Usage of One-Quarter-Car Active Suspension Test Stand for Experimental Verification

KATERINA HYNIOVA
Department of Digital Design, Faculty of Information Technology
Czech Technical University in Prague
Thakurova 9, 1600 Prague 6 - Dejvice
CZECH REPUBLIC
hyniova@fit.cvut.cz

Abstract: - Suspension system is an important part of the car design, because it influences both the comfort and safety of the passengers. In the paper an active suspension using linear electric motor is designed. In particular, the article is focused on experiments with active suspension – developing an appropriate input signal for the test sand and evaluation of the results. Second important point of the active suspension design is energy demands of the suspension system. Modification of the standard controller which allows changing amount of energy required by the system has been designed. Functionality of the modification was verified taking various experiments.

Key-Words: - vehicle, suspension, linear motor, test stand, experiment, control, disturbance

1 Introduction

Suspension system influences both the comfort and safety of the passengers. In the paper, energy recuperation and management in automotive suspension systems with linear electric motor that is controlled by a designed H∞ controller to generate a variable mechanical force for a car damper is presented. Vehicle shock absorbers in which forces are generated in response to feedback signals by active elements obviously offer increased design flexibility compared to the conventional suspensions with passive elements (springs and dampers). The main advantage of the proposed solution that uses a linear AC motor is the possibility to generate desired forces acting between the unsprung (wheel) and sprung (one-quarter of the car body mass) masses of the car, providing good insulation of the car sprung mass from the road surface roughness and load disturbances. As shown in the paper, under certain circumstances linear motors as actuators enable to transform mechanical energy of the vertical car vibrations to electrical energy, accumulate it, and use it when needed. Energy flow control enables to reduce or even eliminate the demands on the external power source. In particular, the paper is focused on experiments with active shock absorber that has been taken on the designed test bed and the way we developed an appropriate input signal for the test bed that as real road disturbance acts upon the vibration absorber. The obtained results are evaluated at the end. Another important point is the active suspension design should satisfy energy supply control that is made via standard controller modification, and which allows changing amount of energy required by the system. Functionality of the designed controller modification was verified taking various experiments on the experiment stand as mentioned in the paper.

At the Czech Technical University in Prague various alternative strategies and innovations [2], [5] to classical passive suspension systems improving ride comfort of the passengers, providing steering stability, maximizing safety and improving handling properties of vehicles has been researched. In order to improve handling and comfort performance instead of a conventional static spring and damper system, semi-active and active suspension systems has been developed. Certainly there are numerous variations and different configurations of vibration suspension as well as control strategies [3], [4], [6]. In known experimental active systems hydraulic or pneumatic actuators usually provide the force input. As an alternative approach to active suspension system design, the research group has studied electromechanical actuators. Such actuators would provide a direct interface between electronic control and the suspension system.

In most active suspension systems, the biggest disadvantage consists in energy demands. Regarding linear electric motors, this drawback can be minimized or even eliminated because under certain circumstances there is a possibility to recuperate energy, accumulate it and use it later for the shock absorber when necessary. This way, it is possible to reduce the posted claims on the external power source as much as possible. In the next paragraphs, also the proposed strategy how to control the energy distribution will be described. In order to regenerate electric power from the vibrations excited by road unevenness a new energy-regenerative active suspension for vehicles has been designed. The active system has been modeled and simulated to show the performance improvement and the performance experiments of the actuator prototype-test stand have been carried out.

All suspension systems are designed to meet variable specific requirements. In suspension systems, mainly two most important points are supposed to be improved - disturbance absorbing (videlicet passenger comfort) and attenuation of the disturbance transfer to the road (videlicet car handling). The first requirement could be understood as an attenuation of the sprung mass acceleration or as a peak minimization of the sprung mass vertical displacement. The second one is characterized as an attenuation of the force acting on the road or - in the simple car model - as an attenuation of the unsprung mass acceleration. The goal is to satisfy both the above given contradictory requirements. Satisfactory results can be achieved when an active suspension systems generating variable mechanical force acting between the sprung and unsprung masses is used. Such an actuator can be a linear electric motor. In comparison with traditional actuators that use revolving electro-motors and a lead screw or toothed belt, the direct drive linear motor enables contactless transfer of electrical power according to the laws of magnetic induction. The gained electromagnetic force is applied directly without the intervention of a mechanical transmission. Linear electric motors are easily controllable and for features like low friction, high accuracy, high acceleration and velocity, high values of generated force, high reliability and long lifetime their usage as shock absorbers seems to be ideal.

