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Experimental analysis of a motorcycle semi-active rear suspension

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ABSTRACT

The topic of this paper is the experimental analysis and development 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 in the rear suspension of a motorbike. The entire design and analysis procedure is carried out: the semi-active damper is characterized; a wide range of control strategies is recalled and an innovative semi-active algorithm (*Mix-1-Stroke*) based on a single-sensor layout is proposed. The strategies are then implemented in the Electronic Control Unit of the motorbike. Tests, both on test-bench and on-road, are presented. The result is the comparative analysis of a wide portfolio of different suspension control strategies, which shows the effectiveness of the *Mix-1-Sensor* rationale.

1. Introduction and problem statement

The topic of this paper is the design and analysis of a semi-active suspension system (see e.g. Ahmadian, Reichert, & Song, 2001; Caponetto, Diamante, Fargione, Risitano, & Tringali, 2003; Choi, Park, & Suh, 2002; Giua, Seatzu, & Usai, 1999; Hong, Sohn, & Hedrick, 2003; Hrovat, 1997; Kawabe, Isobe, Watanabe, Hanba, & Miyasato, 1998; Kitching, Cole, & Cebon, 2000; Nakai, Oosaku, & Motozono, 2000; Poussot-Vassal, Sename, Dugard, Ramirez-Mendoza, & Flores, 2006; Sammier, Sename, & Dugard, 2003; Savaresi, Silani, & Bittanti, 2005b; Tseng & Hedrick, 1994; Valasek, Kortum, Sika, Magdolen, & Vaculin, 1998).

Among the many different types of electronically-controlled suspension systems (see e.g. Campi, Lecchini, & Savaresi, 2003; Fialho & Balas, 2002; Fischer & Isermann, 2003; Silani, Savaresi, Bittanti, Fischer, & Isermann, 2004; Williams, 1997), semi-active suspensions seem to provide an attractive compromise between cost (energy-consumption and actuators/sensors hardware) and performance. In the field of road and off-road vehicles, semi-active suspensions have been recently introduced in production cars, whereas they are still under pre-production testing on trucks, earth-moving machines, agricultural tractors, and motorcycles.

This paper presents a complete case study of the design, implementation and testing of an electronic control system for a semi-active rear suspension on a high-performance motorbike.

Semi-active systems are traditionally based on a layout comprising two sensors (see e.g. Fischer & Isermann, 2003; Hrovat, 1997; Kitching et al., 2000; Silani et al., 2004), such as one accelerometer and one potentiometer. The accelerometer is placed either at body side or at wheel side. The potentiometer is exploited to monitor the suspension deflection. An alternative layout is made up of two accelerometers one on the body side and one on the wheel side: in this layout the deflection velocity of the suspension may be obtained by integrating the difference of the two accelerometers (see e.g. Silani et al., 2004).

In this research area a great improvement may be represented by a semi-active suspension system equipped with only one sensor, without significant degradation of the performances, and with an evident advantage in terms of reduction of costs and complexity (see e.g. Poussot-Vassal et al., 2006; Savaresi & Spelta, 2009). Recently, a control strategy has been theoretically developed in this direction: the *Mix-1-Sensor*. This rationale uses only one body accelerometer and it has been shown to ensure quasi-optimal performances (Savaresi & Spelta, 2009). However, in the application of semi-active systems on a motorcycle, the use of a body accelerometer can be critical. In fact, due to the mechanical layout, the engine vibrations are usually transmitted dramatically to the body and the correct measure of its movements is so deeply affected. Consequently, the performances achievable by a suspension algorithm, based on body dynamics, may degrade. In this scenario, this paper has the main goal of designing a new control strategy (the *Mix-1-Stroke*) able to inherit the theoretical optimality of the state-of-art algorithms by using only a stroke sensor instead of a body accelerometer.

The second goal of this work is the practical implementation and the illustration of results from real tests, moving from an

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ideal environment to a real vehicle. In particular, the motorcycle is a type of vehicle never considered in the existing literature on semi-active control, but only for traditional suspension design (see e.g. Cossalter, Doria, & Lot, 2000; Sharp & Limebeer, 2001).

The outline of this paper is as follows: in Section 2 the semi-active damper is described and modeled, and its main features and control-relevant characteristics are illustrated. In Section 3, three different semi-active control algorithms are briefly recalled and the new Mix-1-Stroke rationale is presented. Section 4 is devoted to the illustration of the test-rig and the experimental protocol used for the analysis. The control algorithms are implemented on a motorcycle and their performances are experimentally evaluated and compared in Section 5. Conclusions end the paper in Section 6.

