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Semi-Active Control Strategies for High-Performance Motorcycle

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Abstract: The topic of this paper is the design and analysis of a control system for a semi-active suspension in a 2-wheel vehicle. The control system is implemented via a semi-active electro-hydraulic damper located on the rear suspension of a hypersport-class motorbike. The entire design and analysis procedure is outlined: the semi-active damper is analyzed and characterized; a wide range of control strategies are implemented in the Electronic Control Unit (ECU) of the motorbike; a complete test-bench analysis of the vehicle is developed. The final result is a complete comparative analysis of a wide portfolio of different semi-active control strategies which shows the potential benefits of a semi-active suspension

1. INTRODUCTION

Among the many different types of controlled suspensions (see e.g. Ahmadiam and Song, 1999; Foo and Goodall, 2000; Campi and Savaresi, 2003; Fischer and Isermann, 2003; Silani *et al.*, 2004), semi-active suspensions have received a lot of attention since they seem to provide the best compromise between cost (energy-consumption and actuators/sensors hardware) and performances. The concept of semi-active suspension can be applied over a wide range of application domains: suspensions in road, rail and agricultural vehicles, suspensions of appliances (e.g. washing machines), architectural suspensions (buildings, bridges, etc.), bio-mechanical structures (e.g. artificial legs) etc.

This paper has the goal of presenting a complete case-study of the design and testing of an electronic control system for a semi-active suspension on a motorbike. This system is implemented on a real vehicle and tested on a modern test-rig. The content of this work is very innovative, since – as far as we know - little or no have been published on the scientific literature on semi-active suspension systems for motorcycles. The comparative analysis proposed in this paper present a wide range of control algorithms, which can be considered the state-of-the art in semi-active suspension control. All these algorithms have been already illustrated in the scientific literature (see e.g. Karnopp and Kosby, 1974; Savaresi *et al.* 2005a; Savaresi and Spelta, 2007), but a complete comparative analysis of all these algorithms on a real vehicle has never been published.

The outline of this paper is as follows: in Section 2 the semi-active damper used on the motorcycle is described, and its main features and control-relevant characteristics are illustrated. In Section 3, four different semi-active control algorithms are described. Section 4 is devoted to the illustration of the test-rig and the experimental protocol used for the analysis. The control algorithms presented in Section 3 are implemented on a motorcycle and their performance are experimentally evaluated and compared in Section 5. Section 6 ends the paper with some conclusive remarks

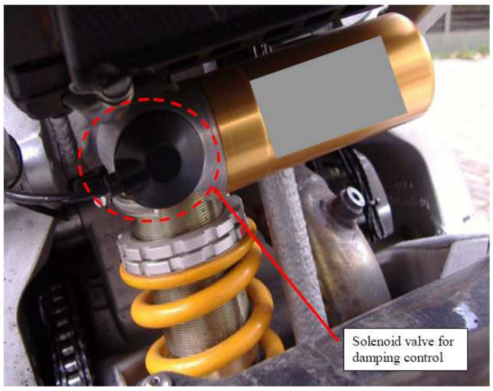

Fig.1. The semi-active rear suspension object of this work.

2. CHARACTERIZATION OF THE SEMIACTIVE DAMPER

The semi-active shock-absorber used in this work is a prototype damper installed on a hypersport-class motorcycle (Fig.1). The shock absorber is equipped with two electro-hydraulic current- driven valves; one for compression and one for rebound. It can continuously change the damping ratio within its controllable range, from 300mA (this current level is called $c_{\min}$ throughout the paper) up to 1200mA (this current level is called $c_{\max}$ throughout the paper). This component hence can be classified as an electronically-controllable device, but not as a "smart" device (Savaresi, 2006).

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The electro-hydraulic valves have no embedded electronics; they must be driven by an external Electronic Control Unit (ECU). An optimized internal PI control loop has been designed and here omitted for the sake of conciseness.

