ENERGY STORING ACTUATORS FOR GROUND VEHICLES AND VIBRATION CONTROL

Donald Margolis

University of California, Davis – Department of Mechanical and Aerospace Engineering
email: dlmargolis@ucdavis.edu

Ground vehicles both on- and off-road use shock absorbers to dissipate energy and control the gross vertical motions of the vehicle. These devices react to the relative velocity across them and generate passive forces that are algebraically related to the relative velocity. In vehicles such as cars and trucks, the shock absorbers exhibit very nonlinear behavior and the design of this relationship is very important to the overall handling of the vehicle. Regardless of the nonlinearity of their constitutive behavior, passive shock absorbers dissipate all the energy they absorb and this dissipation results in heating of the device. In off-road applications the amount of power dissipated by a passive shock absorber can be so large that the working fluid heats to the point of breakdown. In military applications the heated shock absorber allows night time detection using infrared measurement devices. These considerations have led to the concept of having the shock absorber store energy rather than dissipate it. The challenge is to generate the desired damper force, passive or semi-active, while simultaneously, automatically storing energy that enters the device. This report shows one possible approach to this problem.

Keywords: ground vehicles, vibration control, energy regeneration

1. Introduction

Shock absorbers are very common energy dissipation devices that are typically hydraulic and function by forcing fluid through designed ports so as to produce a desired force-velocity characteristic across the device. Shock absorbers are typically built in either a twin tube configuration or a monotube configuration. Both designs share the common function of dissipating all the energy that enters into them. In ground vehicle applications this energy comes directly from the fuel.

A new approach to handling the excessive energy dissipation is to store the energy rather than dissipate it. It is proposed to devise a device that can generate dissipative forces while simultaneously storing the energy that enters the device rather than dissipating it. This energy can then be used for alternative needs.

2. Electro-magnetic Realization

The optimal energy storing shock absorber make use of electro-magnetic devices to convert mechanical energy into electrical energy. The control aspect is much simpler and the energy stored is much more straightforwardly used compared, say, to a hydraulic realization. Figure 1 shows a quarter car model with conventional suspension elements as well as a voice coil connected to a special electric circuit.

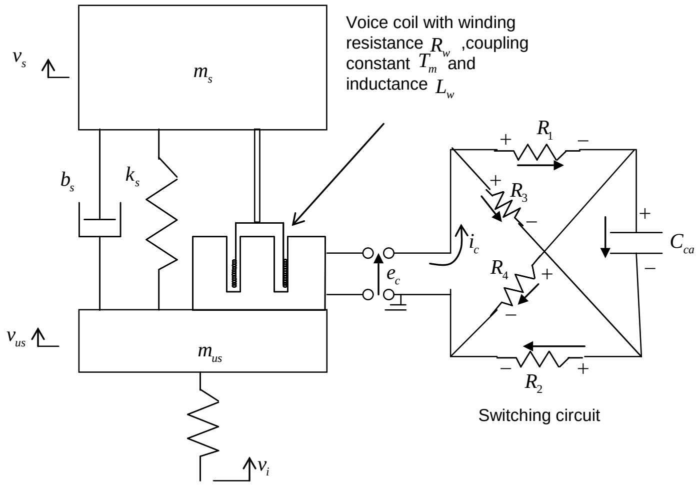

Figure 1 Schematic of a vehicle with an energy storage shock absorber

The resistors in the “switching” circuit of Figure 1 are idealized such that they can switch from a very high resistance to a very low resistance instantly upon command. They thus have virtually no losses when in either their high resistance or low resistance state. The capacitor C_{ca} is the energy storage device. The voice coil exhibits perfect transduction from the mechanical energy domain to the electrical energy domain.

We imagine that we measure the relative velocity $v_{rel} = v_{us} - v_s$ positive in compression and propose a desired force F_{des} such that the desired damper characteristic is achieved. For example, for a passive damper we would have,

$$F_{des} = b_{pass} v_{rel} \tag{1}$$

and for a semi-active damper with “skyhook” control on the sprung mass we would have,

$$\begin{aligned} F_{des} &= -b_c v_s \quad \text{if } v_s v_{rel} \le 0 \\ F_{des} &= 0 \text{ otherwise} \end{aligned} \tag{2}$$

We could propose any damper characteristic, even realistic nonlinear relationships.