2 One-Quarter-Car Suspension Model and Shock Absorber Test Stand

A traditional one-quarter-car model has been used to design a suspension controller design and to simulate the system behavior. The basic configuration of the model is shown in Fig.1. The model involves unsprung (wheel) and sprung (taken as one ideal quarter of the car body mass) masses, conventional passive suspension (a spring and a damper), stiffness of the tire, and linear electric motor as actuator placed in parallel to the traditional passive suspension.

In Fig. 1:

F_a control input (active suspension force) [N]

m_w unsprung mass (wheel) [kg]

m_b sprung mass supported by each wheel and taken as equal to a quarter of the total body mass [kg]

k_2 stiffness of the tire [N/m]

$z_r(t)$ road displacement (road disturbance) [m]

$z_b(t)$ displacement of the sprung mass [m]

$z_w(t)$ displacement of the unsprung mass [m]

k_1 stiffness of the passive suspension [N/m]

c_1 damping quotient of the passive suspension [Ns/m]

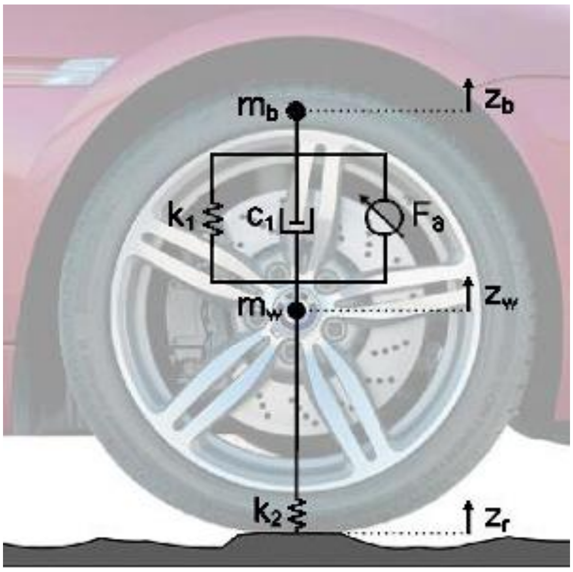

Fig.1 One-quarter-car model

The same configuration has been used for real experiments. Mechanical configuration of the test stand is obvious from Fig.2. Under the tire there is placed another linear electric motor that uses an input experimental signal described in next

paragraphs to generate road displacement (road disturbances) under the running wheel.
As will be mentioned later the controller has been developed via Matlab implemented into dSpace a connected to the test stand system.

Fig.2 Test stand

2.1 Linear Electric Motor

Fig.3 describes the basic principle and structure of the linear electric motor that is used as an actuator in the active suspension system. The appreciable feature of linear motors is that they directly translate electrical energy into usable linear mechanical force and motion, and vice versa. They are linear-shaped.

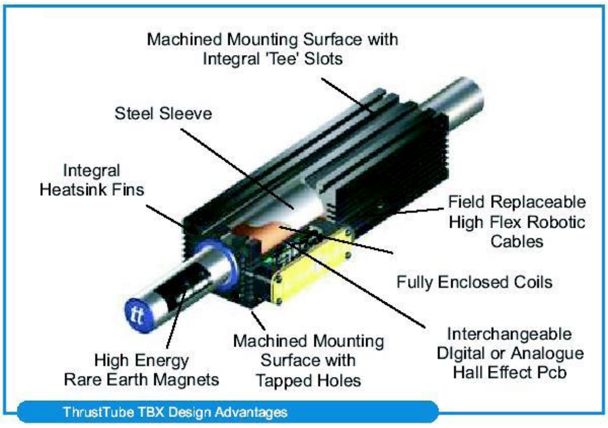

Fig.3 Linear motor basic design (manufacturer spreadsheet)

