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MODELLING AND SIMULATION OF AN EXPERIMENTAL VEHICLE WITH MAGNETORHEOLOGICAL DAMPERS

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Abstract. *Semi-active dampers with magnetorheological fluids are a well suited alternative for the classical hydraulic dampers with controllable orifice in many application areas including automotive. This paper proposes a model of the magnetorheological damper suitable for the simulation of vehicle dynamics. The model parameters are identified from the measurements performed with the hydraulic test rig. The model of the semi-active damper is applied to the 3D functional model (virtual prototype) of the LISA car which includes all its important features.*

1 INTRODUCTION

Current vehicles are equipped with many electronic control devices replacing traditional components and assisting the driver in daily and emergency situations. The complexity of such control devices has significantly risen recently. Moreover, the development will be increasingly focused on the advanced control features. It is expected that about 90 % of future innovations in vehicle development will be based on microprocessors and intelligent control programs.

Vehicle suspensions belong to the systems in which passive design has been almost driven to its limits. Thus the controllable suspension is preferable to solve a conflict between comfort and handling. Semi-active suspended vehicles (i.e. with controllable dampers) have been studied for a long time. However, the main target groups have been high-class or sportive personal vehicles and trucks, [1], [2]. City vehicles are placed on the other side of the vehicle spectra. However, recent developments show that the city vehicles, often designed as lightweight vehicles, should combine good handling with a good standard of comfort and moreover are not in the lowest price range. This enables the vehicle features to be extended by using the recent developments in electronics and actuator technology.

Active and semi-active suspension concepts are nowadays a well developed field. However, most of the vehicles with such suspension concepts are equipped with classic hydraulic dampers which are redesigned with controllable orifices to modify the damping, [3], [4]. Alternatively, experiments with electrorheological and magnetorheological fluids have been performed during the last decades, [5], [6]. Favourable features of magnetorheological fluids allow their application in the challenging automotive environment. The magnetorheological fluids seem to be a suitable alternative for the classical semi-active dampers. The main advantage is that the magnetorheological damper does not contain any moving mechanical parts. It could result in better dynamics of the damper.

The control design approach for active suspensions is of interest from a theoretical point of view; in practice it is less fundamental than the other aspects, such as used actuators and sensors, [7]. Generally speaking, nonlinear control concepts are of advantage because of the strong nonlinearity of the actuator, semi-active damper, [8].

In order to evaluate the contribution of semi-active technology based on magnetorheological dampers to the lightweight city vehicles, magnetorheological dampers manufactured by the Lord Company will be applied to an experimental vehicle LISA (light individual city car)

In the first project phase, the magnetorheological damper will be modelled and the parameters will be identified from measurements. Then the model of the damper will be implemented in the simulation model (virtual prototype) of the light individual city car LISA and the control concepts will be developed. Finally, the control concepts will be implemented in the physical prototype of the light individual city car.

2 LIGHT INDIVIDUAL CITY CAR

Light individual city car (LISA) stands for an experimental vehicle designed and manufactured at Munich University of Applied Sciences (FH München). The goal was to design a lightweight vehicle with minimal space requirements and low environment pollution suitable for individual mobility besides public transport means, which should be acceptable from both economical and ecological point of view. Figure 1 presents the second evolution version of LISA, which has new suspension design and new diesel engine. The basic technical parameters of LISA are presented in Table 1.

Figure 1 Experimental Vehicle LISA

Producer:	Munich University of Applied Sciences
Type of vehicle:	two-seat convertible with hardtop
Engine:	3-cylinder-dieselengine
Length:	2,5 m
Width:	1,5 m
Height:	1,3 m
Wheelbase:	1,95 m
Curb weight:	300 kg
Payload:	200 kg
Operation range:	300 km
Consumption:	3 l/100 km
Max power:	13 kW
Max torque:	37 Nm
Gearbox:	6-gear manual

Table 1 Basic parameters of LISA

The recent developments shows that the city cars, often designed as lightweight vehicles, should combine good handling with a good standard of comfort and moreover are not in the lowest price range. This enables the vehicle features to be extended by using the recent developments in electronics and actuator technology. In order to evaluate the contribution of semi-active technology based on magnetorheological dampers to the comfort and active safety of lightweight city vehicles, the magnetorheological dampers will be applied to LISA.

