Decrease of hysteresis effects in force-speed characteristic of magnetoreologic dampers

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Abstract: Very few materials or devices used in mechanical systems or structures are perfectly elastic. In suspension systems this phenomenon produces significant hysteresis in the force/speed characteristic. In passive suspensions it is hard thinking that hysteresis can be eliminated or significantly reduced, whereas as for active or semi-active suspensions a solution to this problem could be found thanks to their greater flexibility. In this paper the authors propose a first approach for the reduction of the hysteresis loop characterizing the force-speed curve of Magnetorheological (MR) dampers. A solution to the problem has been found in terms of both testing and control techniques based on the intrinsic characteristics of MR fluids. After a description of the idea and of its implementation in a semi active damper, results of the first experimental tests are described.

Key words: MR dampers, semi-active suspension, Hysteresis.

1. INTRODUCTION

The shock absorbers are an important part of automobile and motorbike suspensions, airplane landing equipment, and the supports for many industrial types of machinery. Moreover, transversal dampers, called also yaw dampers, help railcars reduce fluctuations from one side to another, or large shock absorbers are used in civil engineering to reduce the earthquake damage and effects due to resonance. The shock absorber's duty is, then, to absorb or dissipate energy transferred to a body by either an impact or inertia due to acceleration and deceleration. One of design considerations, when designing or choosing a shock absorber, is where that energy will go. In most of them, energy is converted to heat inside the viscous fluid. In hydraulic cylinders, the liquid heats up, while in air cylinders, the heat air is usually bushed to the atmosphere. In other types of dampers, such as electromagnetic types, the energy (to dissipate) can be stored and used later. In any case the way the energy dissipates determines the non linear behavior of dampers. The damping force versus mass speed curve changes from a damper to another and is always non linear. In addition different values of force at the same speed characterize decreasing or increasing speed values. This means that the damper characteristic curve is actually a loop with significant hysteresis.

Hysteresis is the propensity for otherwise elastic materials to rebound with less force than was required to bow them. Hysteresis is common in structural materials, for example the compression of rubber disks, stretching of rubber bands and cords, bending of steel springs, or twisting of torsion bars. Simple vehicles with no separate shock absorbers are even damped, to some extent, by the hysteresis of their springs and frames. Different is the case of vehicles like cars, trucks or motorcycles where the suspension system must assure comfort, safety and drive feelings. Here the result mainly depends on damper characteristic and set up. The damper behavior is expressed by its force-speed curve and some regulations are left to users in traditional mechanical dampers to adapt damper response to driving needs and road inputs. Nevertheless the optimal behavior cannot ever be obtained for the following reasons: i) even though some regulations can be possible, these are discrete, ii) since hysteresis is significant, using average force-speed rather than the actual ones (see figure 1), are so far from the actual damper behaviour.

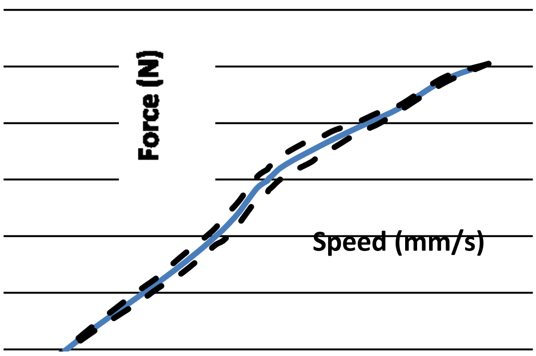

Figure 1 The damper curve characteristic [the real one (dashed), the mean one].

In absence of convincing alternatives, passive devices have represented until now the best solution to the damping problem. By the size of the market is confirmed the success of passive damping technologies in suppressing vibration. However, starting from a kind of material discovered in the early forties, a new class of dampers has been developed, called Magnetorheological (MR) dampers. MR shock absorber is a damper filled with a MR fluid, which is controlled by a magnetic field, usually using an electromagnet. MR fluids are made of magnetic micro-particles suspended within a carrier fluid, usually a type of oil. When subjected to a magnetic field, the fluid greatly increases its apparent viscosity, to the point of becoming a viscoelastic solid. Importantly, the yield stress of the fluid when in its active ("on") state can be controlled very accurately by varying the magnetic field intensity. This allows the damping characteristics of the shock absorber to be continuously controlled by varying the intensity of magnetic field. As the fluid's property of transmitting force can be controlled with an electromagnet, many possible control-based applications can be thought. MR shock absorbers are getting to have several applications. The most notably one is in semi-active vehicle suspensions which may adapt to road conditions, as they are monitored through sensors in the vehicle. MR fluids could permit the construction of real time adjustment if a suitable control strategy is available. The damper model is thus essential both for design and control. The authors have developed and have been patenting an innovative suspension system for motorbikes which is based on both MR fork and shock controlled by an electronic embedded system. In a previous paper [12] the problem of modeling MR damper was tackled by the authors for the first time. Unlike the characteristic curve that comes from a traditional static test (speed sinusoidal) (Fig. 2), the Figure 4 shows how hysteresis effects can be reduced in characterization if the test is performed by keeping constant the damping factor. This method, still close to that used in characterization of passive systems, already allows the MR suspension system to be accurately controlled. Nevertheless, even though the control accuracy reached by this way is higher than that needed for a daily road use of a motorcycle, racing applications ask even more than this.