We would then control the switching of the resistors such that the proper force exists at the attachment points of the voice coil. If power is flowing into the device, which it must if the proper damper force is generated, then this power will automatically be stored in the capacitor except for any power that is dissipated in the coil resistance. It is necessary that this resistance be as low as possible or we defeat the purpose of the energy storage shock absorber. A bond graph of the system is shown in Figure 2.

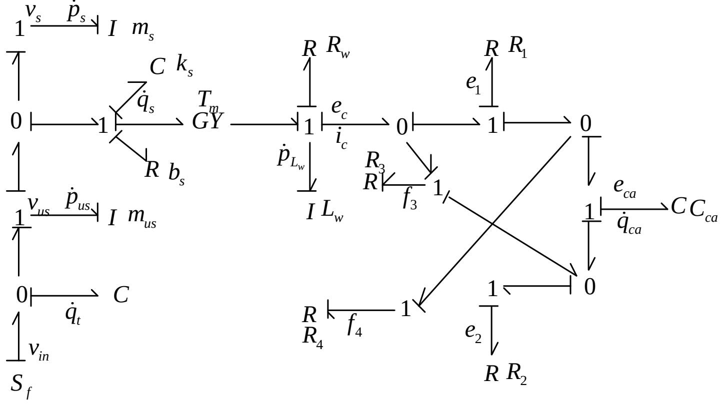

Figure 2 Bond graph of the energy-storing shock absorber in a ¼ vehicle

The causality in the bond graph appears to be complete, but there are algebraic problems that were dealt with to yield the state equations in terms of the state variables indicated on the energy storage elements. The voltage e_c at the output of the circuit turns out to be,

$$e_c = e_{ca}\left[1 - \frac{R_1/R_3}{1+R_1/R_3} - \frac{R_2/R_4}{1+R_2/R_4}\right] + i_c\left[\frac{R_1}{1+R_1/R_3} + \frac{R_2}{1+R_2/R_4}\right] \tag{3}$$

where,

$$\begin{aligned} e_{ca} &= \frac{q_{ca}}{C_{ca}} \\ i_c &= \frac{p_{L_w}}{L_w} \end{aligned} \tag{4}$$

The state equations are,

$$\begin{aligned} \dot{p}_s &= k_s q_s + b_s\left(\frac{p_{us}}{m_{us}} - \frac{p_s}{m_s}\right) + F_{ec} \\ \dot{p}_{us} &= -k_s q_s - b_s\left(\frac{p_{us}}{m_{us}} - \frac{p_s}{m_s}\right) + k_t q_t - F_{ec} \\ \dot{q}_s &= \frac{p_{us}}{m_{us}} - \frac{p_s}{m_s} \\ \dot{q}_t &= v_{in} - \frac{p_{us}}{m_{us}} \\ \dot{p}_{L_w} &= -\frac{R_w}{L_w} p_{L_w} + T_m v_{in} - e_c \\ \dot{q}_{ca} &= i_c\left[1 - \frac{R_1/R_3}{1+R_1/R_3} - \frac{R_2/R_4}{1+R_2/R_4}\right] - e_{ca}\left[\frac{1/R_3}{1+R_1/R_3} + \frac{1/R_4}{1+R_2/R_4}\right] \end{aligned} \tag{5}$$

where $e_c, e_{ca},$ and i_c come from Eqs. (3) and (4) and the force generated by the electro-magnetic system is,

$$F_{ec} = T_m i_c \,. \tag{6}$$

3. Control of Switching Resistors

For the demonstration here a very simple control strategy is used. An error is generated between the desired force F_{des} and the actual force F_{ec} such that,

$$e_r = F_{des} - F_{ec} \tag{7}$$

then,

$$\begin{aligned} &\text{if } e_r > 0 \\ &R_1 = R_{hi}\;\; R_2 = R_{hi}\;\; R_3 = R_{lo}\;\; R_4 = R_{lo} \\ &\text{if } e_r < 0 \\ &R_1 = R_{lo}\;\; R_2 = R_{lo}\;\; R_3 = R_{hi}\;\; R_4 = R_{hi} \end{aligned} \tag{8}$$

This strategy insures that the voltage e_c is always driving the inductor current in the proper direction to move the actual force in the direction of the desired force.