Linear motor translator movements reach high velocities (up to approximately 200m/min), accelerations (up to g multiples), and forces (up to kN). The electromagnetic force can be applied directly to the payload without the intervention of mechanical transmission. In practice, the most often used type is synchronous three-phase linear motor. 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 suspension system design it is necessary to deal with one important question - whether it is more advantageous to include the model of the linear electric motor into the model for active suspension synthesis or if it should be used only for simulations.

Comparing advantages and disadvantages of the model inclusion, it can be said that the closed-loop provides more information so that better control results can be achieved. Unfortunately, there are also some significant disadvantages in such a situation. The first one insists in the rank of the system (and consequently the rank of the controller that increases up to 5 or more) and the second one is that D matrix in the state space description of the motor model does not have full rank and that is why implementation functions are limited or too complicated. For these reasons the linear electric motor model has not been integrated in the model for active suspension synthesis.

There is another important question - whether the entire linear motor model could be omitted and a linear approximation of the desired force could be taken into account. As the mechanical and the electrical constant of the motor are inconsiderable – just about 1ms each, the linear approximation is adequate and satisfactory. Moreover the linear approximation is supported by robustness of the $H\infty$ control design what has been verified by various simulation results and experiments.

3 Energy Balance

As said above, linear electric motors can recuperate energy. When the generated force is of the same direction as the suspension velocity, the energy has to be supplied into the system. Otherwise, it can be recuperated and accumulated for some future usage.

In fact, there are some non-linearity's in the recuperation process and that is why the energy management (control) is difficult. Just for imagination, the 3-D plot (shown in Fig. 4) represents the force-velocity profile of the recuperated energy. It shows how much recuperated (and only recuperated) energy can be obtained under the given forces and velocities. In the plot, when the recuperated energy is equal to zero or bigger it is necessary to supply the energy into the system.

This characteristic surface gives important information regarding one of the requirements on the control system. Optimization objectives are equal to maximization of the recuperated energy (with necessary trade-offs).

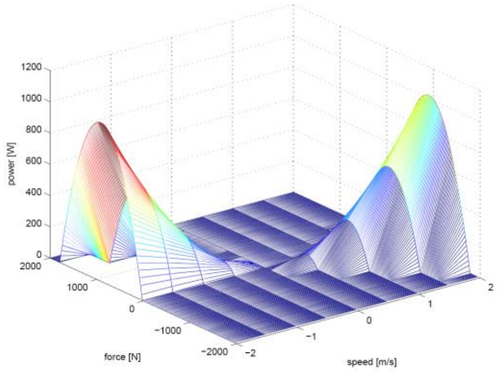

Fig.4 Recuperation area of the linear electric motor

4 Road Displacement Signal

In order to bring about simulation and practical experiments at the test stand it is necessary to find a proper experimental signal that represents the road profile and excites the active suspension). Although the simplified suspension model seems to be linear the truth is that there are many nonlinear parts in the system. Now the question is what signal to generate for experimental testing to reach a true model of the uneven road under the wheel. We can define two types of input signals regarding objectives:

- to prove results of simulations and pre-calculations
- to test real behavior on the road

Let's start with the first objective – to verify simulation results. The best signal might be considered probably white noise because full frequency spectrum could be analyzed then. But it should be noted that the system is nonlinear and even white noise is not satisfactory. Moreover it is not possible to generate easily white noise by the test stand.

