

DESIGN OF ELECTROMAGNETIC DAMPER PROTOTYPE FOR AUTOMOTIVE APPLICATIONS

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Abstract: The paper deals with design of an electromagnetic damper prototype. An introduction to the automotive dampers is given and motivation is mentioned. Modelling of the dampers using quarter car model and full car model are described. Several design variants of the damper were studied and briefly discussed in the text. First case was a passive damper based on energy dissipation due to eddy currents created by movement of permanent magnet inside a massive copper tube. In the second case the copper tube is replaced by set of coils. It allows adjusting damper parameters, applying active and semi-active concepts and opening a possibility for energy recovery. A test facility used designed for out-of-the-vehicle testing of automotive dampers is mentioned at the end of the paper.

Keywords: *shock absorber, electromagnetic damper, energy recovery*

1. Introduction

Automotive suspension is one of the key components in nowadays cars. Proper suspension design can significantly improve vehicle behaviour and safety.

The automotive suspension on a vehicle typically has the following functions [4]:

- to isolate a car body from road disturbances in order to provide good ride quality. i.e. to reduce vibrations transmitted from the axle to the body/passenger, i.e. reduce body acceleration .
- to keep good road holding (cornering, braking, traction) – i.e. variations in normal tire loads are minimized. Since a tire roughly behaves as a spring, it can be directly related to vertical tire deflection.
- to provide good handling – i.e. minimize the roll and pitch motion.
- to support vehicle static weight – i.e. rattle space requirements are kept small.

The analysis of passive automotive suspension in literature (e.g. [1, 2, 3, 4]) shows, that there are significant trade-offs in performance between the ride quality, rattle space and tire deflection transfer functions. Improvements in one of them usually deteriorate the other two transfer functions. Therefore active and semi-active suspensions were introduced.

The fundamental difference between active and semi-active control strategy is in the form of input energy. While active suspension uses force actuator to control motion of the body (i.e. it needs enough energy to move the body with the desired velocity and acceleration), semi-active suspension system utilizes a variable damper or other dissipation component (see Figure1). Compared to active suspension, semi-active one consumes significantly less power.

Various published studies (e.g. [8, 10]) show, that energy of ap. 100–1600 W (depending on other factors) dissipates in a damper of common cars. Studies further show, that ap.10% of the dissipated energy can be recuperated.

2. Suspension modelling

A brief introduction to the suspension modelling is given in this section.

2.1. Quarter car models

Simplified models are very often used for modelling of vehicle suspension. Typical example is using of a quarter-car model for description of vertical motion of vehicle. The model is very simple and gives relevant results. For more complex study (including roll and pitch motions etc.) a half-car or a full-car model must be used.

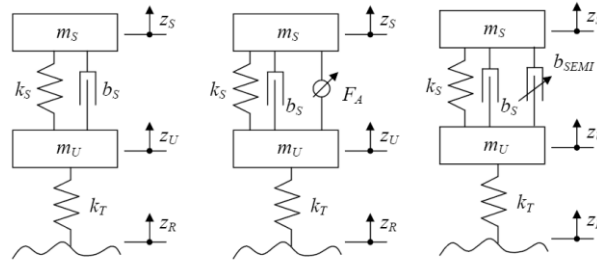


Figure 1. A quarter-car model – from left to right: passive suspension, active suspension, semi-active suspension

Equation of motion for quarter car model can be expressed in the following form [2]:

$$\begin{bmatrix} m_s & 0 \\ 0 & m_u \end{bmatrix} \begin{bmatrix} \ddot{z}_s \\ \ddot{z}_u \end{bmatrix} + \begin{bmatrix} b_s & -b_s \\ -b_s & b_s + b_T \end{bmatrix} \begin{bmatrix} \dot{z}_s \\ \dot{z}_u \end{bmatrix} + \begin{bmatrix} k_s & -k_s \\ -k_s & k_s + k_T \end{bmatrix} \begin{bmatrix} z_s \\ z_u \end{bmatrix} = \begin{bmatrix} 0 \\ k_T \end{bmatrix} z_R + \begin{bmatrix} 0 \\ b_T \end{bmatrix} \dot{z}_R + \begin{bmatrix} 1 \\ -1 \end{bmatrix} F_A$$

Detailed mathematical description of the models can be found in the literature (e.g. [1, 2, 3, 4]). For complex manoeuvre simulation the quarter car model doesn't offer enough information and an integration of the suspension model into full car model is required. The complete full car model usually includes sub models of powertrain, driveline, tires, brakes, steering etc. Development of such a complex model takes lots of effort, and it is easier to use one of the commercially available and proven solutions described in the following section.

