Energy Recuperation in Automotive Active Suspension Systems with Linear Electric Motor

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Abstract—In the paper, energy recuperation and management in automotive suspension systems with linear electric motors controlled using a proposed H∞ controller to obtain a variable mechanical force for a car damper is presented. 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 main advantage of the proposed solution using a linear AC motor 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 the vertical car vibrations to electrical energy, accumulate it, and use it when needed. Energy flow control (management) enables to reduce or even eliminate the demands concerning the external power source.

I. INTRODUCTION

Nowadays, the theoretical research concerning the active suspension of mechanical vibrations and improving ride comfort and handling properties of vehicles is concentrating on various suspension innovations. The main goal of the paper is to describe H∞ controlled active suspension design with respect to the management of the energy flow distribution. In the time of growing interest in the overall minimization of energy consumption, the presented paper could be accepted as a contribution to these efforts. Especially in the application field of automotive vehicles, the energy consumption optimization plays an important role in the design process.

A. Motivation

In most active suspension systems, the biggest disadvantage consists in energy demands. Regarding linear electric motors, this drawback can be eliminated because under certain circumstances there is a possibility to recuperate energy, accumulate it and use it later when necessary. This way, it is possible to reduce or even eliminate the demands concerning the external power source. In the next chapters, we will describe the proposed strategy how to control the energy distribution.

All suspension systems are designed to meet specific requirements. In suspension systems, usually two most important features are expected to be improved - disturbance absorbing (i.e. passenger comfort) and attenuation of the disturbance transfer to the road (i.e. car handling). The first requirement could be presented as an attenuation of the damped mass acceleration or as a peak minimization of the damped mass vertical displacement. The second one is characterized as an attenuation of the force acting on the road or in simple car model as an attenuation of the unsprung mass acceleration. It is obvious that there is a contradiction between these two requirements. With respect to these contradictory requirements the best results can be achieved using active suspension systems generating variable mechanical force acting in the system.

B. One-quarter-car Model

The H∞ controller synthesis for active suspension has been done using a simple one-quarter-car model (see Fig. 1).

The model consists of a spring (stiffness k_f), passive damper (damping quotient c_p), sprung mass taken as one quarter of the body mass (m_b), unsprung mass
representing one wheel (m_w) and a spring connecting the
unsprung mass to the road and representing the tire
stiffness (k_t). The active force (F_a) acting between the
sprung and unsprung masses of the car is generated by a
linear electric motor. For analysis and verification we
have used a more complex model (see [1] for details).

II. LINEAR ELECTRIC MOTOR

A. Linear Motor Description

From the point of view of the aspects discussed above,
the authentic application of a linear electrical AC motor
seems to be very perspective. The beauty of linear motors
is that they directly translate electrical energy into usable
linear mechanical force and motion and vice versa.
Compared to conventional rotational electro-motors, the
stator and the shaft (translator) of direct-drive linear
motors are linear-shaped (see Fig.2). One can imagine
such a motor taking infinite stator diameter. The direct
drive AC linear motor exhibits the property of contact-
less 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. 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. The
main advantage of the proposed solution using a linear
AC motor 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 recuperate energy i.e. to transform mechanical
energy of the car vertical vibrations generated by the road
disturbances to electrical energy, accumulate it, and use it
when needed.

For the automotive suspension system, the application
of the synchronous three-phase linear motor TBX 3810 fy
Copley Controls Cooperation (technical parameters: peak
force 2027N, peak current 21.8A, continuous stall force
293.2N, electrical time constant 1.26ms, continuous
working voltage 320Vac, maximum phase temperature
100°C) has been designed by the research team.

B. Linear motor implementation

It is necessary to answer one important question - if it
is more advantageous to include the model of the linear
electric motor in 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 solution. The first one insists in
the rank of the system (and consequently the rank of the
controller which increases up to 5) and the second one is
that the 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.
On the base of this comparison the linear motor has not
been included in the model for active suspension
synthesis.

There is another important question whether the linear
motor model could be omitted and a linear character of
the desired force could be supposed. The answer is “yes”.
Both the mechanical and the electrical constants are very
small – just about 1ms. Moreover it will be shown that
the robustness of the H∞ control design has been verified
using numerous simulation results and experiments.

C. Energy balance

As mentioned above, linear electric motors are able to
re 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
re recuperated and accumulated for the future usage.

In fact, there are some non-linearities in the
re recuperation process and that is why the energy
management is a bit difficult. The 3-D plot (shown in Fig.
3.) 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 it is necessary to supply the energy into the system.

