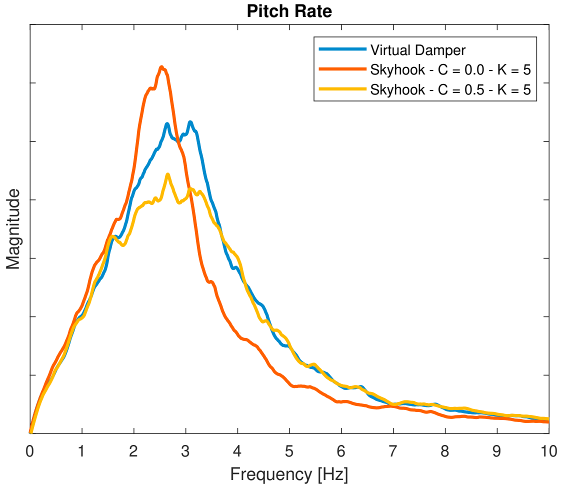

Fig. 8. Spectrum of the pitch rate with semi-active skyhook.

The proposed *morphing* strategy consists in assigning the base curve to $C = 0.5$ and interpolate to the controllability region, as shown in Figure 5 and 6, where the latter is a projection of the former. The curves at the extremes correspond to what the MR damper can achieve when fed by zero and maximum current I.

In Figure 7-8, two different calibrations are proposed and compared against the *Virtual Passive Damper* elaborated in the previous section. The first calibration ($C_{nom} = 0.0$) shows the best filtering of vertical accelerations (*comfort* oriented); in the other tuning ($C_{nom} = 0.5$) *balance* is prioritized over filtering (*sport oriented*). Both manage to enhance the *Virtual Damper* which is constrained by its passive behavior.

6. COMPLETE SYSTEM VALIDATION

In this section, the hierarchical control algorithm is validated in two different settings which are intended to excite both heave and pitch dynamics. Each run is performed in the same road stretch at the same velocity to ensure a fair comparison.

The same way as the previous sections, the results are presented via the estimated spectral density of the vertical acceleration and pitch rate time signals; this is by reason of a clearer evaluation with respect to the time domain analysis.

6.1 Scenario A

These experiments have been performed on a road, traveled at $120km/h$, consisting of a broad range of frequencies which challenges *comfort* and low-frequency valleys which excite the pitch movements.

In Figure 9, the performance on the heave dynamics of the skyhook logic is compared against the passive configuration at minimum and maximum current. The low-current setup provides a very good filtering for the higher frequencies ($f > 3Hz$), whilst the body resonance is totally under-damped; on the contrary, the stiff setup achieves a good stability to the detriment of comfort. The same comments apply to the pitch dynamics in Figure 10.

The skyhook logic combines the best behaviors of both passive configurations: good filtering of high frequency vibrations, as in the configuration with $I = 0A$, and high damping for the heave resonance, as in the stiff configuration with $I = 5A$. The control parameters C_{nom} and K shall be adjusted to ultimately favor one of these two factors.

Two different calibrations are proposed: *comfort* oriented aimed at minimizing high frequency vibrations, and a *balance* oriented which achieves a good damping of the pitch and heave resonance; one calibration's upside is at the expense of the other's upside.

The most influential parameter is C_{nom} which defines the base *virtual* passive curve in the low-level controller as elaborated in the previous sections. Although K plays a significant role, increasing its value leads to undesired vibrations due to the switching between minimum and maximum damping.

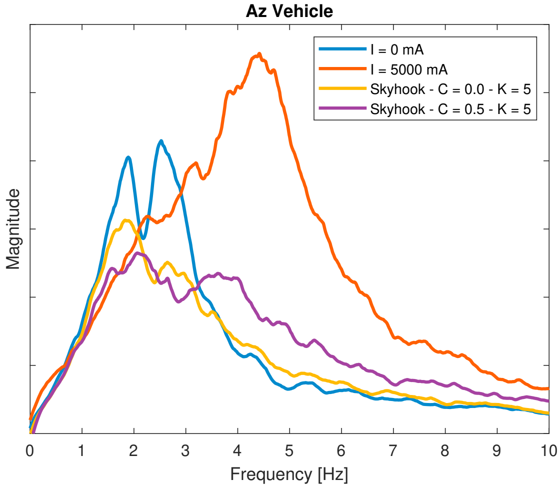

Fig. 9. Spectrum of the pitch rate in *Scenario A*.