For these reasons a bump has been chosen as a signal, that often occurs on the road profiles and that can be generated by the test bed easily. This signal allows observing both directions – bump up and bump-down. Since it is not possible to generate infinite slope the following signal approximation (1) has been used (widely known approximation). Different magnitudes of the signal have been tested because the system is nonlinear. Magnitudes have been chosen according to mechanical dimensions of the suspension system:

$$\dot{z}_r(t) = 0.5\pi \sin 20\pi(t - 0.1) \qquad (1)$$

Thus this signal is used to verify the quality of the simulation model and does not confirm the usability of the controller on a real road surface.

More significant results can be obtained from the input signal, which is alike the road profile. A deterministic random signal is used to approximate it. The input signal for simulation is described by the following equation (2):

$$z_r = \sum_{i=1}^{n} \sqrt{\frac{\dot{\omega}_i}{\pi \cdot v_x}} \Big\{ \mathrm{Re}\Big(\frac{b_o}{-\omega_i^2 + a_1 j\omega_i + a_o}\Big) \cdot \cos(\omega_i t + \alpha) + \mathrm{Im}\Big(\frac{b_o}{-\omega_i^2 + a_1 j\omega_i + a_o}\Big) \cdot \sin(\omega_i t + \alpha) \Big\}$$

$$b_o = 0.121 \cdot v_x$$

$$a_o = 2.249 \cdot v_x \qquad (2)$$

$$a_1 = 30.36 \cdot v_x$$

where v_x represents the car velocity.

Thus resulted signal is obtained as a superposition of the sinusoids with deterministic "random" angles (α in equation (2)). In the experiment, 128 random angles have been generated and used. The used pseudo-random signal is plotted in Fig.5.

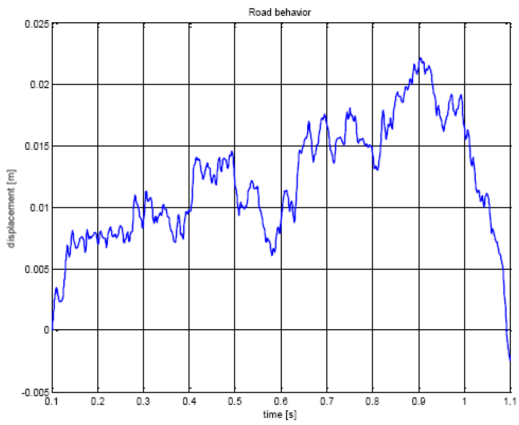

Fig.5 Random signal approximation

4.1 Quantification

Some quantitative measures have to be defined to evaluate the results achieved by the closed loop system and to compare the active and passive systems.

4.1.1 Car stability

First requirement in the active suspension system is to improve car stability and "road friendliness", that can be characterized as the attenuation of the tire pressure, or more precisely the attenuation of the unsprung mass force acting on the road. To get a measurable parameter, the following RMS function has been introduced:

$$J_{stab} = \sqrt{\int_0^T (z_w - z_r)^2 dt} \qquad (1)$$

where z_w represents wheel displacement and z_r road displacement.

4.1.2 Passenger comfort

Second important requirement in the active suspension system is to improve passenger comfort. This requirement can be formulated as the sprung mass acceleration attenuation when the RMS function is defined as:

$$J_{comf} = \sqrt{\int_0^T G_w * \ddot{z}_b{}^2 dt} \qquad (2)$$

where $\ddot{z}_b$ represents body acceleration, G_w is a weighting function for human sensitivity to vibrations and * denotes convolution [3].

5 On The Control loop

5.1 Controller

The controller for active suspension we have designed using H∞ theory. The standard H∞ control scheme is shown in Fig. 6. If the open loop transfer matrix from u_1 to y_1 is denoted as $T_{y1\ u1}$ then the standard optimal H∞ controller problem is to find all admissible controllers K(s) such that $\| T_{y1\ u1}\|_\infty$ is minimal, where $\|\cdot\|_\infty$ denotes H∞-norm of the transfer function (matrix) [2] [3].The H∞ controller is stated minimizing the $\|T_{y1\ u1}\|$-norm. In addition, it is possible to shape open loop characteristics to improve performance of the whole system.