In order to provide a concise characterization of the behaviour of this component, useful for control purposes, the following features must be analyzed: *the controllability range*, namely the damping characteristics at the minimum and maximum damping ratio; *the linearity of the damper; the switching time*, namely the time required to electronically change the damping force.

The controllability range and the linearity of the damper are illustrated in Fig.2, where its behavior is displayed in the classical speed-force domain. More specifically, in Fig.2 the response of the damper to a 10Hz sinusoidal excitation, in its two extreme damping conditions (c_{min} and c_{max}) is depicted (the force scale is omitted for confidentiality reasons; the same scale is used for the two sub-plots for comparison). Notice that the damper is tested over a wide speed range (±0.5m/s). The analysis of Fig.2 clearly reveals the following features of the semi-active damper.

- The ratio between the minimum and the maximum damping is about 1:3. This *controllability range* is enough to obtain good results with semi-active algorithms; a wider controllability range (up to a 1:10 ratio) could be obtained by resorting to a different mechanical layout or to Magneto-Rheological (MR) dampers (see e.g. Savaresi *et al.,* 2005b).

- The device can be considered highly linear: notice that at the minimum damping ratio the speed-force trajectories closely resemble an ellipsoid; in the maximum damping condition only a slight non-linear "regressive" behavior at high speed can be observed.

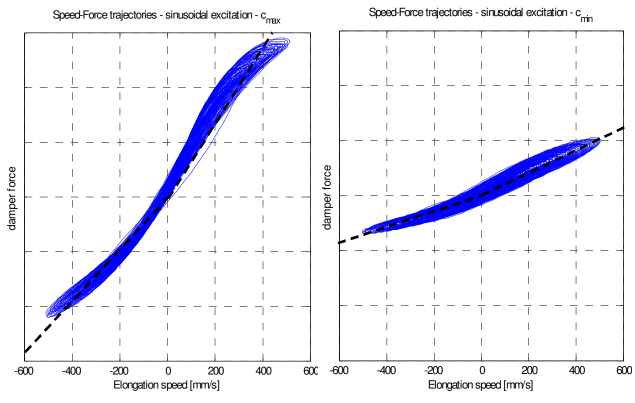

Fig.2. Damper characteristics in the Force-velocity plane, c_{max} (left) and c_{min} (right).

In order to understand the performance of the semi-active device, the analysis of the damping behavior at the extremes of the controllable range must be complemented with the estimation of the switching time, namely the transient behavior of the damper when the valve current is modulated by the ECU. Obviously, the faster is the transient, the better the achievable performance of a semi-active control algorithm are. An example of transient-behavior analysis is displayed in detail in Fig.3. Some interesting comments can be drawn.

- Both the current and the force responses to a step on the current-request show approximately a linear 2nd-order behavior, with an initial zero derivative and a slight overshoot. This behavior is very clean in the current response, whereas the force response looks slightly perturbed in the middle of the rising time. This perturbation is due to the velocity behavior. Notice that when the current is switched a perturbation in the stroke speed is induced because of the test-rig non idealities.

- If we consider the transient time (both for the current and the force) and the time required to reach its steady-state value (hence neglecting the overshoot), it is clear that the force transient time is significantly larger than the current transient time (more than 2-times larger). This is important to be remarked since in many works the simple assumption of a purely-algebraic relationship between the valve current and the damping force is made. This assumption is clearly wrong.

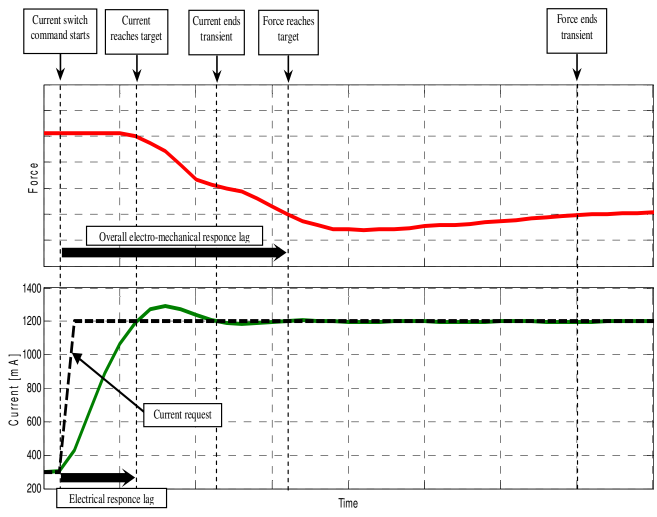

Fig.3. Transient behavior of the damper subject to a step-like variation of the damping request.