4. Simulation Results

The vehicle simulated here is a large off-road military truck. The parameters for the vehicle are representative of a MRAP military vehicle and are listed in Table 1.

Sprung mass, m_s =2727 Kg
Unsprung mass, m_{us} =394 Kg
Suspension stiffness, k_s =201512 N/m
Tire stiffness, k_t = 4 x 296314 N/m
Suspension frequency, f_s =1.37 Hz, $\omega_s = 2\pi f_s$
Damping is asymmetric, $z_{s_{comp}}$ = 0.25 and $z_{s_{ext}}$ = 0.8 such that, $b_{s_{comp}} = 2z_{s_{comp}}\omega_s m_s$ $b_{s_{ext}} = 2z_{s_{ext}}\omega_s m_s$
Forward velocity, U =20 mph

Table 1 Parameters for the passive vehicle.

The input velocity v_{in} was generated by first using a random number generator to produce ground slope data for a spacing of 0.5m. The input velocity is then the forward velocity of the vehicle multiplied by the slope data. The data was signal processed so as to produce a reasonable response of the passive vehicle. The velocity input for the forward velocity from Table 1 is shown in Figure 3. The acceleration response of the sprung mass for this passive vehicle is shown in Figure 4.

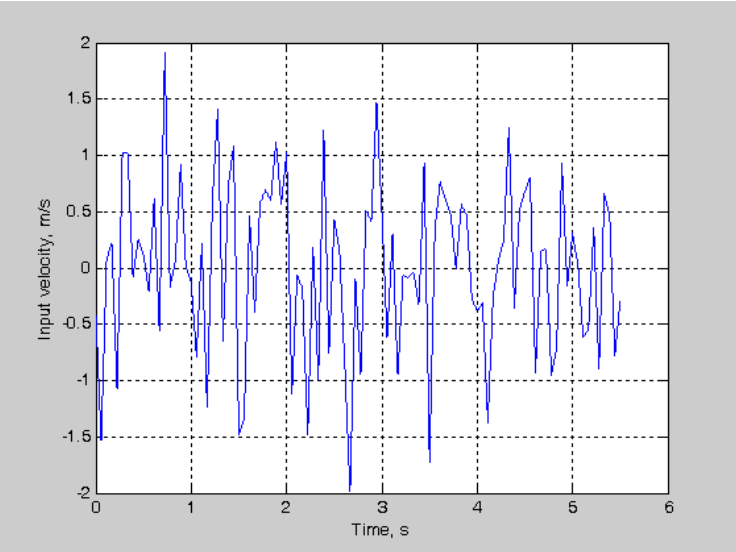

Figure 3 Input velocity to the quarter car model

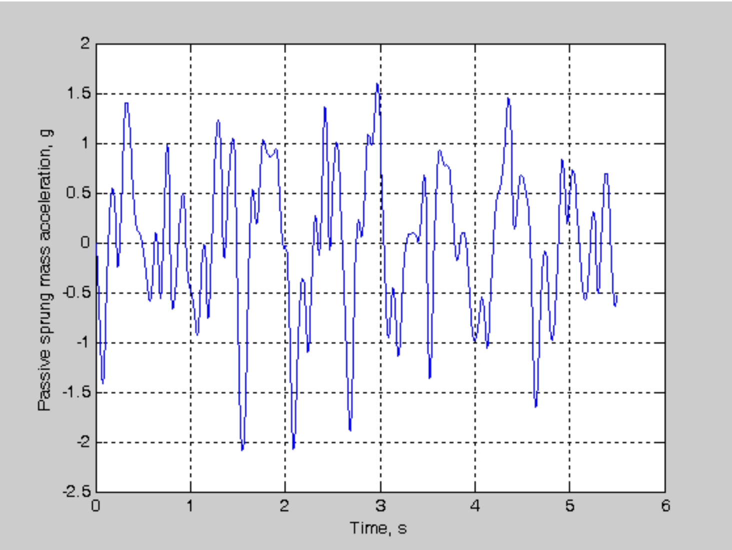

Figure 4 Acceleration response of the passive vehicle traversing the random ground input

As can be seen the sprung mass experiences accelerations in excess of 1g and has an RMS acceleration of about 0.5g. This would be a rather harsh input.