In order to indicate the potential of the semi-active technology for LISA and to design control algorithms, a virtual prototype of LISA is needed. A SIMPACK multibody model of this lightweight car has been prepared, [9], see Figure 2.

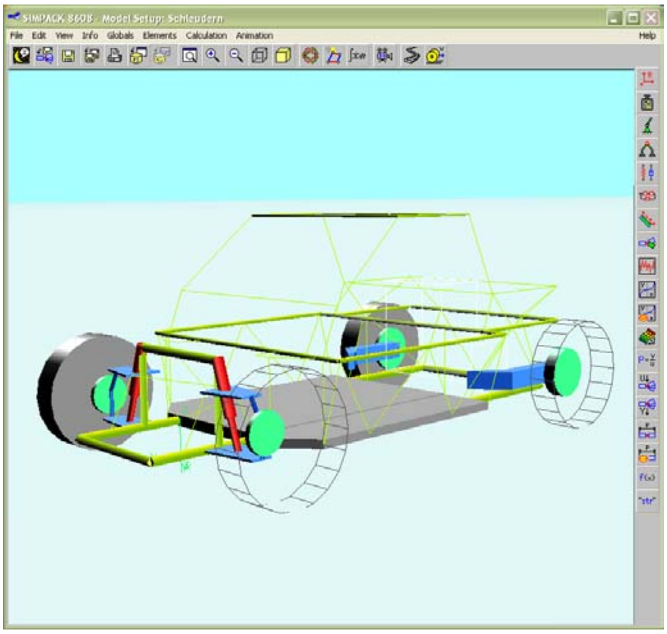

Figure 2 SIMPACK model of LISA, [9]

3 MAGNETORHEOLOGICAL DAMPER

3.1 Magnetorheological Fluids

Magnetorheological (MR) fluids are materials which respond to an applied magnetic field with a change in viscosity. Similar to electrorheological (ER) fluids they include polarizable particles of a micron size, [10], but MR fluids are 20-50 times stronger than ER fluids, [11]. They can also be operated directly from low-voltage power supplies and are far less sensitive to contaminants and extremes in temperature. Similar to ER fluids dates their discovery back to the late 1940s.

The MR fluids are essentially suspensions of magnetizable particles having the size of a few microns in oil. Under normal conditions an MR Fluid is a free-flowing liquid with a consistency similar to that of motor oil, [11], as indicated in Figure 3 left. Exposure to a magnetic field, however, can transform the fluid into a near-solid in milliseconds, Figure 3 right. Just as quickly, the fluid can be returned to its liquid state with the removal of the field. The degree of change in an MR fluid is proportional to the magnitude of the applied magnetic field. If the MR fluid is used in a damper, a damping ration depends on an effective viscosity of the fluid which can be controlled by applied magnetic field.

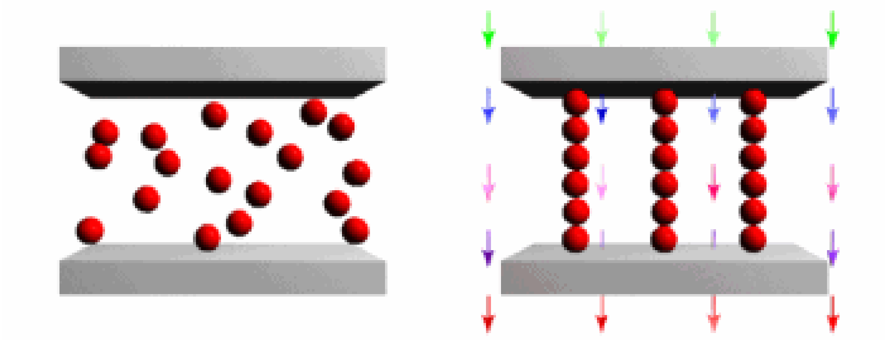

Figure 3 Particles in an MR fluid without (left) and with (right) applied magnetic field from [11]