2.2. Full vehicle models

For overall understanding of vehicle behaviour, it is useful to model the vehicle in one of available commercial software packages, which provide the user proven and quite complex models of vehicle components. Typical example of such a software package is ADAMS and it's automotive modules called ADAMS/Car. ADAMS also offers possibility of co-simulation with software like MATLAB/Simulink and with EASY5.

ADAMS/Car provides the user with an easy way how the overall car model can be build. It uses so called template based approach, i.e. each component is described in a template, which is used to generate a subsystem as a part of the full vehicle assembly.

Shock absorber properties are defined in a property file, an ASCII file with the force-velocity curve definition.

Among above mentioned the SW provide user with a number of pre-defined manoeuvres and a tool – event builder – for creating user-defined manoeuvres. The SW contains a tool Road Builder for creating a test track with various obstacles (compliant road is also available). Many various functionalities as Smart Driver, DoE and optimisation options are available in the SW.

There is an example of a road with several obstacles and a simulation results for a demo vehicle running across.

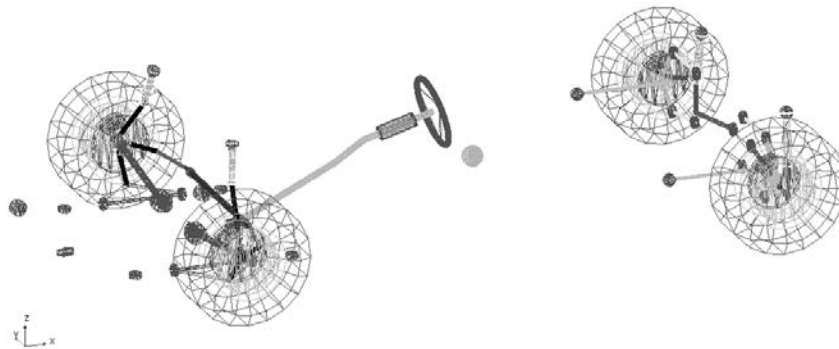


Figure 2. Graphical representation of a full vehicle model in ADAMS/Car package

Complex simulation option of the full vehicle exposed to different road conditions, driver behaviour etc., gives the users an excellent opportunity to investigate complex tasks in the virtual reality.

2.3. Electromagnetic passive damper

However using of electromagnetic shock absorber is quite rare in the commercial applications, it is very often discussed in the scientific papers. There are several principles described on the literature.

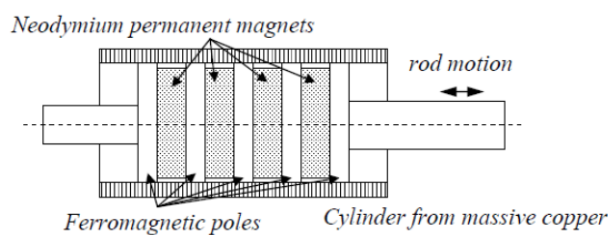


Figure 3. Principle of the EM damper – drawing and testing prototype photography

One of the principles discussed is a passive electromagnetic damper based on eddy currents (see Figure 3). A rod (mover) equipped with a set of neodymium permanent magnet and ferromagnetic poles are moving through a tube made out of a massive copper. The movement of the rod generates eddy currents in the copper tube and force acting

against the motion, which causes required power dissipation. The force can be calculated either analytically or numerically. The principle of such a damper is shown on the Figure 3.