The energy storing shock absorber is installed and Eqs. (3) through (8) are simulated using the additional parameters from Table 2.

Winding resistance, $R_w = 1\Omega$
Electrical time constant, $\tau_{elec} = 0.2s$ such that,

$L_w = \tau_{elec} R_w$ Note: After the inductance is set, the winding resistance is varied in some simulations without changing the inductance value.
Coupling constant, T_m =150 N/A
Switching resistors, $R_{lo} = 1.0E-5$ $R_{hi} = 1.0E5$
Sizing the capacitor: Approximate the energy dissipated over 1 cycle by assuming a 0.7 damping ratio and a harmonic velocity input of amplitude 0.6 m/s. Thus, $E_{dis} = 2\varsigma m_s v_0^2 \pi$ Then set an initial energy, E_{ini} equal to some fraction of E_{dis} . Associate a voltage with this energy, in this case, $e_{ini} = 50v$ Calculate a capacitance from, $C_{ca} = 2E_{ini} / e_{ini}^2$ This value of capacitance is used throughout, but we can start with any initial charge in the capacitor by setting the state variable q_{ca} to any initial value.

Table 2 Parameters for the energy storage shock absorber

For the simulation shown here the desired force was set to be like a passive damper, i. e.,

$$F_{des} = b_{pass} v_{rel} = b_{pass} \left(\frac{p_{us}}{m_{us}} - \frac{p_s}{m_s}\right) \tag{9}$$

where b_{pass} is set for a damping ratio $\varsigma_{pass} = 0.7$. If the energy storing shock absorber is successful at tracking this desired force, then energy is continually flowing into the shock and energy not dissipated by the winding resistance should be stored in the capacitor. Figure 5 shows the desired and actual forces for a simulation where the capacitor starts in a discharged state.

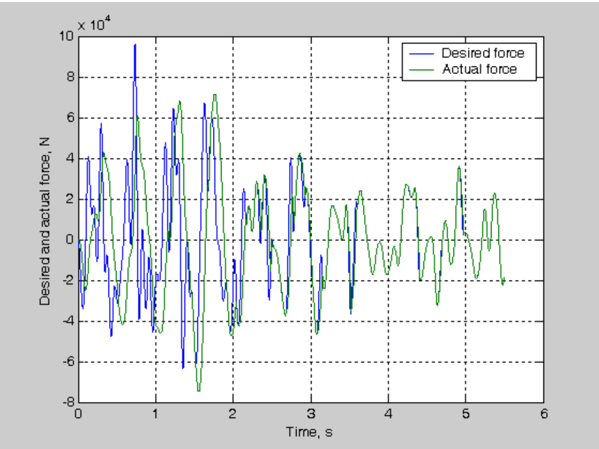

Figure 5 Desired and actual forces for the energy-storing shock absorber

After about 3 seconds the actual force begins to track the desired force and, as shown in Figure 6, the energy in the capacitor continuously grows.

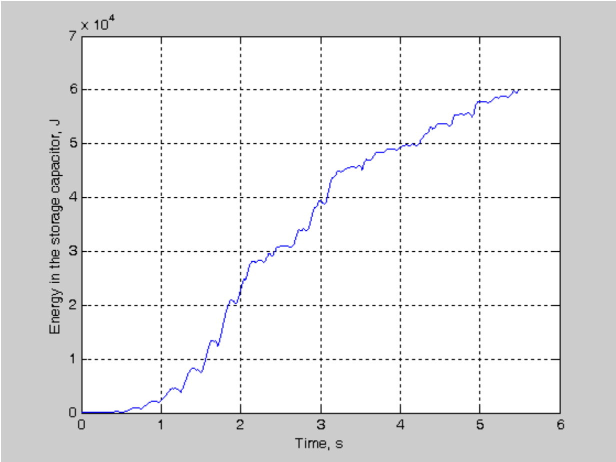

Figure 6 Energy in the capacitor of the energy-storing shock absorber

Figure 7 shows the switching of one of the resistors in the switching circuit.