For the active suspension system the performance and robustness outputs should be weighted. The performance weighting has to include all significant measures as comfort and car stability (body speed, suspension displacement, actuator force, etc). For the linear electric motor in the position of an actuator, an additional weight should be added to control maximum force, energy consumption and robustness of the system. A robust controller is necessary to design for the suspension system, because the system parameters often vary in a wide range. Especially the body mass varies for every single drive. For this reason ,H∞ control theory has been chosen for controller design as the ideal controller design[2],[3]. Matlab Toolbox procedures have been used for H∞ controller computation. The H∞ controller has been designed using appropriate weights to optimize minimum of the energy consumption with respect to the performance.

In the car, where the working conditions change according to the various drive situations it is very difficult (if possible) to say in general what level of performance is sufficient enough and how much energy can be obtained. It would be optimal to find a possibility of real-time control of the energy consumption. The energy management is supposed to be controlled by an external signal depending on the car and road parameters, i.e. on the energy accumulator capacity and on the road surface, respectively.

Nevertheless, the standard H∞ controller cannot handle energy consumption. Modification of the controller had to be done during experiments. Additional input, which controls energy demands was supposed to be connected to the controller. Master controller then can use this input to keep energy balance (design of the master controller is not involved in the paper.). The structure of the modified controller is shown in Fig.6.

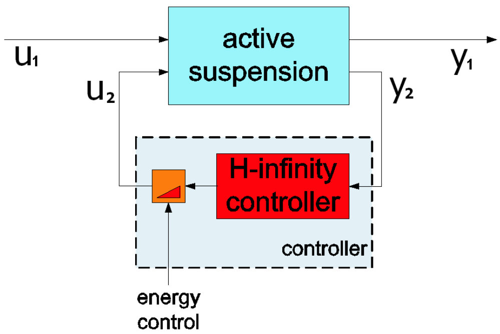

Fig.6 Modified controller structure

5.2. Energy Control Principles

The energy management is supposed to be controlled by an external signal (Fig.6) depending on the car and road parameters, i.e. on the energy accumulator capacity and the road profile, respectively.

First possible way to control energy fed into the suspension system consist in the analysis of the driving conditions and cyclic re-computing of the control signal in real time. For high sampling frequency (over 1 kHz) and because of the performance of the controller this cannot be guaranteed for all operating conditions. That is why this approach has been rejected.

The second possibility is to control the energy consumption by controller deterioration. Then the designed controller is reliably robust and the active suspension system is relatively stable. Simply said, the controller deterioration sort of devalues the suspension performance, but enables to gain some energy to be stored. Strictly speaking, let us assume two kinds of driving conditions:

● the terrain /road surface the car is going on is very rough and uneven and there is enough energy stored in the accumulator system- then the controller works in the standard mode, the linear motor consumes energy from the accumulator (supercapacitors) and the suspension performance is preserved.

● the terrain /surface under the car wheels is relatively smooth and there is not enough energy stored in the accumulator system (supercapacitors) as it was consumed because of the situation described above. The external signal provides the switches the controller to performance deterioration mode in order to reduce energy consumption. The deterioration is stated by the desired force attenuation so that the suspension gets devaluated.

If the force is completely attenuated the suspension system works only via the passive suspension part while the linear electric motor works as a generator generating electrical energy to be stored in the accumulator system. Of course, the suspension performance is devaluated now (to the passive suspension level in the worst case).

That is the basic description of how the control loop with the modified controller works. Now, let us show some results (percentage indicators) of the real experiments taken at the test stand that endorse presumed above.

5.2.1. Energy management analysis

Above, the energy management has been discussed as an extension of the H∞ controller abilities. Now the influence on the performance and robustness will be presented. The H∞ controller is deteriorated by the desired force attenuation using the input coefficient that is given by the superior controller.

At first robustness tests have to be done to find the range of the input coefficient in the energy management block. To test robustness the direct numerical method has been chosen because the rank of the closed system is relatively small (4 for plant + 6 for weights = 10 forthe system, 10 for system + 10 for controller = 20 total for closed loop rank). Hence the poles have been tested for stability for a given input coefficient range.