3.2 Magnetorheological Damper RD-1005-3

In this study a small monotube MR damper RD-1005-3 from the company Lord is used and is presented in Figure 4. The damper is originally designed to be applied in a semi-active seat suspension for heavy trucks. The basic parameters of this damper are presented in Table 2. The damping ration of the MR damper is controlled by input current.

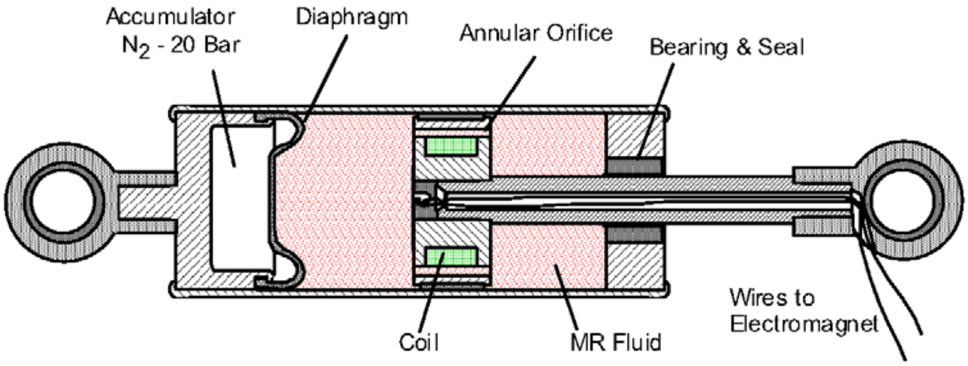

Figure 4 Sketch of a monotube MR Damper for seat Suspension from Lord, [10]

In order to generate the input current for the MR damper a controllable current supply Wonder Box Device Controller RD-3002-3 from the company Lord is purchased. The current supply generating PWM output enables both manual operation and external control with input voltage. The output current is almost linearly proportional to the input voltage beginning at approx. 0.4 to 0.6 V, [11].

Compressed Length	155 mm

Extended Length	208 mm
Body Diameter	41,4 mm
Shaft Diameter	10 mm
Weight	800 g
Electrical Characteristics:	
Input Current	2 A max
Input Voltage	12 V DC
Resistance	5 Ω at ambient temperature 7 Ω at 71°C
Durability	2 million cycles @ ± 13 mm, 2 Hz with input current varying between 0 and 0,8 A
Response Time (amplifier & power supply dependent)	< 25 ms – time to reach 90% of max level during a 0 to 1 A step input @ 51 mm/s

Table 2 Basic parameters of MR damper RD-1005-3, according to [11]

4 MEASUREMENTS OF A MAGNETORHEOLOGICAL DAMPER

In order to get data of the selected MR damper several identification experiments with a hydraulic test rig have been performed. The hydraulic test rig, see Figure 5, consists of a hydraulic cylinder, force sensor and linear position sensor, as indicated in Figure 6.