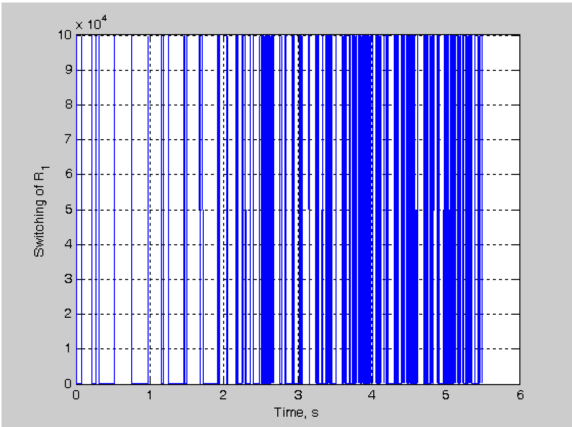

Figure 7 Switching of one of the resistors to accomplish the energy storage

5. Conclusions

The possibility of an energy storing shock absorber has been demonstrated using an electro-magnetic actuator and a resistive switching circuit. By rapidly switching resistors a desired force can be tracked and, if energy is flowing into the device, it is automatically stored rather than dissipated. The concept was simulated in a quarter car environment set up to be a military off-road vehicle.

REFERENCES

1 Basham, D. V. (1980) "Regenerative Drive System", U.S. Patent No. 4,204,405, May 27.
2 Beard, A. (1993) "Regenerative Isolation as an Alternative to Active Vibration Control," Ph. D. Dissertation, Dept. of Mech. Eng., Univ. of California, Davis, CA.
3 Brogan, W. L. (1985) Modern Control Theory, 2nd edition, Prentice Hall, Inc., Englewood Cliffs, N.J.
4 Fruhauf, F. (1985) "Entwurf einer aktiven fahrzeugfederung fiir zeitverschobene anregungsprozesse", *VDI Verlag*, Reihe 12, Verkehrstechnik 57.
5 Grimes, D. L. (1979) "An Active Multimode Above-knee Prosthesis

Controller," Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, MA.
6 Hagin, F. and Merker, P. (1980) "Drive System with Brake Energy Recovery", U. S. Dept. of Energy, 5th International Automotive Propulsion Systems Symposium, April.
7 Heggie, W. S. and Davies, A. S. (1986) "The Development and Testing of a Regenerative Diesel-Hydraulic Power Train for the Urban Bus," *B.H.R.A. Conference,* University of Bath, Sept.
8 Ivers, D. E. and Miller, L. R. (1989) "Experimental Comparison of Passive, Semi-active On/Off, and Semi-active Continuous Suspensions", 1989 SAE Truck and Bus Meeting and Exposition.
9 Jolly, M.R. (1993) "Passive and regenerative solutions for vibration control," Ph. D. Dissertation, Dept. of Mech. Eng., Univ. of California, Davis, CA.
10 Jolly, M. R. and Miller, L. R. (1989) "The Control of Semi-Active Dampers Using Relative Feedback Signals", *SAE publication SP-802,* paper no. 892483, Nov.
11 Jolly, M.R. and Margolis, D.L., (1994) "Energy regeneration in dynamic subsystems," submitted to ASME]. Dynamic Systems, Measurement and Control.
12 Karnopp, D. C. and Trikha, A. K. (1969) "Comparative study of optimization techniques for shock and vibration", *]. Engineering for Industry,* Vol. 91, Series B, No. 4, Nov.
13 Margolis, D. L. (1982) "Semi-Active Heave and Pitch Control for Ground Vehicles", *Vehicle System Dynamics,* Vol. 11, pp. 31-42.
14 Margolis, D. L. and Karnopp, D. C. (1984) "Adaptive Suspension Concepts for Road Vehicles", *Vehicle System Dynamics,* Vol. 13, pp. 145-160.
15 Seth, B. and Flowers, W. C. (1990) "Generalized Actuator Concept for the Study of the Efficiency of Energetic Systems,"]. *Dynamic Systems,* Measurement and Control, Vol. 112, p. 233-238.
16 Sharp, R. S. and Crolla, D. A. (1987) "Road Vehicle Suspension System Design - a review", *Vehicle System Dynamics,* Vol. 16, pp. 167-192.
17 Sharp, R. S. and Hassan, S. A. (1988) "The Relative Performance Capabilities of Passive, Active and Semi-active Car Suspension Systems", *Proc. SAE,* paper no. 881133, Aug.
18 Thomson, W. T. (1981) Theory of Vibration with Applications, 2nd edition, Prentice Hall, Inc., Englewood Cliffs, N.J.