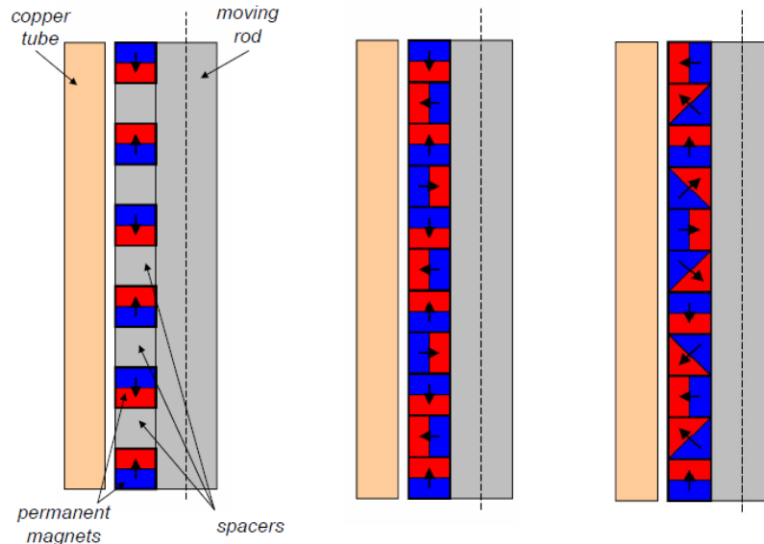


Figure 4. Arrangements of the permanent magnets – from left case 1, 2 and 3

As mentioned above the damping effect is generated by eddy currents arising in the copper stator due to movement of the rod with permanent magnets. Design parameters of such a damper are material and geometrical properties of all components – copper tube, permanent magnets, and pole arrangement (orientation of magnetic field of a single magnet, size of spacers, size of the air gap etc.).

A prototype of such a damper was designed (based on [7]) and manufactured at the author's workplace. Calculations of the magnetic field were done in Comsol Multiphysics and in FEMM software. The focus was given to evaluation of several magnet configurations – see Figure 4.

It was proved, that the magnet arrangement has significant influence to the resulting magnetic field in the air gap, and to the whole system performance.

Three main configurations were studied.

Case 1 consists of axially magnetized neodymium (NdFeB) permanent magnets, ferromagnetic spacers, and non-magnetic rod – see Figure 4a. Case 2 consists of combination of axially and radially magnetized permanent magnets – see Figure 4b. Case 3 is inspired of idea of so called Hallbach's field mentioned in many literature sources. It contains only permanent magnets with axial, radial and axial-radial magnetic field orientation. The magnetic field orientation changes along the rod – see Figure 4c. The main reason for such an arrangement was significant amplification of magnetic field in particular directions, described for Hallbach's field in the literature.

Evaluation of the magnetic field in the air gap was done in SW Comsol Multiphysics and FEMM – see the visualisation example on Figure 5.

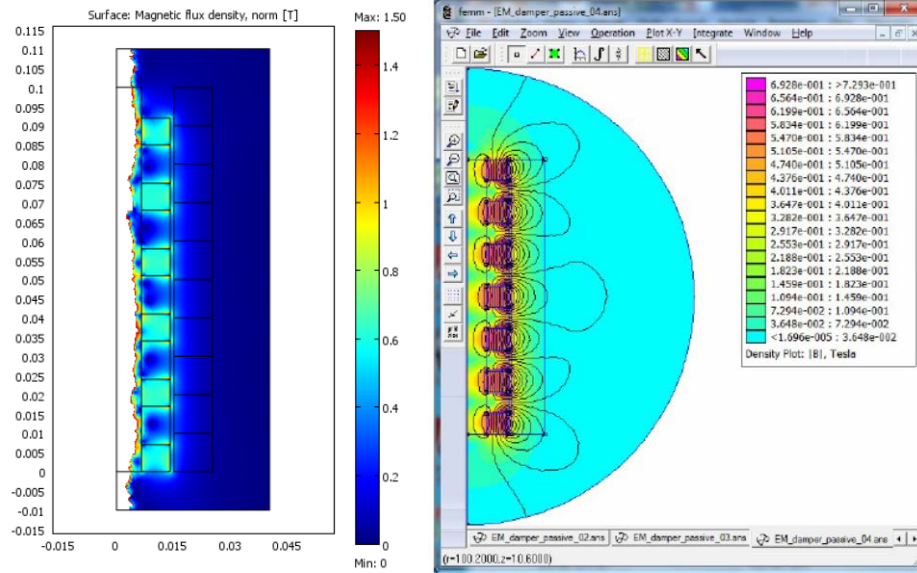


Figure 5. Visualisation of magnetic field for the design case 1 in Comsol Multiphysics and FEMM

