

# Design and control of an active suspension system with integrated electrical tubular linear motor

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## ABSTRACT

This paper focuses on the design and control of an active suspension system, where a tubular linear motor is integrated into a spring damper system of a vehicle. The spring takes up the weight of the vehicle. Therefore the electric linear motor can be designed very compact as it has to provide forces to adjust the damping characteristic only. Design and construction of the active suspension system, a control strategy and validation measurements at a test bench are presented.

## 1 INTRODUCTION

The traveling comfort of automobile vehicles depends on the behavior of the vertical suspension system. Usually a combination of a mechanical spring and a hydraulic damper is used. Although hydraulic dampers allow some adjustment in their force reaction to a movement, a wide change can only be achieved by choosing another damper-spring combination. Hence the behavior is fixed for a particular vehicle. Adjustments during operation in order to optimize traveling comfort requires a suspension system, where the provided force can be actively set. A linear electric drive would be a suitable active component, since it can be easily controlled and allows fast dynamic force changes. A pure electric system is not feasible because electric motors only deliver forces when currents are present. Thus a hybrid topology similar to the approach described in [1] is chosen, where the electric motor is connected in parallel to a conventional damper and spring. So the linear drive can adjust the system behavior by providing comparatively small propulsive forces. This allows to design a linear motor which can be integrated in the conventional system, thus no extra space is needed for the motor. Compared to existing active damping systems, a simpler integration in the vehicle body is possible since no further adjustments to the body are necessary [2].

## 2 DESIGN OF THE ACTOR

The design has to deal with the conflict of an easy to assemble topology for series production on the one hand in line with high performance to guarantee a good ride comfort on the other hand. So the electric actuator consists of a cylindrical rotor and stator, which are arranged concentrically to each other. The air gap between rotor and stator is  $\delta = 1$  mm, which allows a relative tilt movement of these components to each other without damage. The stator is made of a massive, tubular ferromagnetic material. The slots for the coils, which are three-phase interconnected, are milled in the stator unit. As shown in Fig. 1, each coil of a phase is connected in series. The linor is con-

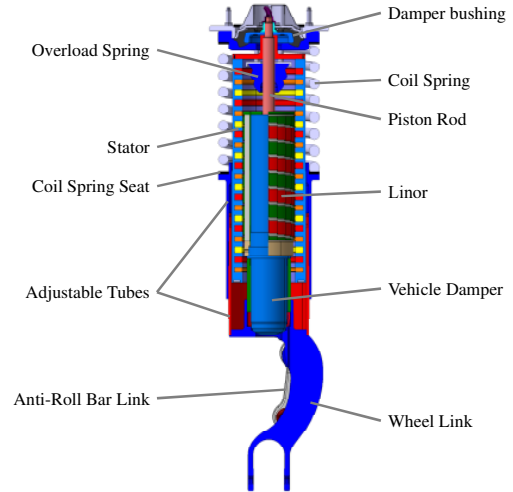


Figure 1: Overview of the designed damping system [2].

structed of soft magnetic laminated sheets that are stacked and braced. The basic magnetic excitation is performed by surface mounted neodymium magnets, which are glued and bandaged. The linor contains 4 pole pairs, each pole pair connected to three stator teeth. Due to the mechanical spring and the oil damper, the complete damping system remains functional during an interruption of the power supply.

### 2.1 Concept

Due to the limited volume of the construction space and the required mechanical strength of the entire system a solid material has to be chosen for the stator. This results, compared to a laminated construction, in barrier-free eddy current paths in the stator which leads to higher eddy current losses in operating points. Since the Energy is generated by the mechanical movement, the eddy currents lead to an additional contribution to the damping. This damping force component will still be present, if the motor is not electrically operated.

The stator is made of two half shells of the material ST27, which was chosen because of its machining properties. On behalf of this geometry the coils are easy to insert into the stator slots. Those coils are designed as concentrated windings because a distributed or helical winding yields no significant advantage in comparison to production effort.