In this section the analysis of the controllability range, linearity and switching-time of the semi-active device has been presented. This device has revealed a very high-performing behavior in all the considered features. The only characteristic which could be further improved is the controllability range. Overall, this device can probably be considered one of the best performing semi-active dampers available today for vehicular applications.

3. CONTROL STRATEGIES

The objective of the section is to illustrate concisely the semi-active algorithms portfolio implemented and tested in this work.

The algorithms are presented using of the classical notation of a "quarter-car" model. More details on the quarter-car model can be found e.g. in Williams, 1997. In Fig.4 it is pictorially represented.

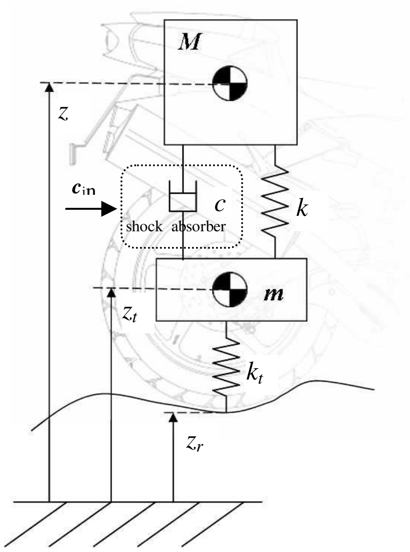

Fig.4. The "Quarter car" model.

The symbols used in the model of Fig.4 have the following meaning: $z(t), z_t(t), z_r(t)$ are the vertical positions of the body, the unsprung mass, and the road profile, respectively; M is the quarter-car body mass; m is the unsprung mass (tire, wheel, brake caliper, suspension links, etc.); k and k_t are the stiffness of the suspension spring and of the tire, respectively; $c(t)$ and $c_{in}(t)$ are the actual and the requested damping coefficients of the shock-absorber, respectively. In order to provide a comprehensive picture of semi-active control strategies, 4 different algorithms have been implemented and tested. They are now briefly recalled using the notation above described. These algorithms belong to the class of "comfort-oriented" algorithms, in the sense that their main goal is to provide a high-quality filtering of the road disturbances, without deteriorating road-contact performance. Despite this "comfort-oriented" flavor, these algorithms are typically used also on high-performance sporty vehicles

3.1 Skyhook Control.

SH control is the semi-active heuristic approximation of the ideal concept of Sky-Hook damping (see Williams, 1997; Yoshida and Okamoto, 1999); it is the most widely used control strategy in semi-active suspension systems. The two-state approximation of the Sky-Hook requires a two-level damper; the control law is given by:

$$\begin{cases} c(t) = c_{\max} & if\ \dot{z}(\dot{z}-\dot{z}_t) \geq 0 \\ c(t) = c_{\min} & if\ \dot{z}(\dot{z}-\dot{z}_t) < 0 \end{cases} \tag{1}$$

If a continuous modulation of the damping coefficient is available, a slightly more sophisticated expression of the SH algorithm can be implemented:

$$c(t) = \underset{[c_{\min}, c_{\max}]}{sat} \left[\frac{\frac{1}{2} c_{SH}\, \dot{z} + \frac{1}{2} c_{SH} (\dot{z}-\dot{z}_t)}{(\dot{z}-\dot{z}_t)} \right] \tag{2}$$

where c_{SH} is a tuning parameter, and represents the desired "ideal-SH" damping ratio. The classical choice for c_{SH} is simply $c_{SH} = c_{max}$.