For building of the model several unified parameters were used for all the design cases to allow simplicity of evaluation and comparison – see below. Performing of the analysis for the whole range of available parameters would probably give more detailed results, but it was not the goal in this case.

Table 1

Unified model parameters

	Case 1	Case 2	Case 3
Copper tube outer/inner diameter [mm]	60/30	60/30	60/30
Copper tube length [mm] / modelled length [mm]	300	300	300
Permanent magnet inner/outer diameter [mm]	13/28	13/28	13/28
Permanent magnet length [mm]	7	7	7
Number of permanent magnets	6	13	13
Rod diameter/length [mm]	13/450	13/450	13/450
Spacers outer/inner diameter [mm]	13/28	N/A	N/A
Spacers length [mm]	15	N/A	N/A
Number of spacers	5	N/A	N/A
Air gap between PM and copper tube [mm]	1	1	1
Air gap between spacers and copper tube [mm]	1	N/A	N/A
Permanent magnet material – NiFeB	N40	N40	N40
Rod - non-magnetic steel – relative permeability	1	1	1
Spacers material – soft steel – relative permeability	3000	N/A	N/A

It was assumed, that the damper has the same outer dimensions (copper tube outer diameter and length), i.e. we are comparing dissipation of energy related to the same volume of the damping device. The overall size of the damper is approximately in the same range as common damper size in nowadays personal vehicles.

It was assumed, that the size of PM is the same for all cases. The size (outer and inner diameter and length) was selected from a shopping list of a distributor of permanent

magnets. The reason was to fit the analysis to the particular design configuration, which could be later manufactured.

Model parameters are given in the Table 1.

Table 2

Comparison of design cases

	Case 1	Case 2	Case 3
Magnetic field in the middle of the air gap avg $ B $ [T]	0.38	0.56	0.28

The evaluation is given in the Table 2 – showing comparison of magnetic field in the air gap for the studied cases (measured in the middle points of the air gap).

Figure 6 shows an example of calculated magnetic field along the inner surface of copper tube for the Case 1.

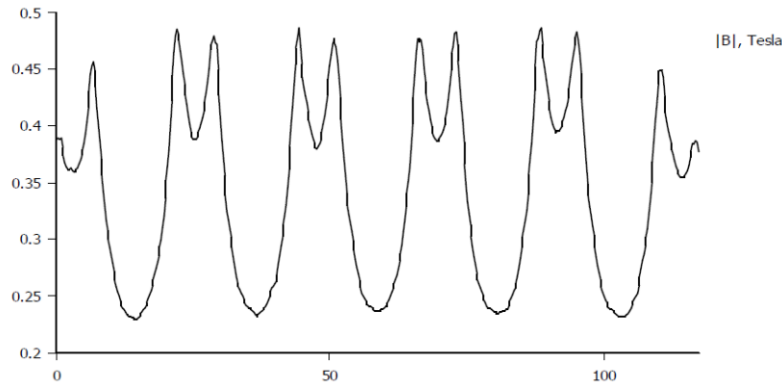


Figure 6. Magnetic field along the inner surface of copper tube for the Case 1 (x-axis length of tube)

It shows that Case 2 is the best arrangement from the magnetic field intensity point of view. The most complicated and economically less suitable case (Case 3) generates quite low magnetic field in the air gap. Manufacturing of the magnets with given magnetic field orientation would be much expensive than other variants.

Case 1 is the simplest one from the design point of view. Permanent magnets with required magnetic field orientation can be easily purchased on market. Number of permanent magnets is lower than in other cases. Magnetic properties of the Case 1 are lower than in the Case 2, but still acceptable.