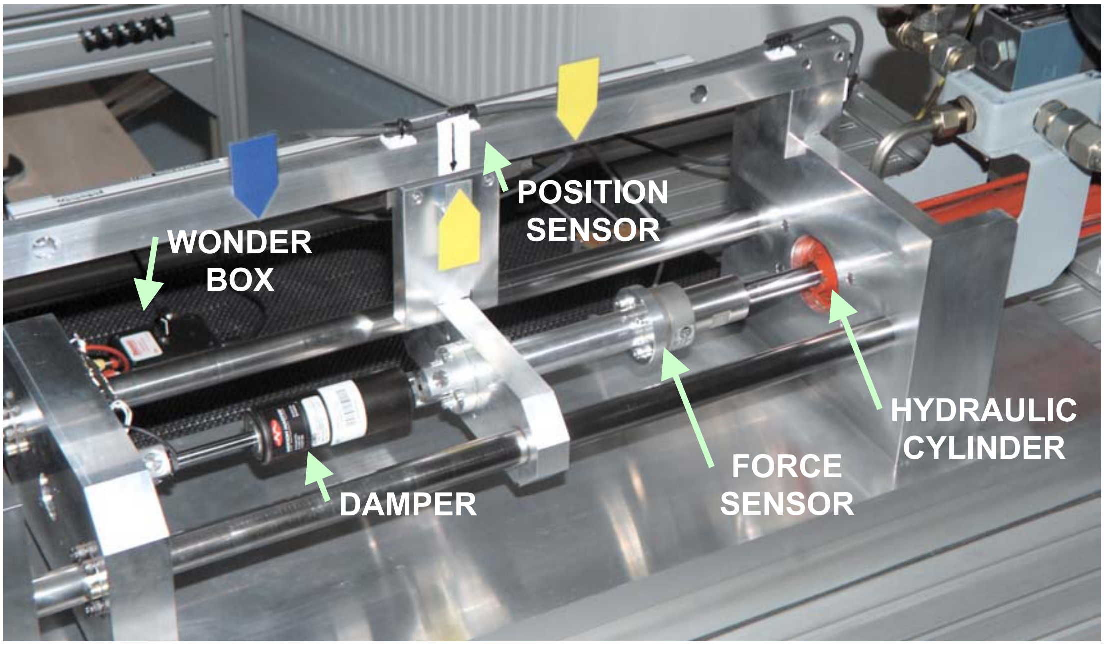

Figure 5 Hydraulic test rig

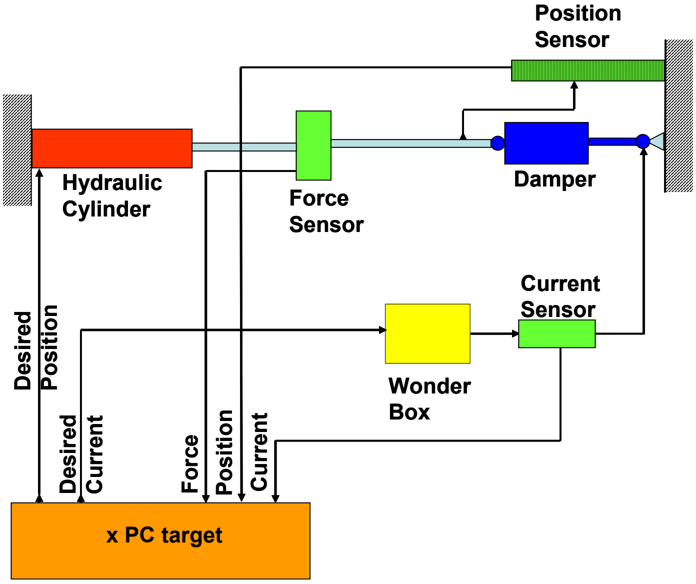

Figure 6 Schematic draft of the hydraulic test rig setup

The data are captured and the experiments are controlled with xPC target computer. Position feedback from the linear position sensor has been used as a basis for the excitations of the MR damper. The measurements have been performed with the sampling frequency 1 ms.

In total 39 different experiments have been carried out in order to measure the properties of the MR damper. The experiment can be divided into three series: (i) harmonic motion of the damper with different frequency and amplitude and with constant current, (ii) static deformation of the damper in order to measure the static preload and (iii) pulse excitation of current at constant damper velocity to measure the damper response to current variation. Furthermore, the static voltage/current characteristics of the Wonder Box have been measured.

