# VIBRATION CONTROL IN AUTOMOTIVE SYSTEMS

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Abstract: In the paper, the design of a linear motor as an actuator in vehicle active suspension systems will be presented. The attention is focused on several interesting design aspects of the non-traditional actuator (linear synchronous permanent magnet motor with electronic commutation) controlled to obtain a variable mechanical force for a car damper. The main advantage of such a solution is the possibility to generate desired forces acting between the unsprung (wheel) and sprung (car body) masses of the car, providing good insulation of the car sprung mass from the road surface disturbances. In addition, under certain circumstances it is possible to reduce or even eliminate the demands concerning the external power source. 

Keywords: Robust control, active vehicle suspension, actuators, linear motors, modelling, power control, power management.

## 1. INTRODUCTION

Nowadays, the theoretical research at the Department of Control Engineering, FEE CTU Prague, concerning the active suspension of mechanical vibrations and improving ride comfort and handling properties of vehicles is getting to the application stage. Contrary to the conventional suspension system, a quite non-traditional solution has been chosen.

Current approaches to active/semi-active damping (Williams, 1997a; Williams, 1997b) are limited by the accessible dynamics of the responses. Typical semi-active actuators are based on hydraulic damper where the by-pass of hydraulic cylinder is controlled either by electromagnetic orifice-valve or by electromagnetically controlled viscosity of magnetorheologic fluid. Typical active actuators are based on hydraulic or pneumatic systems. Such traditional actuators can achieve the time constant about 10 ms. This time constant can be improved by feedback control of the desired damping force but the resulting time constant cannot be decreased significantly below 10 ms. Such actuators are usually applied as vehicle shock absorbers. If vehicles move by the velocity of 30 m/s then they cover the distance of at least 0.3 m before the controlled damper reacts. The consequences of this dynamics limitation for the properties of vehicle suspension are very severe. Therefore any alternative actuator of damping force with accessible time constant of about 1 ms is highly desirable.

In the paper, the usage of linear motors as actuators in vehicle active suspension systems will be presented. From the point of view of the limitations discussed above, the application of linear electrical motor is very perspective. Vehicle suspensions in which forces are generated in response to feedback signals by active elements obviously offer increased design flexibility compared to the conventional suspensions using passive elements such as springs and dampers. The attention is concentrated on several aspects of such a non-traditional actuator controlled to obtain a variable mechanical force for the car suspension. The main advantage of such a solution is the possibility to generate desired forces acting between the unsprung and sprung masses of the car, providing good insulation of the car sprung mass from the road surface disturbances. In addition, under certain circumstances using linear motors as actuators enables to transform mechanical energy of vibrations to electrical energy, accumulate it, and use it when needed. This way, it is possible to reduce or even eliminate the demands concerning the external power source. Compared to traditional drives that use rotational electromotors and lead screw or toothed belts, the direct drive linear motor exhibits the property of contactless transfer of electrical power according to the laws of magnetic induction. The electromagnetic force is applied directly without the intervention of a mechanical transmission. Low friction and no backlash resulting in high accuracy, high acceleration and velocity, high force, high reliability and long lifetime enable not only effective usage of modern control systems but also represent the important attributes needed to control vibration suspension efficiently.

## 2. LINEAR MOTORS

The beauty of linear motors is that they directly translate electrical energy into usable linear mechanical force and motion, and vice versa. The motors are produced in synchronous and asynchronous versions. Compared to conventional rotational electro motors, the stator and the shaft (translator) of direct-drive linear motors are linear-shaped. One can imagine such a motor taking infinite stator diameter.

Linear motor translator movements take place with high velocities (up to approximately 200m/min), large accelerations (up to g multiples), and forces (up to kN). As mentioned above, the electromagnetic force can be applied directly to the payload without the intervention of a mechanical transmission, what results in high rigidity of the whole system, its higher reliability and longer lifetime. In practice, the most often used type is the synchronous three-phase linear motor.

For the most part, linear motors function within a system in the same manner as other types of motors. The major difference lies in commutation. Linear motors commutate based on linear position; rotary motors commutate based on angular position.