2. Description of the actuator: the semi-active damper

The semi-active shock absorber used in this work is a prototype damper installed on the rear axle of a hypersport-class motorcycle. This component is equipped with two current driven solenoid electro-hydraulic valves; it can continuously change the damping level within its controllability range. The shock absorber damping limits have been designed in order to avoid the end-stops in a normal use of the vehicle. The two valves can manage the damping of the compression and of the rebound phase independently, as it is customary in high-performance motorcycle suspensions. These electro-hydraulic valves have no embedded electronics; they must be commanded by an external Electronic Control Unit (ECU), which implements a fast servo-loop having the goal of regulating the current at the desired value (further details on the design of this internal standard "current-loop" can be found e.g. in Savaresi & Spelta, 2007). Overall, both the valves have the same dynamics and there is no difference in terms of damping between compression and rebound. Thus, they can be equally controlled. This shock absorber can be addressed as an electronically controlled device, but not as a "smart" device (Savaresi, 2006).

A concise model of the controllable shock absorber is given by the following equations:

$$F_{damping} = c(t)\left(\dot{z}(t) - \dot{z}_t(t)\right) \qquad (1-a)$$

$$\ddot{c}(t) = \alpha\dot{c}(t) + \beta c(t) + \gamma c_{in}(t-\tau) \qquad c_{in}(t) \in [c_{min}, c_{max}] \qquad (1-b)$$

The symbols used in (1-a) and (1-b) have the following meaning: $F_{damping}$ is the damping force delivered by the damper, $\dot{z}(t)-\dot{z}_t(t)$ is the stroke speed defined as the difference between the body and the wheel vertical velocity of the vehicle, respectively (see also Fig. 4); c_{in} and c are the requested and actual damping coefficients, respectively; τ is the physical delay between the request and the actuation of the damping coefficient; c_{min} and c_{max} are the minimum and maximum request of the damping level, respectively; α,β, and γ, are the parameters of the closed-loop damping actuation driven by the vehicle ECU.

2.1. Remark: the dead-time τ

The damping force delivered by this shock absorber depends on the fluid velocity flowing in the hydraulic circuits: one for the compression phase and one for the rebound phase. The damping ratio may be changed by varying the orifices of the electrovalves. For control purposes, the dead-time τ in model (1) represents the overall interaction between the electric command, the mechanical movements of the valve orifices, and finally the hydraulic effect converted into a force, as experimentally revealed in Fig. 2.

Model (1) represents a non-linear multiple-inputs-single-output dynamical system. The inputs are the requested damping and the stroke speed of the shock absorber; the output is the damping force. The dynamical behavior of the damping coefficient is described by a second order differential equation with a delayed input, namely the requested damping. The force delivered by the shock absorber is proportional to the stroke speed, scaled by the actual damping. Notice that a model of a non-controlled ("passive") shock absorber, characterised by a fixed damping $\bar{c}$, can be obtained from (1-a) and (1-b) by simply setting $c_{in}(t) \equiv \bar{c} = \text{const}$.

In the existing literature the damping behaviors are usually described by both algebraic and dynamical models (linear and non-linear, see Codeca, Savaresi, Spelta, Montiglio, & Ieluzzi, 2008, and references therein). In this paper a second order dynamic is considered in order to provide a precise description of electro-hydraulic shock absorber, useful for control strategy design, as it will be discussed in the next section. The damping request can be actuated proportionally to the current driven into the solenoid electro-hydraulic valve. The current range used for these valves is 300–1200 mA (c_{min} is the damping ratio obtained at the fixed current of 300 mA; c_{max} the damping ratio obtained at the fixed current of 1200 mA).

The passive-like behavior of the damper is concisely illustrated in Fig. 1, where the characteristics of the damper are displayed in

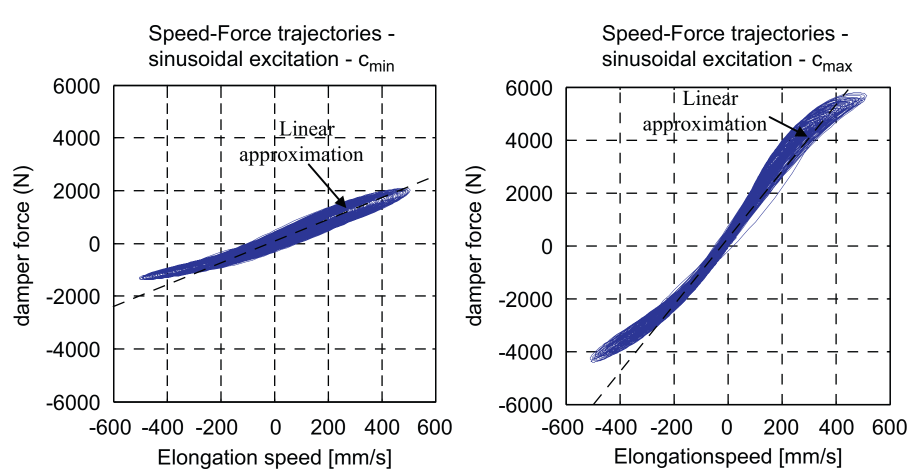

Fig. 1. Damper characteristics in the speed-force domain. Left: minimum damping (c_{min}); right: maximum damping (c_{max}).