Rationale (2) is a "smooth" version of algorithm (1) and it is named as Continuous Skyhook.

3.2 Acceleration Driven Damping Control (ADD).

The implementation of ADD control requires a two-level damper; the control law is given by:

$$\begin{cases} c(t) = c_{\max} & if\ \ddot{z}(\dot{z}-\dot{z}_t) \geq 0 \\ c(t) = c_{\min} & if\ \ddot{z}(\dot{z}-\dot{z}_t) < 0 \end{cases} \tag{3}$$

ADD control has been recently proposed by Savaresi *et al.*, 2005a: it is based on nonlinear and optimal control theory and it has been proven to be the optimal control strategy, when the goal objective is the minimization of the body vertical acceleration, the disturbance is completely unpredictable, and the optimization is made on a single-step horizon only. Interestingly enough, the SH and the ADD algorithms have a very simple (and similar) structure.

3.3 Mix SH-ADD (or Mix-2-Sensors) Control

Similarly to SH and ADD, also this strategy requires a two-level damper; the control law is given by:

$$\begin{cases} c(t) = c_{\max} & if \left[(\ddot{z}^2 - \alpha^2 \dot{z}^2) \leq 0 \ \wedge\ \dot{z}(\dot{z}-\dot{z}_t) > 0 \right] \\ & \quad \vee \left[(\ddot{z}^2 - \alpha^2 \dot{z}^2) > 0 \ \wedge\ \ddot{z}(\dot{z}-\dot{z}_t) > 0 \right] \\ c(t) = c_{\min} & if \left[(\ddot{z}^2 - \alpha^2 \dot{z}^2) \leq 0 \ \wedge\ \dot{z}(\dot{z}-\dot{z}_t) \leq 0 \right] \\ & \quad \vee \left[(\ddot{z}^2 - \alpha^2 \dot{z}^2) > 0 \ \wedge\ \ddot{z}(\dot{z}-\dot{z}_t) \leq 0 \right] \end{cases} \tag{4}$$

This control law is extremely simple since – similarly to SH and ADD - it is based on a static rule, which makes use of $\dot{z}, \ddot{z}, (\dot{z}-\dot{z}_t)$ only. For further details and analysis see the work by Savaresi and Spelta (2007).

3.4 Mix-1-Sensor Control

This strategy requires a two-level damper; the control law is given by (see Spelta and Savaresi, 2007):

$$\begin{cases} c(t) = c_{\max} & if\ (\ddot{z}^2 - \alpha^2 \dot{z}^2) \leq 0 \\ c(t) = c_{\min} & if\ (\ddot{z}^2 - \alpha^2 \dot{z}^2) > 0 \end{cases} \tag{5}$$

This rationale is extremely simple and requires only a sensor of the body motion (typically an accelerometer). Note that (5) simply selects, at the end of every sampling interval, the minimum or the maximum available damping ratio, according to the dominant frequency content of the body movement: if $(\ddot{z}^2 - \alpha^2 \dot{z}^2) > 0$, the minimum damping is selected; otherwise the maximum damping is used.

The SH-algorithm is the most classical and widely used semi-active control algorithm. Also ADD is a well-know approach. The "Mix" algorithms are much more innovative: they have been recently proposed and patented.

It is important to remark that the SH, ADD and Mix-SH-ADD algorithms require two sensors: the body-side accelerometer and the stroke sensor; the Mix-1-sensor algorithm instead only requires 1 sensor. This 1-sensor configuration represents a non-negligible benefit, in terms of cost-reduction and in terms of augmented reliability of the control system.

It is important to note that SH and ADD algorithms have no "tuning-knobs"; the "Mix" algorithms instead have a key tuning parameter, which is the so-called "cross-over" frequency α. This parameters is typically set at the classical *c*-invariant frequency of the suspension, but it can be moved from that position to fine-tuning the performance of the Mix algorithms (see Savaresi and Spelta, 2007, for a simulation-based tuning of this parameter).