For a brushless motor to produce force, the windings must be switched in polarity and amplitude relative to the permanent magnetic field. In the case of brush-type motors, the magnets are usually stationary (stator). In brushless motors, the magnets are typically on the moving shaft, either rotating or sliding. Commutation is cyclical in nature, and is based on a fixed ratio of magnetic poles to electric coils. With rotary motors, these cycles repeat every revolution. With linear motors, the cycles repeat over a fixed distance.

## 3. ENERGY ACCUMULATION

The power amplifier requires a DC power supply for the switch bridge. If the motor works as an actuator, electrical energy is lead in the terminal $U_0$ (see Fig.1). In the braking mode, it is possible to get back accumulated energy from the terminal. To achieve a good function of the power amplifier, the level of the voltage $U_0$ cannot exceed a permitted range. Because the maximum of the linear motor force is limited within the given permitted range, it is useful to hold $U_0$ at the upper limit. There are several ways of energy accumulation, but some of them do not allow holding $U_0$ at the upper limit of the range. One of the possibilities is shown in Fig.1a. $U_0$ is held constant and equal to $U_{max}$.

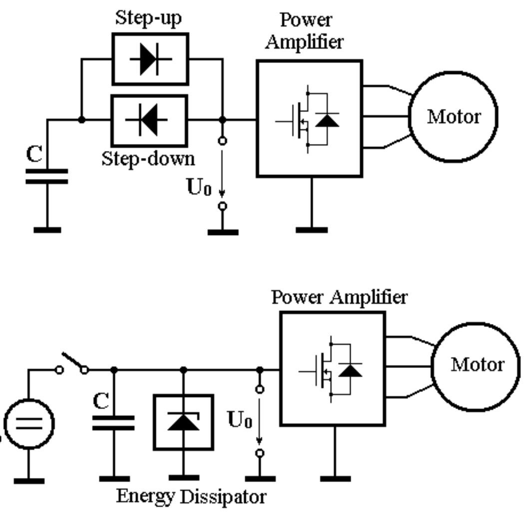


Fig. 1a,b. Energy accumulation.

The electrical energy is impressed across the terminal $U_0$ from vehicle supply network here represented by the capacitor C with the help of a DC/DC step-up converter. The voltage of the capacitor C is held within the range of $0 \div U_{max}$ [V]. With respect to the short-time (hundreds of ms) instantaneous power (of the order of kW), both the converters have to be adjusted to such a high peak power. Consider the average efficiency of each converter as equal to $\eta$=0,85. The recuperated energy can be reused with the efficiency of $\eta^2$=0,72. It results in a disadvantage when 28% of the recuperated energy is lost during one cycle of the energy accumulation and its following reusage. If the vehicle supply network is represented by a capacitor C then its accumulation capacity (taken in the range of $0 \div U_{max}$ ) enables to store the energy of:

$$E_{CL} = \frac{1}{2} C U_{max}^2 \qquad (1)$$

Another way how to accumulate the electrical energy is shown in Fig.1b. In this case, it is assumed that the voltage $U_0$ does not have to be necessarily timeinvariant and varies within the range of $U_{min} \div U_{max}$ . Now, the capacitor C is connected directly to the terminal $U_0$ . The peak-power dimensioned auxiliary voltage supply is non-active for $U_0 > U_{min}$. Vice-versa, the energy dissipator dissipates energy in case of exposure of the capacitor when $U_0 > U_{max}$. The main advantages of such a solution are: its simplicity, the fact that the energy taken from the terminal $U_0$ is stored with the efficiency of 100% (loss resistance of the capacitor C is neglected), and no problems concerning the DC/DC converters (efficiency, disturbances, cooling etc.). As the main disadvantage is taken the fact that the stored energy is limited by:

$$E_{c2} = \frac{1}{2} C (U_{max}^2 - U_{min}^2) \qquad (2)$$

To store the same energy as in the first case, it is necessary to use the capacitor with $E_{C1}/E_{c2}$-times higher capacity.