5 MODEL OF A MAGNETORHEOLOGICAL DAMPER

Different sorts of models of diverse complexity can be derived to model the semi-active damper. Since the model for vehicle dynamic simulation should approximate the outer behaviour of the damper and not the internal physical states of the magnetorheological fluid, as in a case of physical models, mathematical models are proposed. An overview of the development of a model for an MR damper is given in [12]. A semi-active damper can be considered as a device with two inputs and one output. The inputs are the current velocity and electrical current, the output of the damper is the force.

5.1 Mechanical Model

This paper presents an alternative mechanical structure which is depicted in Figure 7. This model structure originates from the previous modelling of semi-active dampers with controllable orifice. It consists of one damping *d* whose damping ration is nonlinear and depends on the input current. The serial stiffness k_1 stands for parasite elasticity of the MR damper, such as the elasticity of bearing eyes, elasticity of the damper coat or compressibility of the fluid. The serial connection of the damping *d* and the stiffness k_1 results in a system of order one with a newly introduced state ξ. The nonlinear stiffness k_2 in parallel results from the preload in the accumulator required for temperature compensation and to prevent cavitations (see Figure 4).

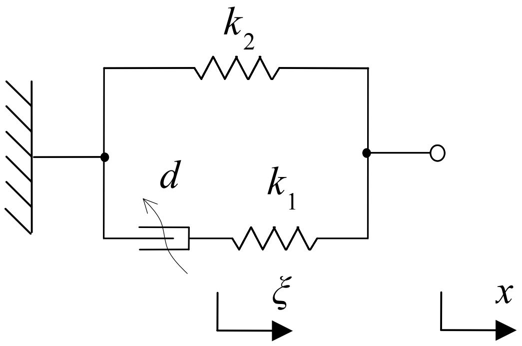

Figure 7 Selected model of the damper

The model in Figure 7 has been implemented in MATLAB/Simulink. The model parameters have been step-by-step identified from the measurements described in the previous section with the aid of parameter optimisation from several measurements. The identified parameters of the stiffness k_1 and k_2 are presented in Table 3. The characteristics of the damping *d* are presented Figure 8.

k_1 [N/m]	$2.505 \cdot 10^6$
k_2 [N/m]	$66736\,x^2 - 165\,x + 162$

Table 3 Parameters of the damper model

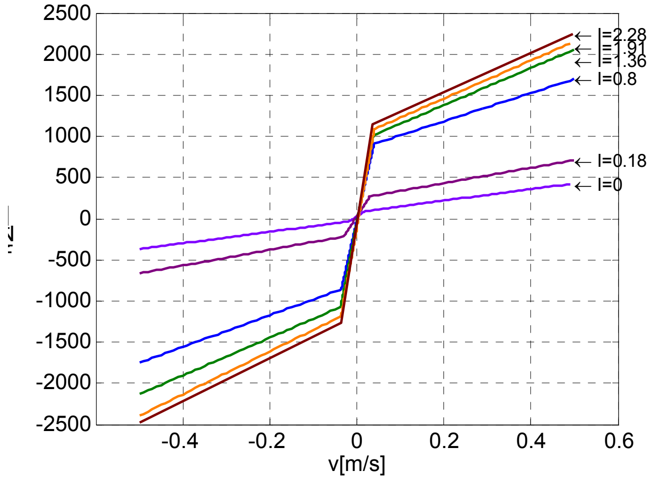

Figure 8 Characteristics of damping d

5.2 Dynamics of Wonder Box

The dynamic response of the semi-active damper plays an important role because its dynamics are usually the limiting factor for the overall effectiveness of the whole control loop. The dynamic response of the damping ration of the MR damper to the electrical input can be divided into two parts. Firstly the dynamics of the electrical current source Wonder Box should be considered. Secondly the dynamic response of the MR fluid itself to the current signal should be included into the model of the MR damper. The consideration of the MR damper dynamics in two parts is motivated by the potential to improve the damper dynamics. On one hand the dynamics of the current source can be relatively easily improved either by feedback current control or by another current source, but on the other hand, the dynamics of the MR fluid are given and cannot be easily changed.