Based on an operational profile the maximum propulsive force has been identified to  $F_{max} = 2$  kN and the maximum mechanical frequency to  $f_{max} = 30$  Hz as well as the maximum linor travel length of  $s = +60$  mm and



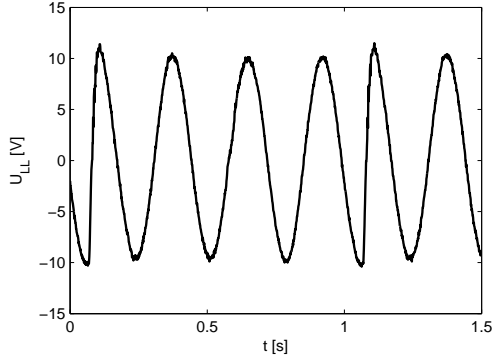


Figure 6: Induced voltage measured for a rectangular speed profile (amplitude 42.5 mm/s, frequency 1 Hz).

the winding at standstill. The permanent magnet flux linkage and the stator inductance  $L$  can be determined by a no load pulling test and a continued short circuit test, respectively. The limited linor moving range requires some adjustments compared to a rotating machine. The no load test has to be performed with constant linor speed and the acceleration to reverse the travel direction has to be kept small. Therefore a comparatively small mechanical speed is chosen, the measured line-to-line voltage is shown in Fig. 6. The induced voltage is distorted at the reversing points, but unaffected during the travel with constant speed. Thus the peak voltage value is taken from the undistorted travel period and the flux linkage can be calculated:

$$\Psi_F = \frac{\hat{u}_{line} \tau_p}{\sqrt{3}v}. \quad (3)$$

The short circuit test is usually carried out at higher speeds to eliminate the influence of the stator resistance. But here the travel length is too small, thus a steady state cannot be reached at higher speed values. The measurement is carried out at low speed instead to ensure that a steady state is reached during the linor travel. The inductance  $L$  can now be calculated from (1) by choosing  $u_d$  and the derivative of  $i_d$  to zero. The identified parameter values are summarized in Table 1.

Since the linor magnets are mounted on the surface, there is no significant reluctance torque to be expected and the direct current set point is thus always zero. The induced voltages are calculated from the measured currents and used as feed forward control signals to linearize the system:

$$u'_d = Ri_d + L \frac{di_d}{dt} \quad \text{and} \quad (4)$$

$$u'_q = Ri_q + L \frac{di_q}{dt} \quad (5)$$

Table 1: Identified electrical motor parameters.

Motor parameter		value
Stator resistance	$R$	2.4 $\Omega$
Inductance	$L$	8.2 mH
Permanent magnet flux linkage	$\Psi_F$	0.2585 Vs

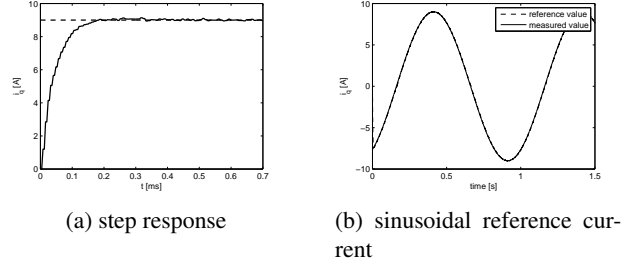


Figure 7: Current controller performance at standstill.

For the feedback path PI controllers are used. The controller reset times are set equal to the electrical time constant to compensate the model pole. The gain is chosen experimentally by evaluating the step response during standstill. Figure 7 shows the measured quadrature current for a choice of  $k_{PI} = 5R$ . The chosen value leads to a fast response without overshoots. Afterwards, a measurement with a sinusoidal reference current is carried out. Here, a frequency of  $f = 1$  Hz was chosen. As seen in Fig. 7, the controller can impress a sinusoidal current as well.

For further validation additional measurements during movement are taken. The linor is sinusoidally moved by a hydraulic actor with a position amplitude of 25 mm and a frequency of 0.8 Hz. Figure 8 shows the results for a constant reference quadrature current. The mechanical position amplitude is increased and decreased sinusoidally at start up and end of the measurement to avoid high oil pressure peaks in the hydraulic system. The same experiment was then repeated with a sinusoidal reference current, as shown in Fig. 9. The results indicate that the current controller performance is not affected. Since for the moving measurements the reference current frequency is increased to 30 Hz, a higher phase delay between reference and actual current is observed in Fig. 9. This could be compensated by a faster controller setting, since further measurements indicated that a stable operation would still be possible with increased controller gains.

### 3.2 Force control

The motor force could be controlled by an outer feedback loop, but in the combined actor only the overall force

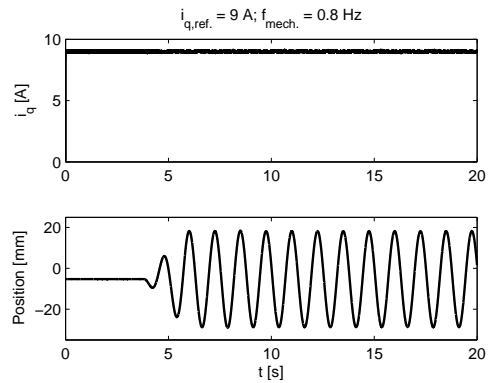


Figure 8: Controller performance at constant reference current during movement.