4. TEST BENCH

The experimental facility used in this work is a state-of-the-art four poster MTS® test-rig (Fig.5) located at the ISMA-CRA Treviglio testing station (near Milan, Italy); this test-rig is designed for full-scale vehicles up to 15.000Kg. The test-rig is basically composed by an high pressure hydraulic system, a reinforced concrete seismic mass, and an electronic control device.

For motorcycle testing, since a two-wheel vehicle has no an intrinsic equilibrium condition when stands still, the test-rig has been equipped with an additional structure having the aim of keeping the vehicle in the vertical position, while leaving all the "in-plane" movements (pitch and heave) completely free.

Fig.5. The MTS test rig at ISMA with a sustaining structure for two wheels testing.

The basic sensor set used for implementing the control algorithms and for evaluating their performances is simple. It is illustrated in Fig.5. It is constituted by: *a body-side* vertical capacitive accelerometer (by Kistler), having the range ±10g; a *wheel-side* vertical capacitive accelerometer (by Kistler), having the range ±25g; a *stroke sensor*, constituted by a shaft potentiometer (by Atleps), having the range of 0-60mm.

The testing protocol using for evaluating the performance of the semi-active algorithms is basically constituted by two types of experiments. These experiments are now briefly described and discussed (see Fig.6).

- The first type of test-rig experiment is a time-varying sinusoidal excitation (typically called "frequency-sweep"). The explored frequency range is 0-30Hz. The whole experiment lasts about 2 minutes, and the amplitude of the sinusoidal excitation decreases as the frequency increases. So that the low frequency dynamic is appropriately excited and the wheel contact loss is avoided.

- The second type of excitation differs significantly from the sinusoidal sweep, since it is constituted by a set of well-separated impulse-like signals. Each impulse has a triangular profile and lasts a few milliseconds; as illustrated in Fig.6 a set of positive and negative impulses is used, with different amplitudes (the maximum amplitude is 4.5cm). These impulse-like signals are used to reproduce the effect of bumps and potholes.

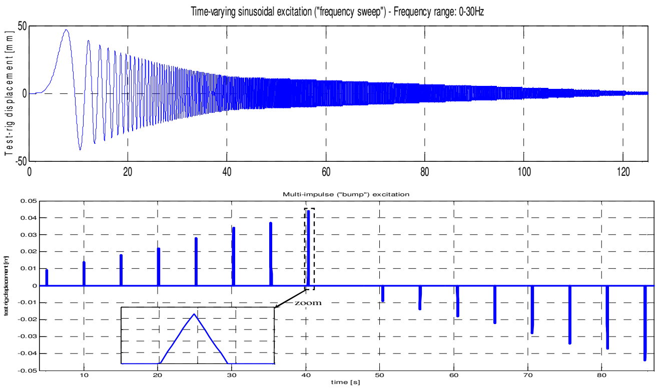

Fig.6. Time domain profile of sweep excitation (a, top) and multi-impulse test-rig excitation.

5. EXPERIMENTAL RESULTS

In this section the results obtained at the test rig on the vehicle are presented and discussed. In the presentation of the experimental results the scales are omitted for confidentiality (however the same scale is used in similar pictures, so allowing a comparative analysis).

In order to understand the basic behavior of the rear suspension of the vehicle, first it is interesting to analyze the performance of the vehicle without control algorithms (namely in a "passive-like" configuration). In Fig.7 the estimated (measured) frequency response from the road acceleration to the body acceleration is displayed, when the damping radio is kept fixed at its minimum value $c_{\min}$ and at its maximum value $c_{\max}$.