The stability test in graphical form is shown in Fig. 7 and Fig. 8. In Fi.7, closed loop poles are plotted for the input coefficient range of (-0.5 ÷ 1.7). Zoomed surroundings of the stability region from Fig. 7 is shown in Fig.8. The original H_∞ pole placement is plotted by *, pole placement for stable region by # and unstable region by ■, respectively.

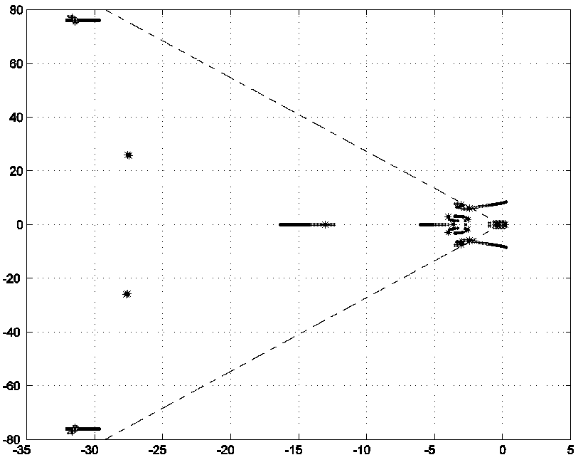

Fig. 7. Pole plot in energy control

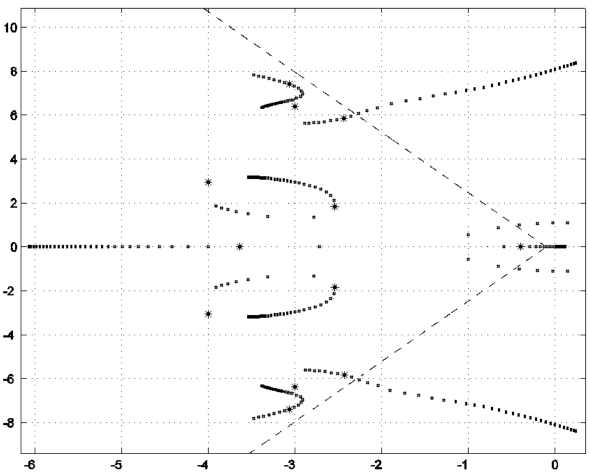

Fig. 8. Pole plot in energy control (zoom)

On the base of the test mentioned above, we have stated the maximum and minimum stable input coefficients. To achieve stability the coefficient must not exceed the range of $(0.000 \div 1.613)$.

The coefficient range should be determined to achieve also certain robustness. That is why we have chosen the pole region of relative damping 1.4 and maximum real part -0.1 as a condition. In Fig. 7, the selected region is represented by the dashed line. According to the previous section it does not have any sense to set the input coefficient greater than one. The resulting input coefficient range that satisfies the defined conditions is as follows:

- minimum: 0.512
- maximum: 1.000

At the end, the influence of the input coefficient on the active suspension performance has been tested.

The quantitative measures we have compared using passive suspension performance. The random road disturbance we have used as a first test input and the driving over a bump as a second input. The comparison for minimum and maximum input coefficients and their influence on the active suspension system performance is summarized in Table 1. The percentage values are computed as relative improvements of the active system compare to the passive suspension.

Table 1 Influence of Input Coefficient on Performance

coefficient	0.512	1
H_∞ norm	0.455	0.359
comfort	20.13%	29.89%
stability	8.92%	12.83%
energy	-71.1J	127.6J

6 Results

Deterministic random signal stated in (2) has been used for real experiments taken on the shock absorber test stand. Two important things should be followed during experiments – suspension comfort improvement and energy consumption (see Fig. 9). In Fig 9, the road profile input, energy consumption, and corresponding body displacement for standard controller setting are displayed.

As an indicator of the comfort improvement body (sprung) mass displacement can be taken.