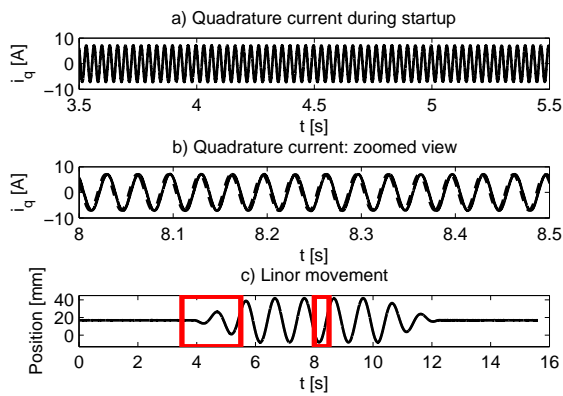


Figure 9: Controller performance at sinusoidal reference current during movement start up (a) and steady-state (b). The shown time intervals are highlighted in the position trajectory plot (c).

is measurable, which contains components generated by linear motor, hydraulic damper, friction in the case bearing and the inertia of the moving parts. Due to the non-linear behavior of damper and friction forces, a separation of the motor force is complex. Therefore a feed-forward control scheme is implemented instead. In a first step, a static test bench shown in Fig. 10 is used to identify the propulsive motor force. The coil spring is removed and a manual spindle drive allows to change the linor position. During the measurements the linor is at standstill, thus the damper does not generate any force and the motor force can be measured directly. The force is measured for different positions and quadrature currents, the results are shown in Fig. 11. With the acquired data a control matrix can be

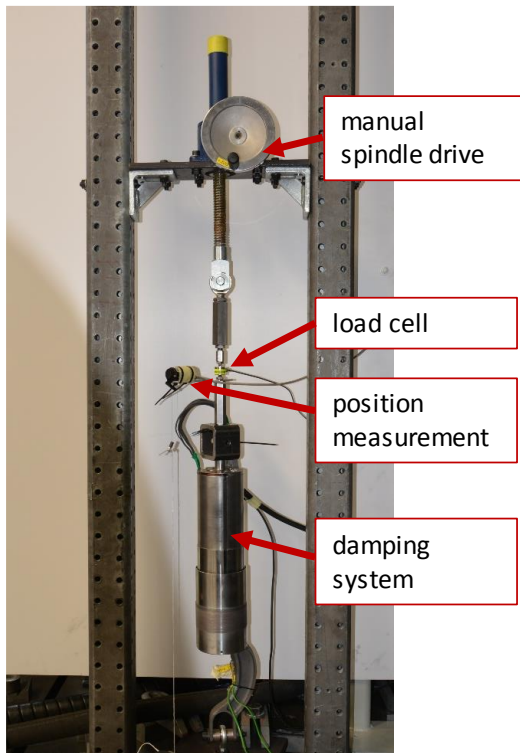


Figure 10: Testbench for force measurements.

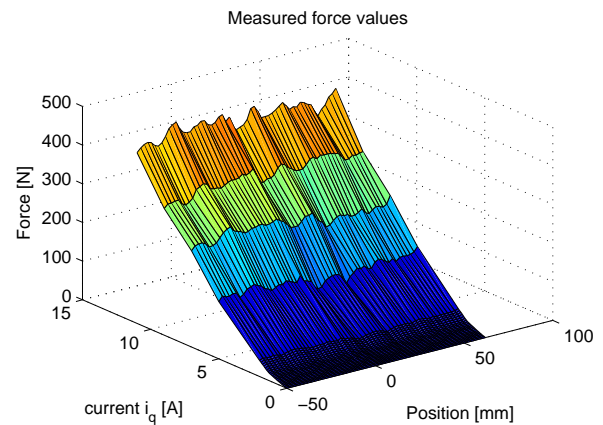


Figure 11: Measured force for different positions and reference quadrature currents.

generated, which contains the reference current for different linor positions and force command values. With the control matrix, the difference between measured and reference force was limited to 10 %.

#### 4 CONCLUSION

For an active automobile suspension system a compact electric linear motor with skewed permanent magnets is designed. By impressing an additional force the designed actuator is able to change the behavior of the damping system. The functionality of the field oriented control is validated by measurements at standstill and during linor movement. A feed forward force control strategy is designed based on force measurements on the testbench. In a future work, the damping system can be mounted in a testbench setup containing additional parts of the vehicle suspension. Furthermore, the system can be tested in an actual vehicle.

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