In this paper, a technique for characterization and optimal control of MR dampers is presented. It eliminates the hysteresis of the damper thus improving performance while simplifying the control algorithms.

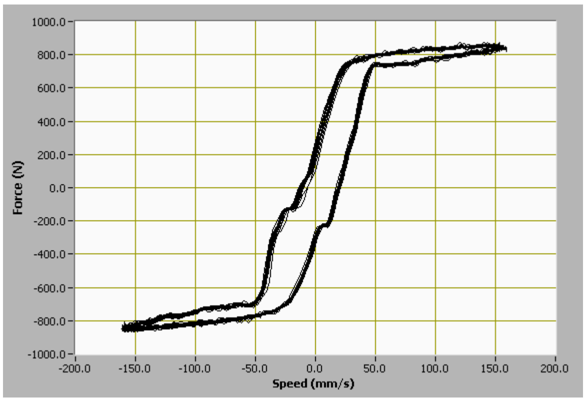

Figure 2 Force vs Speed characteristic of MR damper (with fluid MRF 132LD).

2. DAMPER CHARACTERISTICS

3.

The MR fluid is different from a Ironfluid, in which the particles are much smaller. MR fluid particles are primarily on the micrometer-scale and are too dense for “Brownian Motion” to keep them suspended (in the carrier fluid with low density). Ironfluid particles are primarily nanoparticles that are suspended by “Brownian Motion” and generally will not reconcile under normal conditions. As a result, these two fluids have very different applications.

When a magnetic field is applied the microscopic particles (usually in the 0.11-10 µm range) align themselves along the lines of magnetic flux. When the liquid is contained between two poles (typically of separation 0.50 – 2.00 mm in the majority of devices), the resulting chains of particles confine the movement of the liquid, perpendicular to the direction of flux, effectively increasing its viscosity. If this typical effect of MR devices is to be used, it is crucial to be sure that the lines of flux are perpendicular to the direction of the motion to be restricted. This condition can be satisfied in different modes.

As a consequence, the first parameter to be assigned in designing a MR damper is the mode. Devices which employ MR fluid are in fact divided into three different categories: each category is characterized by a different way (mode) the fluid moves (slips) respect to the surfaces which constrain it into a gap [1]-[3]. The first mode is called Shear Mode. In this case the surfaces bounding the gap slip, while the magnetic field is orthogonal to the slip direction. In the second type, called Flow Mode, the gap surfaces don’t move, while the fluid flows between them [4]. Also in this case the flow direction is orthogonal to the magnetic field. Finally, the third type is called Squeeze Mode. The two surfaces slip again but the magnetic field lines are parallel to the slip direction. Shear and Flow mode are mostly used in the realization of dynamic dampers or shock absorbers, whereas the third mode, well used for short strokes, only finds application to vibration dampers. The chosen mode is obtained through a suitable design of the piston and the solenoid whose characteristics mainly influence the damping performance. Either analytical relationships between the characteristic parameters of the piston and the damping performance of the MR damper, or any other analytical model could help designers make their choices in suitable simulation environments. Performance of dampers is usually evaluated on the basis of two characteristics: the force provided versus displacement; and the force provided versus speed. One of these two characteristic curves can be chosen either to compare a damper with another, or to develop analytic models. While for passive dampers analytical models are used only in the design phase, as for semi-active systems accurate analytic models are indispensable also for implementing robust control strategies. Unfortunately all dampers, whose nonlinearity is considered significant, cannot be represented by simple models. In literature, many solutions can be found about modeling MR dampers and they are classified into quasi-static models [5]-[7] and dynamic models [8]-[10]. The latter are too complex to be applied to a real time control. The former consist more often in force vs speed curves rather than force vs displacement curves, which are usually obtained by sinusoidal speed tests. This kind of curve describes an entire shock stroke (360° in the case of mechanical tester), showing the positive and negative values of speed (see the test station in fig.3). The line speed is zero in the center. During the sinusoidal test, due to influence of gas compression a curve is first created in compression on the first half of the stroke, and a second curve for the second half of stroke. The same happens in extension phase, caused by inertia of valve systems in acceleration o deceleration. As a consequence the two curves, put together, describe a “hysteresis curve”. Also in magnetorheological dampers there is the “hysteresis phenomenon” [11], but their actual advantage is given by the control capability. In this diagram (fig. 2), concerning a MR damper supplied with a constant electrical current, on the horizontal axis is shown the speed (in mm/s) whilst on the y-axis is shown the force (expressed in N). The authors started from the consideration that the force gap between positive acceleration and negative acceleration is too significant (some percent) for low values of speed. In particular, it came clear that in these sinusoidal tests the damper was led to generate a non-null force at zero speed. This is in contrast with the regular working condition of a damper, whose actual characteristic curves should all include the origin point (null force when null speed). This happened because the test method requires that current be kept constant during the whole cycle, and this probably also increased the entity of hysteresis. On the basis of this considerations, the authors tried to find out a new characterization method to obtain force-speed curves of MR dampers free of hysteresis [12], [13].