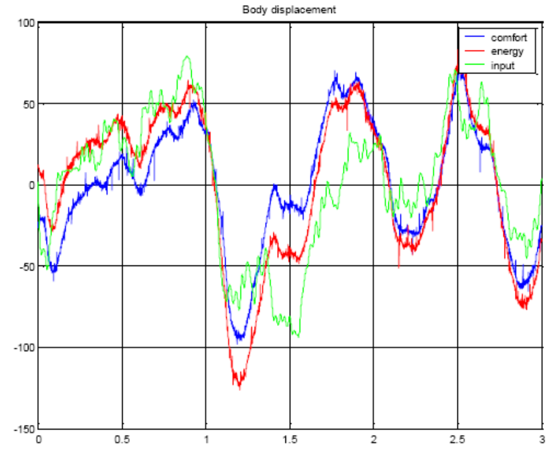

Fig.9 Sprung mass displacement

Fig.10 shows two curves - energy demand for standard energy consumption setting (called “comfort setting”) and energy demands for lower consumption (called “energy setting”).Both curves were measured when excited with the same input- the deterministic random signal (road profile). Actually, negative values of energy in the figure represent the recuperated energy.

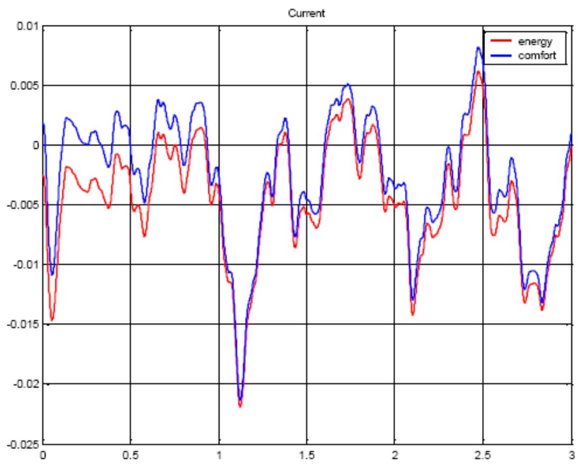

Fig.10 Energy demands (demands on electrical current)

Let’s show the results as mean values of “comfort” and “energy” indicators stated in [1]. Tab.1 involves mean values for the body displacement as absolute values of the defined body displacement indicator and also as a percentage of its improvement.

Table 2 Displacement mean values

	Mean value	Percentage
Body displacement – comfort	38.6	100%
Body displacement – energy	47.4	123%

In Table 2, the first line shows that for standard controller setting the comfort indicator (38.6) is taken as 100%. In the second line, when the controller was deteriorated, the comfort is devaluated to 47.4, i.e. to 123% .

Table 3 involves mean values of energy indicator. Lower value corresponds to the lower energy demand. Similarly the first line shows that for standard controller setting the comfort indicator (2.689) is taken as 100%. In the second line, when the controller was deteriorated, the energy indicator is devaluated to 1.598, i.e. to 59%. Table 3 involves mean values of energy consumption. Lower value corresponds the lower energy consumption.

Briefly, controller deterioration causes comfort devaluation to 123% while energy consumption decreases to 59 %.

Table 3 Energy consumption mean values

	Mean value	Percentage
Comfort setting	2.689	100%
Energy setting	1.598	59%

7 Conclusion

In the paper, energy recuperation and management in active suspension systems with linear electric motors controlled using a proposed H∞ controller to obtain a variable mechanical force for a car damper is presented.

The strategy for direct real-time energy management has been designed to decrease the energy consumption in the closed loop system. The control design modifies the standard H∞ controller and develops a stable controller with variable energy demands. All expected results has been verified in numerous experiments and simulations.

The H∞ controller for active suspension with linear electric motor has been used for experiments done on the test stand. Experiments verified results of the simulations and showed that it is possible to change energy demands according to the road profile and status of the energy storage in the car (battery or supercapacitors). The method can be extended to general plants with considerable energy demands, where the decreasing actuator signal in a given range can preserve system stability. Thus this controller with linear motor as an actuator can be used in any suspension system.

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