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

The controller for active suspension we have designed using $H_\infty$ theory. The standard $H_\infty$ control scheme is shown in Fig. 4. When the open loop transfer matrix from $u_1$ to $y_1$ is denoted as $T_{y_1 u_1}$ then the standard optimal $H_\infty$ controller problem is to find all admissible controllers $K(s)$ such that $\| T_{y_1 u_1} \|_\infty$ is minimal, where $\| \cdot \|_\infty$ denotes the $H_\infty$-norm of the transfer function (matrix). For more information, see [2].

The $H_\infty$ controller is stated minimizing the $\| T_{y_1 u_1} \|_\infty$-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.

### III. CONTROLLER

### IV. 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.

#### A. 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:

$$J_{\text{stab}} = \sqrt{\frac{1}{T} \int_0^T (z_w - z_r)^2 \, dt}$$  \hspace{1cm} \text{(1)}$$

where $z_w$ represents wheel displacement and $z_r$ road displacement.

#### B. 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:

$$J_{\text{conf}} = \sqrt{\frac{1}{T} \int_0^T G_w * \dot{z}_b \, dt}$$  \hspace{1cm} \text{(2)}$$

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

### V. ENERGY CONTROL

#### A. Energy control principles

The $H_\infty$ 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.

First possibility consists in the analysis of the driving conditions and cyclic re-computing of the control signal in real-time. While the time requirements of the $H_\infty$ controller design are too high (sampling period has to be less than 1ms!) and moreover the performance of the $H_\infty$ controller cannot be guaranteed for all operating conditions this approach has been rejected.

The second possibility is to control the energy consumption by controller deterioration. Then the designed $H_\infty$ controller is reliably robust and the active suspension system is relatively stable.

Let’s assume two driving conditions:

- the terrain/surface the car is driving 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 motor consumes energy from the accumulator and the suspension performance is preserved.
- the terrain/surface the car is driving on is relatively smooth and there is not enough energy stored in the accumulator system because of the situation described above. The external signal provides the information to the $H_\infty$ controller to deteriorate its performance and to reduce the energy consumption. The deterioration is stated by the desired force attenuation.

If the force is attenuated too much then the active suspension system works similarly to the passive suspension and the linear electric motor works as a generator producing energy for the accumulator system. Of course, the suspension performance is deteriorated now (to the passive suspension level in the worst case). The influence of these controller modifications to the suspension system performance we will discuss in the section below.

The principle of the proposed energy management strategy is illustrated in Fig. 5. The $H_\infty$ controller is extended by the variable gain block controlled by the external signal (energy management control input).

B. Energy management analysis

In paragraph V (A), the energy management has been discussed as an extension of the $H_\infty$ controller abilities. Now the influence on the performance and robustness will be presented. The $H_\infty$ controller is deteriorated by the desired force attenuation using the input coefficient that is given by a 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 for 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. 6 and Fig. 7. In the figures, closed loop poles are plotted for the input coefficient range of (-0.5 ÷ 1.7). Zoomed surroundings of the stability region from Fig. 6 is shown in Fig. 7. The original $H_\infty$ pole placement is presented by *, pole placement for stable region by # and unstable region by ■, respectively.
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 \( 0.000 \leq \theta \leq 1.613 \).

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 I. The percentage values are computed as relative improvements of the active system compare to the passive suspension.

<table>
<thead>
<tr>
<th>TABLE I.</th>
<th>INFLUENCE OF INPUT COEFFICIENT ON PERFORMANCE</th>
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</thead>
<tbody>
<tr>
<td>( H_\infty ) norm</td>
<td>0.455</td>
</tr>
<tr>
<td>comfort</td>
<td>20.13%</td>
</tr>
<tr>
<td>stability</td>
<td>8.92%</td>
</tr>
<tr>
<td>energy</td>
<td>-71.1J</td>
</tr>
</tbody>
</table>

VI. CONCLUSION

In the paper, energy recuperation and management in active suspension systems with linear electric motors controlled using a proposed \( H_\infty \) controller to obtain a variable mechanical force for a car damper has been presented.

The strategy for direct real-time energy management we have designed to decrease the energy consumption in the closed loop system. The method used modifies the standard \( H_\infty \) controller and develops a stable controller with variable energy demands. All expected results has been tested in numerous experiments and simulations.

The experiment stand representing a one-quarter-car and road disturbances is shown in Fig. 8.

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