4. THE MEASURING STATION

The experimental characterization of dampers is usually carried out through sinusoidal testers (see Fig. 3). The sinusoidal movement of a tester is obtained by a crank which converts the rotating motion of an electrical machine into a reciprocate one. The sinusoidal tester is equipped with suitable sensors and acquisition system. The main sensors of the sinusoidal tester are: a load cell ("S" TYPE LOAD CELLS SERIES 560QDT, ±550kg range and ±0,03% FS repeatability), a sensor measuring the displacement of the damper (PCR-A-1 type 150 mm range and ±0,02% FS repeatability), and a temperature sensor (type PT100). The solenoid current has been converted into a voltage signal by an active current probe (Tektronix P6021, 1mA-7,5A input range, 60 MHz Bandwidth, ±0,2% accuracy).

The tester provides sinusoidal movements along the damper's axis. The electric motor is an asynchronous motor whose rotation speed is controlled by an inverter. It is also possible to change the frequency of the displacement by changing the rotation speed of the motor. Also the stroke can change by means of certain regulations of a rod position on the crank. Once all of the mechanical connections have been completed, the tester is ready to submit the damper to as many test cycles as you want. Hereinafter one can measure the quantities of interest and can draw the force-displacement and force-velocity curves of the damper that is under testing.

The measurement station is made up of: i) a PC, ii) a data acquisition device NI^{TM}USB-6009, iii) a linear potentiometer sensor for measuring displacement along the damper axis, and iv) a power card to convert the PC control signal into a power signal to send to the MR damper.

By means of the NI USB-6009 the user can start the damper test. The PC software communicates with the NI device and shows the result of the tests. Through the NI USB-6009 it is able to control the shock speed by controlling the motor speed, and in the same time acquire the sensor data. Finally, the PC software elaborates the data to show the damping characteristic of the shock under test.

The linear potentiometer covers the same displacement of the MR damper, and as a consequence it has a stroke of 150 mm. The potentiometer is supplied by the NI-6009 with 5 V. The potentiometer has been mounted so that: position completely closed corresponds to 5 V, whereas potentiometer fully extended 0V. As a result of this convention, in the compression phase, the sign of the voltage derivative is positive. The power board has been used to provide an output of electrical current controllable in the range of 0-2 A, for an input control signal in the range of 0-5 V. With the power board and by means of the outputs of the NI USB-6009 device it is possible to control the current in the shock under test.

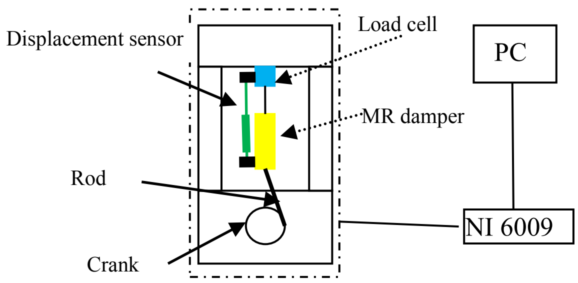

Figure 3 Block diagram of measuring stations and control

4. THE PROPOSED METHOD

During the sinusoidal test cycle, the solenoid current value, instead of being kept constant, has continuously been changed in order to keep constant the force/speed ratio which, unless of a constant parameter, corresponds to the "damping factor" of the damper. Of course, unlike the traditional characterization, the electrical current needs to be real time controlled by a suitable measurement and actuation system. Moreover in this case the force range is explored by another family of curves in the force-speed plane where each curve corresponds to a different damping factor value.

As it can be noted in fig. 4, the hysteresis in these curves is lower than before even if it still remains. Finally, in this work the authors want to demonstrate that it is possible to further reduce the hysteresis phenomenon with right control logic. With the approach that will be presented, the user could control a MR damper obtaining the desiderated damping force with high accuracy.