The magnetic field needed to modify the viscosity of the MR fluid is produced by a coil. Since the electrical current is the input of the damper itself, the conversion of the voltage created by the control electronics to current is required to be the task of Wonder Box.

The measurements supported the expectation that the dynamic behaviour is different for falling and growing current. The selected model of the controllable current source Wonder Box is presented in Figure 9. It consists of three blocks. The first block represents the static current/voltage characteristic of the Wonder Box. The dynamic behaviour of the Wonder Box is modelled as a first order system with different time constants for growing and falling input signal (the second block) and time delay (the third block). The parameters of the model are presented in Table 4.

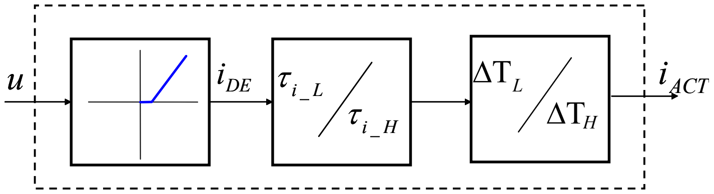

Figure 9 Model of Wonder Box

current	growing (LH)	falling (HL)
τ_i [ms]	7.2	6.4
ΔT [ms]	1	0

Table 4 Parameters of the Wonder Box model

Figure 10 presents the comparison of the measured response of the Wonder Box and the simulation model for the growing current. The simulated current copies relatively precisely the measured one. The experiment has been performed with a step of an input voltage from 0 to 5 V, which causes the current over 2 A. The velocity of the damper has been kept constant.

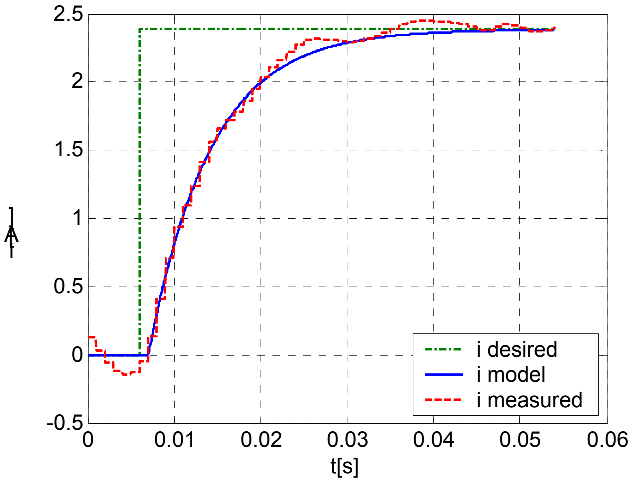

Figure 10 Measured and simulated dynamics of the Wonder Box

5.3 Dynamics of the MR Fluid

The MR fluid brings further dynamic behaviour to the model, which results from the magnetisation and de-magnetisation of the MR fluid. In the case of the magnetisation, i.e. growing input current, it is hard to find any dynamics. However, for the falling current the magnetisation seems to bring significant losses because the polarised domains should be again distributed at random. This behaviour is again modelled as a first order system with different time constants. The second block represents the damping characteristics presented in Figure 8.