## 4. LINEAR MOTOR MODEL

To verify control algorithms a linear motor model including the power amplifier has been created in Matlab/Simulink. The model enables to demonstrate the conversion of electrical energy to mechanical energy.

In the model, it is assumed that: the magnetic field of the secondary part with permanent magnets is sinusoidal, the phases of the primary part coils are star-connected, and the vector control method is used to control the phase current. Here, PWM voltage signal is substituted by its mean value to shorten (about 10 times) the simulation period (inaccuracies caused by such a substitution can be neglected). The principal inner representation of the model is shown in Fig.2. The model input vector is given by the instantaneous position [m] (necessary to compute the commutation current of the coils), instantaneous velocity [m/s] (the induced voltage of the coils depends on the position and velocity) and desired force [N].

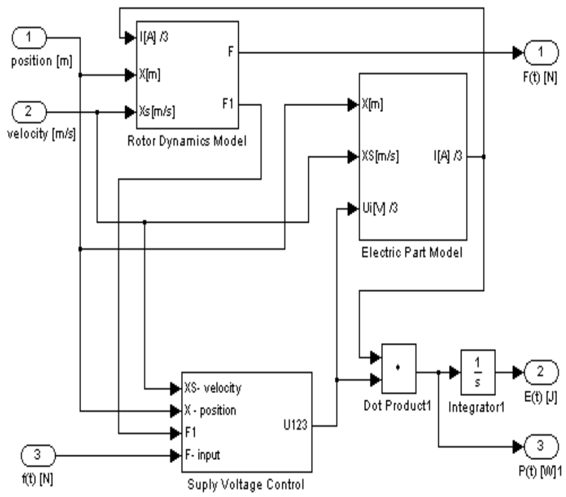


Fig. 2. Principal inner model representation.

The designed model function has been verified comparing dynamics of the model and the real motor. The simulation parameters correspond to the catalogue parameters of TBX3810 linear motor fy Copley Controls Cooperation. For example, time responses cased by changes of the desired force has been compared. The linear motor input-output model is shown in Fig. 3.

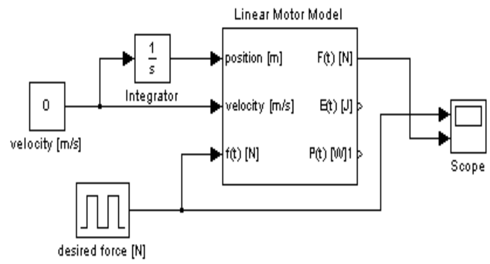


Fig. 3. Linear motor input/output model for dynamics verification.

Figs. 4. and 7. represent simulated and real time responses (step series: 0N→200N / 200N→0N, power supply: 150V, velocity: 0m/s).

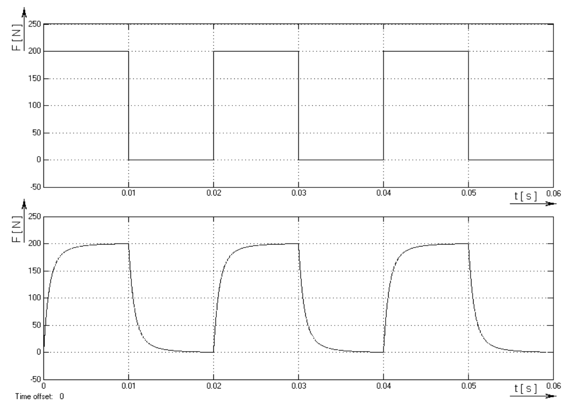


Fig. 4. Simulated time responses.

On the base of the experiments completed on the model, the value of the electric power necessary to be supplied or consumed when the velocity and force of the motor are constant has been gained. The model output vector is given by the actual value of the force [N], electric energy [J] that has been consumed at the switch bridge terminal since the start point of the simulation (its negative value represents the recuperated electrical energy), and instantaneous electric power demand of the motor [W]. In Fig. 5 there is represented an input/output model (with concrete simulation values) of the linear motor.