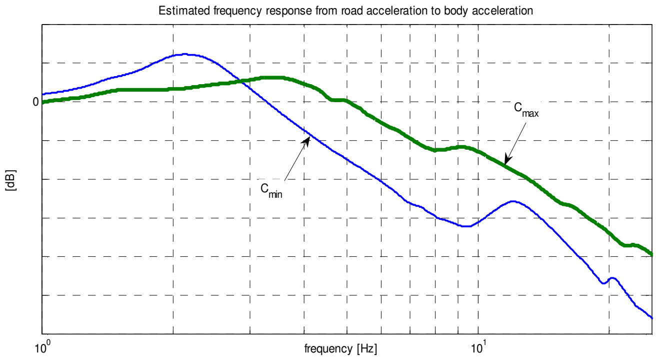

Fig.7. Frequency-domain filtering performance of the two extreme fixed damping ratio.

The obtained results are very clear and reflect the classical behavior of an under-damped and an over-damped suspension. When $c_{\min}$ is used, due to poor damping, the two main resonances are clearly visible: the "body" resonance at 2.5Hz and the "wheel" resonance at 12Hz. These resonances are fully damped when the damping ratio is set at its maximum value $c_{\max}$. This better damping is paid in terms of poor filtering of the road disturbance. Given this trade-off, in a standard passive suspension an intermediate damping ratio is typically used, in order to find an acceptable compromise between resonance-damping and high-frequency filtering.

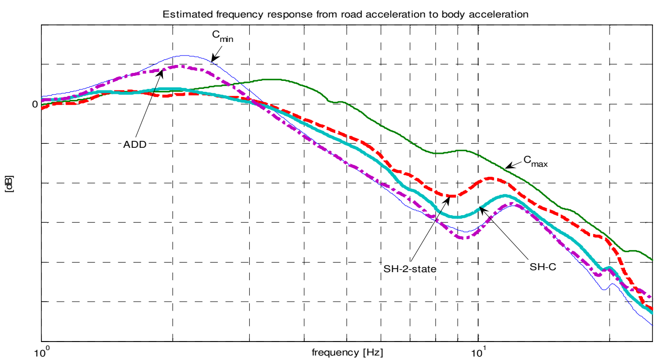

Fig.8. Frequency-domain filtering performance of the Skyhook and ADD algorithms.

In Fig.8 the performance of the classical SH and ADD algorithms is analyzed, and it is compared with the fixed-damping suspension. For the class of Sky-Hook algorithms, both the 2-state (equation (1), labeled "SH-2-state") and the continuous (equation (2), labeled "SH-C") approximations of the ideal SH concept are tested. Also in this case, the results are very clean and easy to be interpreted.

- The ADD algorithm provides optimal performance beyond the body resonance (equal to $c_{\min}$), while providing a medium damping at the body resonance (better than $c_{\min}$ but worse than $c_{\max}$).

- The SH algorithms provide optimal performance at the body resonance (equal to $c_{\max}$), while guaranteeing a medium filtering effect beyond the body resonance (better than $c_{\max}$ but worse than $c_{\min}$). Their performance are similar; as expected the continuous algorithms slightly outperforms the 2-state algorithm.

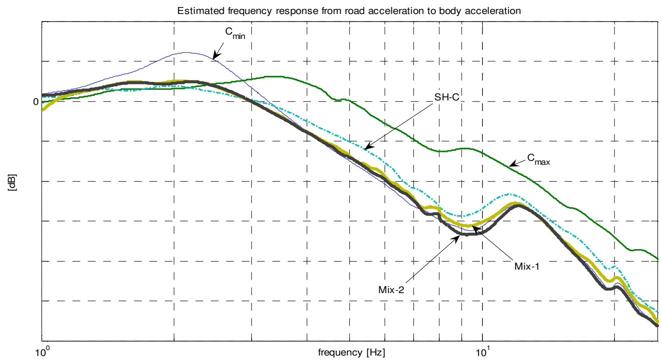

Fig.9. Frequency-domain filtering performance of the "mix" algorithms.

Overall, the best compromise of these classical algorithms is given by the continuous SH. The behavior of SH and ADD clearly shows a strong complementarity. As already said, this peculiar feature has been exploited by the recently developed "mix" algorithms. Their behavior is analyzed in Fig.9; as usual, they are compared with the two fixed-damping settings; in this comparison also the continuous SH algorithms is included. The following remarks are due.