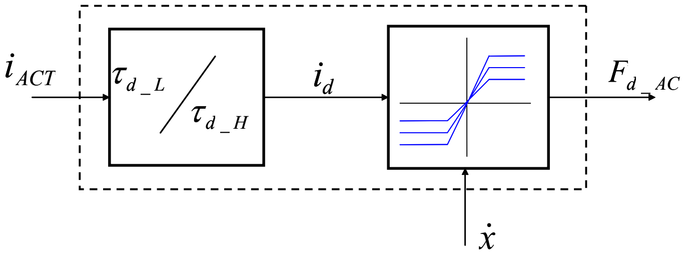

Figure 11 Force dynamics for falling current

current	growing (LH)	falling (HL)
τ_d [ms]	0	16.0

Table 5 Parameters of the model of MR fluid

One can also consider the dynamic behaviour of variation of the damping ratio as with one first order dynamic system covering both Wonder Box and MR fluid dynamics. In such a case the time constant for the falling current describing the overall dynamics would be about 25 ms. The time constant for the growing current would be equal to the time constant of the Wonder Box.

5.4 Final Model

The mechanical model is merged with the model of dynamic response of Wonder Box and MR Fluid. The simulation results are compared with the measurements as presented in

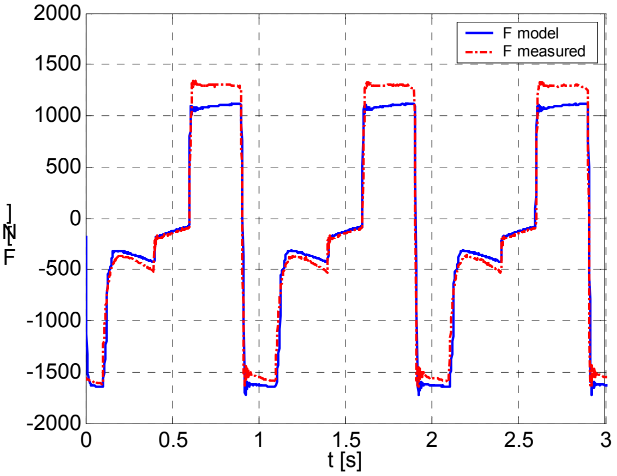

Figure **12**. The simulation results for negative forces copy the measurements with a negligible difference. The measured and simulated positive maximal forces (rebound) differ slightly from each other. The reason could be in a difference of the measured force for the, which could be caused by a temperature influence because the temperature of the damper during last measurements was closed to the maximal operating temperature.

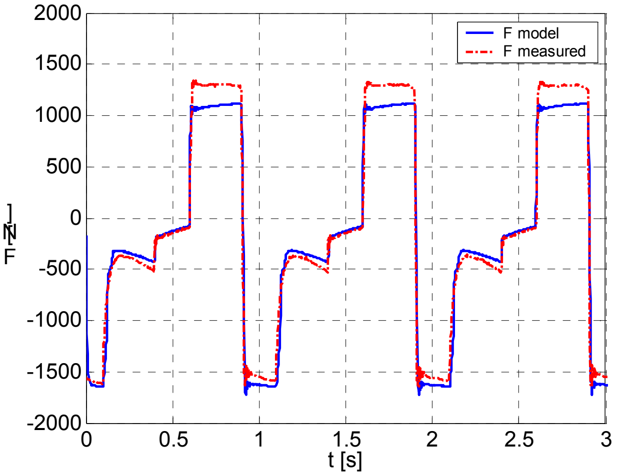

Figure 12 Comparison of simulation and measurements

8 CONCLUSIONS AND OPEN PROBLEMS

In the first phase of the development of a lightweight vehicle with semi-active suspension based on magnetorheological dampers, the model of the damper has been defined and the parameters have been identified based on the measurements. Special interest has been devoted to the modelling of the dynamics of the MR damper, which plays an important role in the efficiency of the control law. The difference of the dynamics for the growing and falling current seems to be significant.

The correlation between measurements and simulation results indicates that the MR damper model structure has been chosen correctly, i.e. it considers all important features of the MR damper and that the parameters have been properly identified. The only difference in the maximal positive force is the topic for the future research and probably also experiments.

Further work will be focused on the optimisation of the controller for typical vehicle manoeuvres and the hardware implementation of the semi-active dampers and their controllers on the prototype of the light individual city car LISA.

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