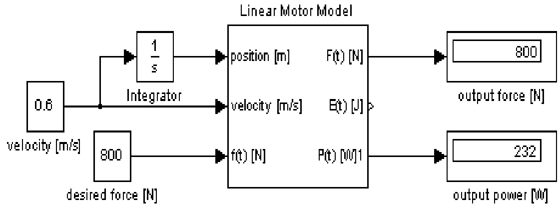


Fig. 5. Linear motor input-output model.

To obtain the simulation results given in Tab.1, the linear motor motion of constant velocity v [m/s] and constant force F [N] has been simulated (the results given below are valid for the supply voltage of 300V).

Table 1 Simulation results

| F \ v | 0 | 0.1 | 0.2 | 0.4 | 0.6 | 1 |
|---|---|---|---|---|---|---|
| 2000 | 4931 | 4693 | 4459 | 3991 | 3523 | 2591 |
| 1800 | 3996 | 3780 | 3569 | 3148 | 2727 | 1889 |
| 1600 | 3157 | 2965 | 2778 | 2404 | 2030 | 1286 |
| 1400 | 2417 | 2249 | 2085 | 1758 | 1432 | 781 |
| 1200 | 1776 | 1632 | 1492 | 1211 | 932 | 376 |
| 1000 | 1233 | 1014 | 967 | 763 | 531 | 68 |
| 800 | 789 | 694 | 600 | 414 | 232 | **-140** |
| 600 | 444 | 372 | 302 | 163 | 24 | **-250** |
| 400 | 197 | 150 | 103 | 11 | **-81** | **-261** |
| 200 | 49 | 26 | 3 | **-43** | **-87** | **-173** |
| 0 | 0 | 0 | 1 | 2 | 5 | 13 |
| -200 | 49 | 74 | 98 | 146 | 196 | 298 |
| -400 | 197 | 246 | 293 | 389 | 485 | 671 |
| -600 | 444 | 516 | 587 | 730 | 873 | 1163 |
| -800 | 789 | 886 | 980 | 1170 | 1360 | 1744 |
| -1000 | 1233 | 1354 | 1471 | 1708 | 1946 | 2424 |
| -1200 | 1776 | 1920 | 2062 | 2345 | 2630 | 3202 |
| -1400 | 2417 | 2585 | 2750 | 3081 | 3413 | 4079 |
| -1600 | 3157 | 3349 | 3538 | 3916 | 4294 | xxxx |
| -1800 | 3996 | 4212 | 4424 | 4849 | 5274 | xxxx |
| -2000 | 4931 | 5173 | 5405 | 5876 | xxxx | xxxx |

To verify pseudo-static characteristics given in Table 1 white noise as displacement has been taken as an input in order to obtain energy requirement map (see Fig.6.).

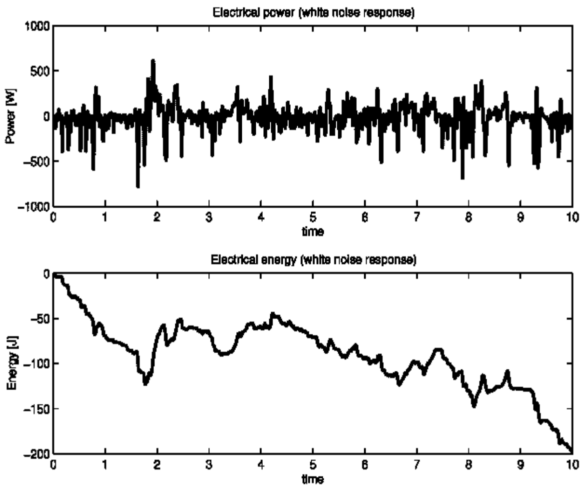


Fig. 6. White noise response – electrical power and energy.

In this case the model of the linear motor is incorporated into a one-quarter-car model and the control loop with a controller set up according to the $H_\infty$ theory is closed (Kruczek and Stribrsky, 2004).