- Both the Mix-SH-ADD (labeled "Mix-2") algorithm and the Mix-1-sensor (labeled "Mix-1") algorithm show a nearly-optimal behavior: they are able to stay on the lower bound of the $c_{\min}$ - $c_{\max}$ filtering curve (see Savaresi and Spelta, 2007, for the optimality analysis of these algorithms). They clearly outperform the continuous SH algorithm.

- It is interesting to observe that the loss of performance of the Mix-1 algorithm with respect to the Mix-2 algorithm is negligible: this is a key feature of this algorithm, since it capable of providing the same near-optimal performance using a single-sensor configuration (while all the other algorithms, including SH and ADD, require a 2-sensor configuration). This feature is very appealing in terms of cost reduction and improved reliability

We conclude this analysis by presenting an example of time-domain analysis. More specifically, Fig.10 displays the motorcycle response to a 45mm bump. To make the interpretation of the figure more clear, only the responses of $c_{\min}$, $c_{\max}$ and the "best" semi-active algorithm (the "Mix-1") are illustrated.

The time-domain behavior of the suspension stroke and body acceleration shows very clearly the benefit of a good semi-active algorithm (Fig.10).

- When a c_{min} fixed damping is used, the suspension reacts to the bump with a large stroke movement (almost 30mm peak-to-peak); the benefit is a good filtering (the acceleration peaks body-side are small); the drawback of this setting is that, when the bump is passed, the settling time is long and characterized by obnoxious undamped oscillations.

- When a c_{max} fixed damping is used, the suspension reacts to the bump with a small stroke movement (less than 15mm peak-to peak); a poor filtering is the main consequence (the acceleration peaks body-side are large); however, the benefit of this fixed tuning is clear in the second part of the transient: when the bump is passed, the settling time is short and very well damped.

- The semi-active Mix-1 algorithm inherits the best of the two fixed settings: in the first part of the transients keeps the damping low, to get a good filtering (low acceleration peaks); in the second part of the transient sets the damping to the maximum value, in order to provide a short settling time. This is done automatically by the algorithm (5). This behavior can only be achieved by electronic feedback control of the damping; and it fully overcomes the traditional trade-off of passive damper tuning.

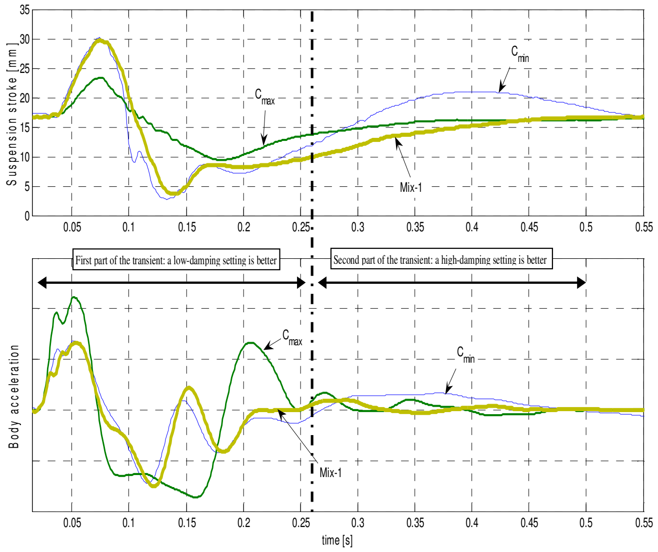

Fig.10. Response to a 45mm bump. The 1-sensor-Mix algorithm performance.

6. CONCLUSIONS

In this work the complete development and analysis of a semi-active control system for the rear suspension of an high-performance motorbike has been presented The experimental analysis clearly shows that a semi-active suspension with a good control strategy can almost completely remove the trade-off of a classical passive suspension. It has been shown that these results can be obtained also with a single-sensor configuration, using the recently developed "Mix-1-sensor" control strategy.

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