The previous results reduce the significance of the hysteresis and allow the implementation of a single look up table which implements the basic control method, so reducing both the computational burden and the memory requirement. The good compromise reached has allowed the implementation of the control strategy on a control unit whose dimension and cost are compatible with an actual application of MR dampers to motorcycles. Starting from this result the authors have been set up the new method for the characterization of shock described in the following.

Tanks to the sinusoidal tester (see fig.3), the damper has been characterized with a fixed damping constant providing the results reported in fig.4. The figure 4 shows twenty different damping cycles. An electric current has been provided to the shock to achieve the curves with a fixed damping factor. In parallel with the damper a displacement sensor has been used during the test to measure the velocity and the sign of acceleration. This sensor is usually applied to the actual suspension systems based on MR dampers, whose control logic has to based on the sign of the acceleration and on the speed value. Given the speed value and the sign of the acceleration a correction coefficient (on the applied electric current) can be evaluated starting from the curve of fig 4.

On the basis of the aforementioned correction factor, some real improvements begin to be evident (fig. 5) in characterization tests carried out with this new control method. The fig. 5 shows how the hysteresis can be reduced by this way and how the resulting characteristic curve can model the actual behavior of the damper. The hysteresis reduction is of about 130 N at speed of 50 mm/s, it is due to the effective of the hysteresis cycle.

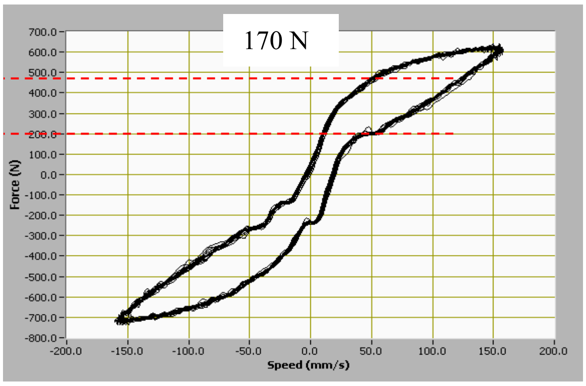

Figure 4 Force vs Speed characteristic of MR damper with hysteresis.

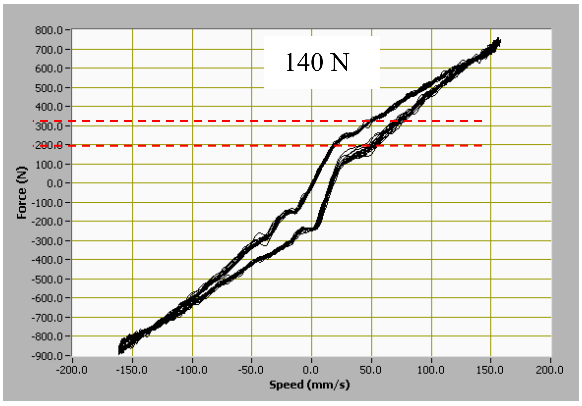

Figure 5 Force vs Speed characteristic of MR damper with hysteresis reduction.

The figure 6 shows the block diagram of the control logic: the signal are sampled and filtered, than the speed and the acceleration sign are calculated and used for generating the right electric current. The generated electric current is proportional to the speed of the shock with a correction factor depending on the sign of the shock acceleration.

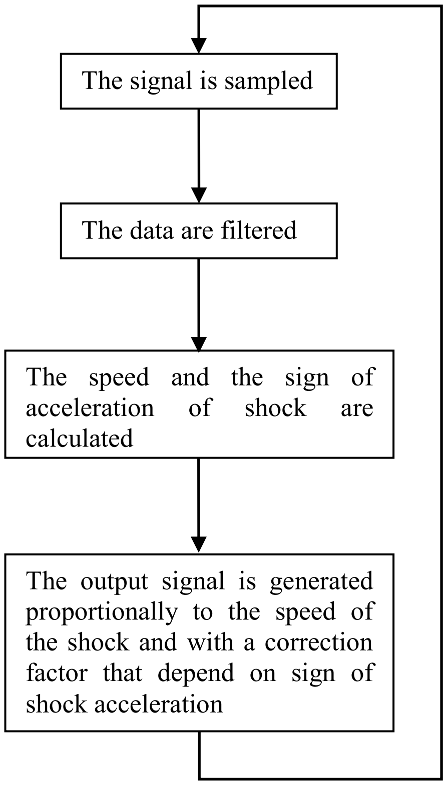

Figure 6 The block diagram of implemented algorithm.

5. CONCLUSIONS

A new characterization technique for MR dampers has been presented in the paper. The first obtained results demonstrated that this technique allow a further reduction of the hysteresis phenomenon in MR dampers. The proposed methodology can be traduced in a very simple algorithm that can be run on low-cost microcontrollers, and it can be useful for several applications. In particular, it can find place in automotive applications, that require an accurate control of semi-active suspension systems.

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