## 5. EXPERIMENTS

All experiments with the active damper has been performed according to Fig. 1b. using the linear motor TBX3810 fy Copley Controls Cooperation equipped with two different control units. First of them uses two microcontrollers AT90S4434 fy Atmel (control unit, communication) and the second one DSP 1104 fy dSPACE. PWM amplifier 7426ACH fy Copley Controls Cooperation proved to be a satisfactory power amplifier. As an energy dissipator the model No. 145 fy Copley Controls Cooperation has been used. All the experiments (Figs. 8., 9. and Table 2) have been measured to verify validity of the results obtained using the Simuling model. The experiment stand representing a one-quarter-car and road disturbances is shown in Fig.7.

Fig. 7. Experiment stand.

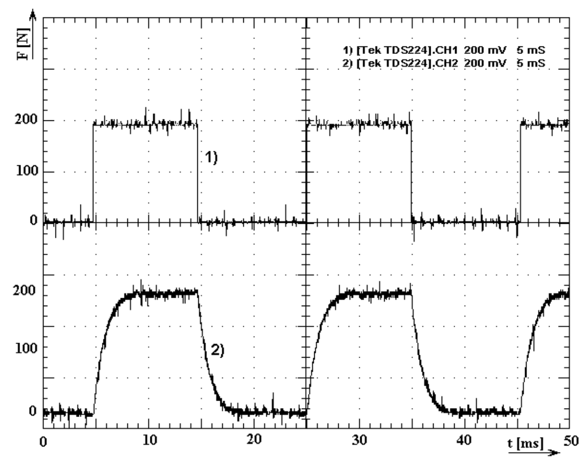


Fig. 8. Real time responses.

Table 2 Experiment results

| F \ v | 0 | 0.1 | 0.2 | 0.4 | 0.6 |
|---|---|---|---|---|---|
| 800 | 758 | 662 | 589 | 396 | 218 |
| 600 | 434 | 361 | 289 | 152 | 20 |
| 400 | 192 | 146 | 98 | 10 | **-78** |
| 200 | 48 | 25 | 2 | **-40** | **-85** |
| 0 | 0 | 0 | 1 | 1.9 | 4.8 |
| -200 | 48 | 71 | 92 | 142 | 187 |
| -400 | 192 | 239 | 281 | 378 | 465 |
| -600 | 434 | 501 | 559 | 721 | 849 |
| -800 | 758 | 865 | 942 | 1120 | 1290 |

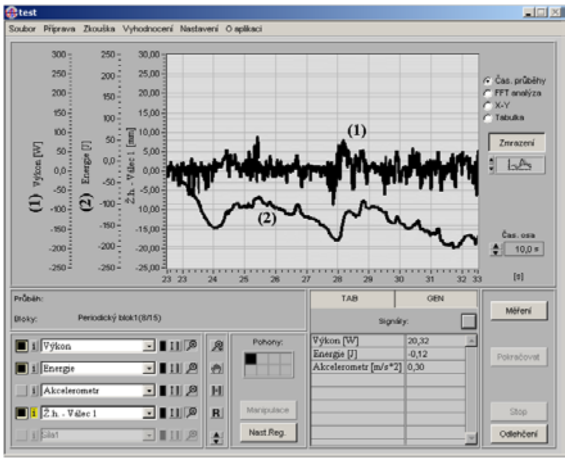


Fig. 9. White noise response – electrical power and energy.

## 6. CONCLUSION

It results from the experiments that the designed model describes the real linear motor equipped with necessary auxiliary circuits very authentically and enables to verify control algorithms developed to control the linear motor as an actuator of the active suspension system. On the base of the simulation results, it is obvious that the power order of up to hundreds of W can be obtained when the motor velocity is exceeding 0,4 m/s and the force is not exceeding about 200 N. As an example, it is possible to note that if the motor velocity is less than 1,5 m/s the energy can be obtained if and only if the braking force is not exceeding 1400 N.

Recently the research tends to optimize the energy distribution. In case of energy insufficiency it seems to be advantageous to adjust the weighting function for the controller $H_\infty$ design to reduce the energy demands of the system. Such a limited active suspension using less energy than really needed then represents a sub-optimal solution.

## ACKNOWLEDGEMENT

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