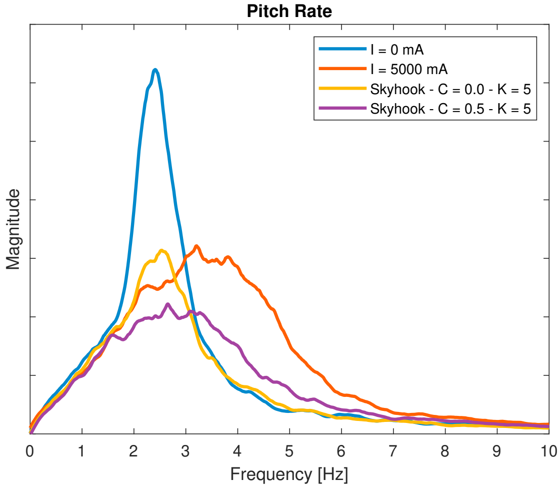

Fig. 10. Spectrum of the vertical acceleration in *Scenario A*.

6.2 Scenario B

These experiments have been performed on a test track consisting of a straight section which is traveled at $160km/h$. It consists of three sections: i) a high-frequency wave, ii) a low-frequency wave and iii) a rough section with asperities; it is ideal to have a good representation of the spectral behavior of the controller at different frequencies of excitation.

In Figure 11, the skyhook logic is compared against the minimum[1] and maximum current settings providable by the MR damper. The higher frequencies ($f > 3Hz$) are completely filtered out by the low current, whereas the stiffer configuration introduces more vibrations to the body; in this bandwidth, skyhook mimics the low damping configuration. In the frequency range $[2, 3]$ Hz, the skyhook control can dampen the vehicle more efficiently than the high-current configuration. Eventually, the skyhook for the low frequencies cannot again achieve as good a

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[1] Actually, the minimum current which can be supplied is $I = 0A$ but for safety matters (the vehicle was unstable on that road) it has been increased up to $I = 500\,mA$.

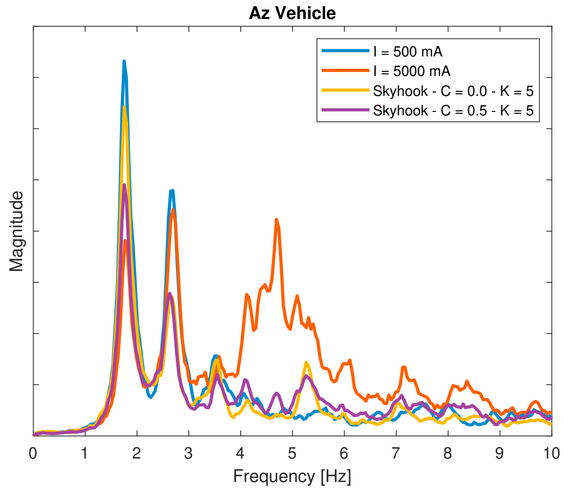

Fig. 11. Spectrum of the vertical acceleration in *Scenario B*.

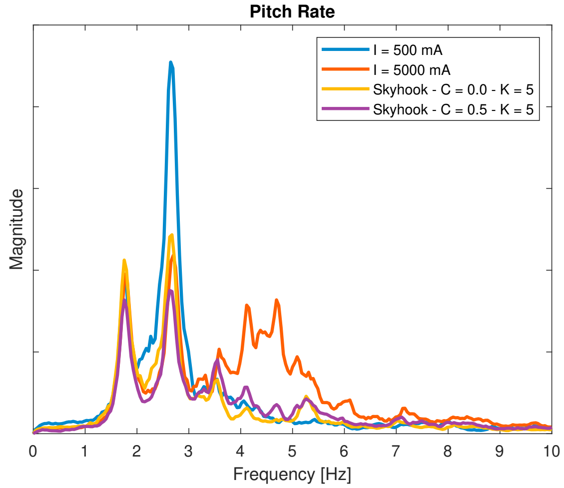

Fig. 12. Spectrum of the pitch rate in *Scenario B*.

damping as the configuration with $I = 5A$ since increasing the control parameters C_{nom} and K introduces undesired collateral effects (*e.g.*, vertical jerk) which deteriorate performance. Similar comments hold for the pitch dynamics shown in Figure 12, where the advantage of the skyhook logic is even stronger: around $3Hz$ the soft configuration is completely under-damped, whereas the proposed logic guarantees an optimal *balance*.

In this scenario, the two skyhook configurations yield quite similar results apart from the damping of the heave resonance: the *comfort* configuration allows more freedom of movement to the vehicle body, whereas increasing C_{nom} has a significant effect on the vehicle damping.

The driver praised the ability to filter the high-frequencies and the feeling of stability at low-frequencies which does not go to the detriment of comfort.

7. CONCLUSIONS

This paper presented a novel hierarchical control framework for the control of vibrations in a sports-car. It consists of two sub-system: i) a low-level controller which fully exploits the MR damper technology and ii) a high-level controller based on a variation of the skyhook control logic.

The proposed controller is thoroughly validated on a real vehicle by a professional driver in official proving grounds. Both objective and subjective evaluations praise the capabilities of the presented controller which can achieve a good damping of the body resonance and good filtering for the higher frequencies.

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