When taking into account both functional and economical point of view the Case 1 was selected for development of the first prototype.

2.4. Coiled design, energy recovery

Another principle of the electromagnetic damper is an arrangement similar to linear drive, so called tubular drive (see Figure 7, compare with Figure 3) – passive copper can be replaced by a stator winding or some mechanism can be used to convert linear to rotary motion. There are several principles mentioned in the literature using rotary actuators and planetary gear or various techniques to change linear motion of the rod to the rotary motion

of the actuator. The actuator (either rotary or linear) is in principle an electric drive, either rotary or linear) containing a coil or several coils, which can be fed by constant or variable electric currents. Such an actuator can act as an active or semi-active damper and it also offers ability of energy recuperation. Energy recuperation option can be extremely interesting topic in nowadays electrical vehicles, because of large amount of energy dissipated in the damper during normal operation.

Combination of both principles mentioned above leads to a hybrid damper (see also [7]). Inspired by the text [7] similar damper was designed at author's workplace, and will be manufactured and tested in the nearest future.

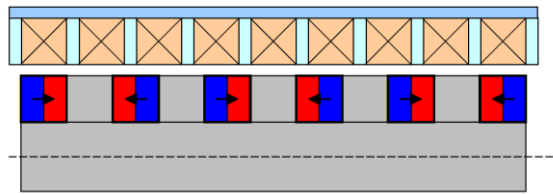


Figure 7. Active and adaptive EM damper with energy recovery option

3. Testing facility for shock absorbers

Mathematical models of the suspension require detail information about the shocks and their behaviour. Understanding of the shock absorber behaviour requires not only virtual testing (modelling and simulation), but also performing several physical tests.

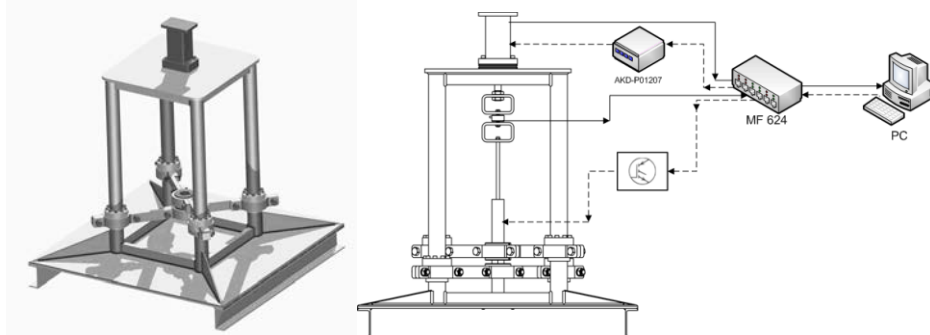


Figure 8. Test rig for automotive shocks design and manufactured at the UWB

Therefore we have built a test device able to measure basic characteristics of the shock absorbers, change properties of the semi-active shocks, understand the behaviour of the dampers and identify parameters further used for simulation models (either simple quarter car model or the full vehicle model). A simple structure (see Figure 8) with four columns for fixing the damper was designed. The rod is driven by linear electric motor. Force sensor is located at the end of the rod. Displacement sensor is included in the drive. Simple amplifier with IGBT transistor driven by analogous voltage from 0 to 10V is used to change the damping characteristics. The whole test rig is controlled from MATLAB via card MF624 and Real Time Target.

The device for testing allows us not only to acquire desired damper characteristic (force-velocity curves) required for modelling and simulation, but also to perform out-of-

the-vehicle tests of shocks with simulated environment and hardware-in-the-loop. The whole system includes the simulation environment mentioned in the paragraph 2, based on SW MATLAB and ADAMS/Car, and the model described in the same chapter.

4. Summary

The paper gives an overview of a design process for a damper for an automotive application, demonstrated on a passive electromagnetic damper. Based on the magnetic field calculations the damper was designed and manufactured. It will be physically tested to evaluate fundamental characteristics of the system and use them in the calculations of mechanical behaviour of the entire system.

5. Acknowledgement

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6. References

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